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# **AERATION AND RHEOLOGY OF HIGH FIBRE BREAD DOUGHS**

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A thesis submitted to the University of Huddersfield in partial fulfilment of  
the requirements for the degree of Doctor of Philosophy

University of Huddersfield

December 2019

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## Abstract

Although there is continuous advice to increase consumption of dietary fibre, the intake of dietary fibre by individuals remains inadequate. Bread is potentially a major source of dietary fibre in the population; however, a factor mitigating against adequate consumption of high fibre bread is the damage caused by the fibre to the aerated structures of bread, which is key to its palatability and appeal. Wheat bran is a rich source of dietary fibre but its presence in wholemeal bread damages the aerated structures and lessens its appeal.

Addition of wheat bran and other sources of dietary fibre to bread tends to give decreased dough strength and loaf volume, impaired crumb structure and reduced crumb softness. Potential mechanisms reported in the literature by which bran exerts its deleterious effects include dilution of the gluten protein, mechanical disruption of gluten films, and starch gelatinisation at a lower temperature during baking (as a consequence of the increased water availability) giving less oven spring and lower loaf volumes. The particle size of the wheat bran mediates its detrimental effect, with smaller particles generally giving finer crumb textures, although not necessarily producing larger loaf volumes or the most appealing or healthy bread.

However, the full complexity of the effects of bran within the range of dough formulations and breadmaking processes is not yet understood, making it hard to find ways to produce acceptable high-fibre breads. Meanwhile, another potential new class of fibre-based bakery ingredient are Arabinoxylans (AX) which can be extracted from biorefinery by-products such as wheat bran, oat bran and sugarcane bagasse. AX can have either beneficial or detrimental effects on the dough depending on the type or level of AX used. This thesis therefore presents work to understand effects of bran and AX on dough aeration and rheology in order to better understand their effects in bread.

The effects of ethanol and retardation time (over 18 hours at 4°C) were investigated with the use of the Dynamic Dough Density (DDD) system, to investigate the hypothesis that retardation affected dough expansion through the production of ethanol by the yeast during the retardation period, and to demonstrate the sensitivity and usefulness of the DDD system prior to its use to investigate fibre effects in doughs. The addition of ethanol even at small levels decreased the maximum expansion of dough, while retardation showed the reverse, giving an increase in maximum dough expansion over time. It was therefore concluded that the effects of retardation did not arise as a result of ethanol. The DDD system proved a sensitive discriminator of these effects.

The Solvent Retention Capacity (SRC) test was used to determine the effect of fibre addition on water absorption. The SRC test uses four solvents to distinguish effects related to protein, starch damage and pentosans. The test was sensitive to addition of bran and AX, but its interpretation was ambiguous as it is conventionally used for characterising white flours.

Rheological studies were carried out using creep-recovery measurements and the expansion capabilities of dough formulations were investigated using the DDD system. Bread doughs were found to be less compliant with an increase in the level of fibre added; AX also inhibited the expansion capacity of bread doughs.

Bread aeration and dough rheology were investigated simultaneously by varying processing and ingredient factors during mixing. Dough aeration was quantified using dough density measurements, while dough rheology was characterised under dynamic oscillatory deformations using a Kinexus rheometer. Doughs were prepared using a bench top Minorpin mixer and a high-speed laboratory scale Tweedy 1 mixer. The high-speed Tweedy 1 mixer developed the gluten network better, leading to greater DDD expansion than the doughs produced from the Minorpin mixer. Dough formulations containing wheat bran gave less expansion in the DDD system. Dough formulations containing AX from wheat bran and from sugarcane bagasse also decreased DDD expansion, more so for AX from bagasse than wheat bran. Bread loaf volume decreased in all formulations with added fibre.

The current work has expanded understanding of the effects of fibre on aspects of dough and bread quality: aeration and rheology of doughs, water absorption, expansion of doughs, and baked loaf volume.

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## Acknowledgements

I would firstly like to say Alhamdullillah to the Almighty Allah for guiding me to this point, giving me the strength to carry out my research and for a super supportive supervisor. Professor Grant Campbell, thank you very much for your supervision and valuable guidance throughout my time in research at the University of Huddersfield. I will be forever grateful to have been blessed with a supervisor like yourself. I would also like to say thank you to Dr Vassillis Kontogiorgos, who was my co-supervisor for his vital input and help during my time in the laboratory. Every member of my research group, I thank you for all the times together. I am grateful to Dr Katerina Alba for her time during challenging times and assisting me with experiments. To all the technician in the School of Applied Sciences, I say a massive thank you for all your help and support.

To my family, God bless you. I am eternally grateful for the most supportive and loving parents a child could ever wish for. My siblings (Emi, Rukky, Halima, Awwal and Musa), you are a crucial part of my life and a constant motivation when things were tough so thank you very much for your love, support and moments of laughter from thousands of miles away. To my uncle and guardian thank you for opening your home to me and giving me a space to call home here in the UK. Selasi my love, you have been my backbone throughout my writing up period and I am grateful for you and your unending love and patience, God bless you abundantly. To all my friends, thank you for your care, support and constant reminders that I can do this I am grateful.

## List of Abbreviations

AACC	American Association of Cereal Chemist
API	Arabinoxylan Performance Index
AX	Arabinoxylan
CBP	Chorleywood Bread Process
DDD	Dynamic Dough Density
DF	Dietary Fibre
GPI	Gluten Performance Index
H <sub>2</sub> O-SRC	Water Solvent Retention Capacity
La-SRC	Lactic Acid Solvent Retention Capacity
LVR	Linear Viscoelastic Range
MDD	Mechanical Dough Development
Na <sub>2</sub> CO <sub>3</sub> -SRC	Sodium Carbonate Solvent Retention Capacity
RVA	Rapid Visco Analyser
SCBAX	Sugarcane Bagasse Arabinoxylan
SRC	Solvent Retention Capacity
Su-SRC	Sucrose Solvent Retention Capacity
TPA	Texture Profile Analyser
WAC	Water Absorption Capacity
WBAX	Wheat Bran Arabinoxylan
WHC	Water Holding Capacity

## List of Definitions/Terminologies

Aeration	The process by which and the amount of air bubbles and gas cells present in the dough and bread
Baking absorption	The amount of moisture taken up by the bread dough during baking in order to produce quality end-product
Brown and white bread	Brown bread is a bread that has a higher amount of wholegrain (containing bran) flour while white bread is made from just the endosperm of a wheat bread and not the bran
Chewiness	This is the mouthful sensation due to chewing process mimicked using a texture profile analyser
Deleterious effects	These are the negative effects observed from the addition of fibre to flour. Negative effect used in the current work to mean deleterious.
Dough development	Changes in the physical properties of bread dough to improve its ability to retain carbon dioxide gas thus, encouraging dough expansion
Dynamic dough density	The dynamic dough density is the change in dough density over time which indicates the expansion capacity of the dough
Expansion capacity	The expansion capacity of the dough is the ability of the dough to stretch due to bubble growth in the Dynamic Dough Density (DDD) system without breaking
Firmness	The quality of having a solid, almost yielding surface or structure of bread
Gas retention	The ability of a dough to hold gas during the breadmaking stages
Gluten dilution	The breakdown or disruption of the gluten network by addition of fibre into a dough formulation
Hard flour	A hard flour is one with high protein content and higher gluten content e.g. bread flour
Hardness	The Hardness value is the peak force that occurs during the first compression. The hardness need not occur at the point of deepest compression, although it typically does for most products
Hildebrand solubility parameter	Provides a numerical estimate of the degree of interaction between materials and can be an

	indication of solubility, particular to non-polar materials
Insoluble fibre	Indigestible carbohydrates that do not dissolve in water
Loaf gradient	The rate of change of the loaf over the baking time
Maximum capacity	The highest expansion ability of a dough before deformation
Palatable	Pleasant to taste
Quality	The standard of something as measured against other things of a similar kind
Retarding	To delay the process of dough development
Rheology	The study of flow and deformation of materials
Soft flour	A flour is said to be soft when it has a less protein content and weaker gluten content e.g. cake and pastry flour
Soluble fibre	A form of water-soluble carbohydrates that cannot be digested by the body
Static dough density	The density of a dough without yeast production and expansion
Viscoelasticity	The property of a substance exhibiting both elastic and viscous properties
Water absorption (capacity and rate)	The ability and amount of water required to hydrate a dough adequately
Water holding capacity	The ability of a substance to retain water
WEAX	Water Extractable AX are shorter chains AX polysaccharides with less cross-linking and less linkage to the other cell wall components (Biliaderis, Izydorczyk, & Rattan, 1995)
Whole-wheat wholemeal bread	or Whole-wheat and wholemeal are the same with the only difference being 'whole-wheat' is American while 'wholemeal' is British. This flour is a powdery substance derived by grinding or mashing the wholegrain of wheat to produce flour used for bread making
WUAX	Water Unextractable AX are strongly attached to the cell wall matrix by covalent and non-covalent linkages to adjacent AX and other cell wall constituents (Biliaderis et al., 1995)

## **Chapter 1. Bread Introduction**

Bread is a unique food because of its unparalleled importance to the history, technology and sociology of mankind. It is consumed in every part of the world in large amounts and in widely differing countries. Bread consumption dates as far back as the Neolithic era, by a process called baking using an oven (Mondal & Datta, 2008).

Consumption of bread is recommended as part of a healthy diet. The USDA Food Guide, the Canadian Food Guide and the UK Eating Right Pyramid all have bread contributing to the largest food group, being both healthy and nutritionally dense. Bread is consumed daily in the UK and in almost every household. It is the traditional and staple item in the UK diet, with household penetration of almost a 100%. The average UK household buys slightly over 80 loaves of bread per year, spending an average of £54 (Federation of Bakers, 2018). The UK bread market has been fully saturated but in 2007, due to poor harvest and the rise on energy and processing cost, the standard loaf was priced at £1 for the first time (Federation of Bakers, 2018). The top three UK bread manufacturers are Allied Bakeries, Hovis and Warburtons who together account for about 75% of wrapped bread (Federation of Bakers, 2018). The total market (bread and bakery product) reached a value of £3.6 bn in the UK in 2018 and is one of the largest markets in the food industry. About 11 million loaves and packs are sold every day (Federation of Bakers, 2018).

Bread has been used for political influence among governing population for over two thousand years (Mondal & Datta, 2008). Brexit is likely to have a negative impact on the bread industry and the Federation of Bakers (FOB) is monitoring the issue very closely to reduce the impact as much as possible (Federation of Bakers, 2018). Some processed food companies (such as Kellogg's and Mondelez) can stockpile materials ahead of a Brexit deal or a no-deal outcome but the bread industry does not have such flexibility. While some stakeholders say there will be minimum impact from Brexit, others advise that plans should be put in place as the impact would be detrimental. 85% of the wheat used in the UK is home grown, according to the National Association of British and Irish Flour Millers and this is a positive source of resilience for the UK. Another reason why it is believed that there would be minimum impact from Brexit is that Canada is the UK's main source of importing hard wheat. However, there might be challenges of importing soft wheat especially from Germany and France if a Brexit no-deal happens. Another potential issue is the rise of the cost of ingredients, as most ingredients are imported from the European Union. These are actions manufacturers can think about to help prepare for the unknown outcome of the Brexit.

One of the biggest impacts to the bakery industry is likely to be the sourcing speciality ingredients from neighbouring European countries. This is because the market will not be as flexible. However, a positive of a Brexit deal is that the British people's expectation of high-quality products could be achieved (World Bakers, 2018).

The baked goods market comprises two sectors, bread and bakery products. The bread market is further subdivided into three sectors; white breads, brown and wholemeal breads, and ethnic and speciality breads. White bread is the most consumed and favourite choice (71%) of the total bread consumption in the UK, followed by brown and wholemeal bread (22%) and ethnic and speciality breads account for 7% of the total market (Federation of Bakers, 2018). Bakery products known as ‘morning goods’ consist of rolls, baps, muffins, crumpets, teacakes, scones, buns etc. These three sectors are found within the large plant bakeries, in-store bakeries and craft bakers (Table 1.1). Bread, as a staple food and representing the most important sector of bakery products, remains as an important subject of study.

*Table 1.1: Market share of UK bread production by value and volume (Federation of Bakers, 2018)*

	% by value	% by volume
<b>Large plant bakers</b>	75	85
<b>In-store bakeries (ISB)</b>	20	12
<b>Craft bakers</b>	5	3
	100	100

The distinctive aerated structure of bread that is central to its appeal is made possible by the unique rheological characteristics of the dough, arising from the viscoelastic and strain hardening properties of the wheat gluten proteins. Although many bread studies have focused on the rheological aspects, for a more complete understanding of bread and dough behaviour the aeration and rheology of doughs should be studied simultaneously (Campbell *et al.* 2008c; Trinh, *et al.* 2013). While aeration gives bread its unique textural and organoleptic characteristics, dough rheology through the presence of gluten

proteins enables adequate gas retention to occur, while aeration during mixing contributes to oxygen availability and hence development of the gluten network (Campbell & Martin, 2012; Trinh *et al.*, 2013). Therefore, it is important to study aeration and rheology together.

Most previous bread studies have focused on either aeration or rheology, with few studies being carried out on the relationship or interaction of both together (Chin & Campbell, 2005a; Chin *et al.*, 2005; Martin *et al.*, 2004). An even more limited number of studies have been carried out on the relationship and interaction of aeration and rheology in high fibre breads and doughs (Hemdane *et al.* 2015, 2017; Noort *et al.* 2010; Packkia-Doss *et al.* 2019).

To view this research field from a broader perspective, it can be observed that rheology has been prominent in the bread research literature for a long time; the unique rheology arising from wheat gluten proteins that allow the production of raised loaves has been a natural focus of research to understand and characterise this rheology and relate it to gluten protein quality and to bread structure (Hemdane *et al.* 2017; Jacobs *et al.* 2015; MacRitchie, 2016; Packkia-Doss *et al.* 2019). Aeration has been a more recent focus over the last few decades (although the pioneering work of Baker and Mize on the origin of aerated structures in bread took place in the 1930s and 40s). In both cases, however, most studies have been on white flour doughs. The current work aims to combine some of the recent advances in understanding the creation of aerated structure with the longer-standing knowledge of dough and gluten rheology, to apply both perspectives of the science and technology of bread to

high-fibre formulations. If the appeal of bread arises from its aerated structure, enabled through the unique rheological properties of gluten, but consumption of high-fibre breads is compromised because of the damage fibre causes to gluten and to aeration, then understanding the effects of fibre on rheology and aeration is key to understanding how to produce high-fibre breads that retain palatability and appeal for consumers, and thereby deliver the health benefits of a high-fibre diet.

### **1.1 Bread, its history and significance**

Bread is one of the most studied foods due to its long history as one of the principal forms of food for mankind (Dukes *et al.*, 1995; Mondal & Datta, 2008; Qarooni *et al.*, 1992). Archaeological evidence indicates that original unleavened (unraised) bread, baked on heated stones, was first made during the Neolithic period (Stone Age) (Chin, 2003). Baked leavened bread was believed to be first made by Ancient Egyptians (Chin, 2003; Qarooni *et al.*, 1992), the frontier settlers of the breadmaking process, making it a worldwide food (Mondal & Datta, 2008). The fermentation of bread started around 3000 B.C. using wild yeast in the presence of water to mix flour and water (Abang Zaidel *et al.*, 2008; Chin, 2003; Faridi & Rubenthaler, 1983). After some time, the Egyptians created ovens that could bake several loaves at the same time. Interestingly, breads and baked rolls were found around Egyptian tombs; probably because the workers who built the pyramids were paid in bread (Chin, 2003; Federation of Bakers, 2018). From 1800 B.C. - 1 A.D. (the Bronze and Iron ages), bread was consumed

in Europe and later became a staple European food (Abang Zaidel *et al.*, 2008; Chin, 2003; Dukes *et al.*, 1995; Faridi & Rubenthaler, 1983). The Egyptians passed the knowledge acquired about baking to the Greeks and Romans who consumed a lot of bread (Chin, 2003; Faridi & Rubenthaler, 1983; Federation of Bakers, 2018; Qarooni *et al.*, 1992). Bread is very important in the Roman culture and religion (catholic Holy Communion). A lot of bread was produced by the Romans during the time of Emperor Aurelian (270 A.D.) to feed the poor (Abang Zaidel *et al.*, 2008; Chin, 2003; Faridi & Rubenthaler, 1983; Qarooni *et al.*, 1992).

Even as far back as the time of Emperor Aurelian, people argued about whether white bread was better than brown bread and vice versa. Wealthy Romans used to insist on the more exclusive and expensive white bread (which is presently advocated against and the wealthy of society now want the brown bread) (Chin, 2003; Federation of Bakers, 2018). By 1202 A.D., England had adopted laws to regulate the price of bread and the limit of bakers' profits. Bread became extremely popular and the staple in every part of the world including the Scandinavian countries and America. Breads are consumed in its unleavened form (flat bread) in the Middle East and North Africa. Western style loaves are gaining a very high popularity in traditional rice bowl countries like China, Korea and Japan. Bread has been consumed for a long time and will continue to be an integral part of human diet throughout human existence (Mondal & Datta, 2008). Presently, bread is still associated with the state of people's living conditions; bread shortage is associated with difficulty while the possibility of the availability of bread is associated with hope for a better life (Mondal & Datta, 2008; Scanlon & Zghal, 2001).

Bread is eaten in different shapes, sizes and, forms in response to cultural, textural and sensorial preferences. Globally, bread varies according to ingredients used for production, processing techniques and methods for storage to prolong bread shelf life (Chin, 2003; Faridi & Rubenthaler, 1983). Reasons why there are different types of breads include environmental conditions of wheat cultivation due to difference in geographic locations, cultural factors (traditional and religious beliefs) and also the possibility of change to economic and political conditions (Cauvain, 2015; Chin, 2003). For these reasons, it is difficult to term a bread as 'good' or 'bad' as personal preferences and values play a large part in the type of bread an individual eats (Cauvain, 2015; Chin, 2003). Breads have different sensorial characteristics; English bread is generally considered to be plain, American bread is buttery and sweet, French bread is uniquely characterised with having large aerated holes and a plain taste, Scandinavian bread is often made with milk, Scottish bread has a pronounced flavour due to batch fermentation during production, the traditional Chinese bread is steamed into buns shapes and finally the Middle Eastern and traditional Indian breads are round and flat in shape (Chin, 2003; Faridi & Rubenthaler, 1983; Qarooni *et al.*, 1992). Irrespective of these variations, bakers are continually challenged by consumers to produce acceptable breads of specific quality and characteristics (Cauvain, 2015; Chin, 2003). A particular bread type is usually described by its physical appearance, starting from the external form (Cauvain, 2015; Chin, 2003; Faridi & Rubenthaler, 1983; Qarooni *et al.*, 1992).

Over many years, bread consumption by humans has taken a wider range based on local and traditional preferences from all over the world. But the term 'bread'

stands for a staple food made from a dough derived from cereal wheat cultivation. In recent years, other types of cereal flour types such as rye, oats and barleys have been used to produce different types of breads (Chin, 2003; Drzikova *et al.*, 2005). This is as a result of a higher awareness in health conditions such as coeliac diseases (Chin, 2003; Drzikova *et al.*, 2005). The superior nutritional profile of wheat makes bread capable of supplying the majority of nutrients necessary to sustain life (Chin, 2003; Dukes *et al.*, 1995). One reason why bread is so popularly consumed is because it is an excellent nutritional source; energy source (from carbohydrates), growth and development (from proteins), good health, good nerves and good digestion (from essential B vitamins), healthy blood (from iron) and strong bones and teeth (from calcium) (Chin, 2003). Bread (brown and wholemeal) also contains substantial levels of fibre which is important in elimination of bodily waste (resulting in a healthy gut) (Chin, 2003). White flour which is used to make most consumed bread can be enriched with fibre to make breads that are more of a healthy option (Chin, 2003; Dukes *et al.*, 1995).

Bread is not only important for its significance to humans as food, it also has religious as well as cultural significance. In religion to religious, bread has a strong significance as illustrated by a number of customs, traditions and articles and as being described as the 'staff of life' (Scanlon & Zghal, 2001). Christians give bread during the Holy Communion along with wine, symbolizing a believer's connection to the body of Christ. In Islam, bread is considered a gift from Allah as provision for his followers.

The baker's trade is recognised as one of the oldest crafts in the world due to the significance as well as long history of bread (Chin, 2003). Breadmaking was less of a science and more of an art in ancient years; but with help of science and research, a more focused light has been shed into this unique craft, thus, providing more understanding. Although bread science is now a well-established and mature field (MacRitchie, 2016), most of the research is probably focused either around a particular attribute or linking a particular attribute to a specific processing condition (Hayman *et al.*, 1998; Scanlon & Zghal, 2001).

This thesis is concerned with studying breads and bread doughs fortified using fibre ingredients during the mixing, proving and baking stages of the breadmaking process. In this thesis, 'bread' refers to the Western yeast leavened white sandwich loaf (unless stated otherwise) and 'breadmaking' refers to the process of making such bread.

## **1.2 Aims of the research**

Bread gains its distinctiveness from the characteristics of its gas cells, and mixing is the process of creating those gas cell structures, starting as air bubbles in dough. Hence, aeration of dough during mixing is a very important process (Campbell, 1991); understanding the breadmaking process should start by first looking at the aeration of the bread dough during mixing, a premise that applies to understanding wholemeal and high-fibre breads as well as the more extensively studied white bread. The main objective of the current research is

therefore to improve the existing knowledge on bread aeration affected by fibre. The effect of high fibre ingredients (wheat bran and arabinoxylans) on bread dough microstructure is investigated extensively. Arabinoxylans (AX) are a prominent component of wheat bran and potentially a fibre source that could act as an ingredient in breads, thereby increasing fibre intake by consumers and improving the health of the population. Experimental investigations use the Dynamic Dough Density (DDD) system to describe the proving process in bread dough, as this has been shown to be a sensitive indicator of factors affecting the ability of doughs to expand and retain gas. In addition, the behaviour of doughs is investigated using dynamic oscillatory rheological studies. Addition of fibre to bread formulations always raises the issue of how much additional water to add; a further objective is to seek a suitable method for quantifying the amount of water required for fibre-enriched bread dough formulations.

### **1.3 Scope of the thesis**

Production of bread that is rich in fibre while retaining sensory is a continuous challenge in the breadmaking industry. While white bread is enjoyed because of its aerated structures, these are less palatable in wholemeal breads due to the competition of fibre with the rest of the dough formulation ingredients for the available water needed for proper dough formation and gluten interaction. For this reason, understanding the effects of high fibres on dough will provide important information as to how to improve wholemeal bread to enhance consumer acceptability and preference.

This thesis presents studies of bread dough aeration and rheology during mixing and proving at both microscopic and macroscopic levels.

Chapter 2 overviews previous studies carried out on aeration and rheology of bread and dough in order to clarify the context and landscape of this research area and to identify the motivation for and objectives of the current work. The roles of air bubbles in bread dough and the mechanisms by which they create aerated structure are reviewed, along with studies on the effects of processing and ingredients to create and control bubbles in bread dough. Rheological studies of dough and the effect of wheat bran on dough rheology and processing and baked loaf quality are also reviewed.

Chapter 3 presents an overview of previous studies carried out on arabinoxylans and bread dough. The functionality of arabinoxylans and their effects on dough and potential as a bakery ingredient are discussed.

Dynamic dough density (DDD) is a sensitive technique developed in recent years for measuring the effects of processing and ingredients on the ability of dough to expand and retain gas under conditions mimicking proving. DDD was used in the current work to quantify effects of wheat bran and AX on dough expansion and gas retention. Prior to this work, the DDD technique was used to investigate another phenomenon of interest, the effect of retarding doughs (storing at low temperature) on their subsequent ability to expand during proving. It was hypothesized that observed effects were related to ethanol production by yeast; this hypothesis was tested both for its own interest and to demonstrate the value of the DDD technique. Chapter 4 introduces the DDD

system and describes its application for this preliminary study, prior to subsequent studies focussed on wheat bran and AX.

A major factor influencing the effects of wheat bran and fibre is their capacity for absorbing water, requiring additional water to be added to the dough formulation, and affecting water partitioning later in the breadmaking process. Chapter 5 presents the Solvent Retention Capacity (SRC) test used for the determination of water absorption as affected by different components of the flour. SRC uses four different solvents to elucidate effects of arabinoxylans, gluten and damaged starch on water absorption. As determining the adequate amount of water for a fibre-rich dough is still an ongoing challenge, the SRC test offers a basis for addressing this issue. This chapter evaluates the SRC method in the context of other methods used to determine dough water absorption.

Chapter 6 presents a systematic investigation of the effects of fibre on dough aeration and rheology in doughs prepared in the Henry Simon Minorpin mixer. The effect of fibre ingredients on dough expansion is investigated using the DDD system, while rheological studies are carried using the Malvern Kinexus rheometer for different flour types and water levels.

Chapter 7 extends the investigations of dough aeration and rheology to doughs mechanically developed in a high speed Tweedy 1 mixer, and extends the investigation to include baked loaves, which are characterised using a Stable MicroSystems Texture Analyzer. The effects of processing factors (mixer type

and pressure) and ingredient factor (fibre type and amount of water) are also investigated using the Tweedy 1 mixer and DDD system.

Chapter 8 summarises the findings and progress made in this current research and presents recommendations for further research and for industrial relevance of the current work.

## Chapter 2. Aeration and rheology of bread doughs

### 2.1 Introduction

Bread is a staple food obtained from a mixture of wheat flour, salt, water and yeast through the process of baking (Dobraszczyk & Morgenstern, 2003). According to a food scientist or technologist, bread is an unstable, elastic, solid foam. It is defined in this way because of the viscoelastic properties obtained from the gluten network interaction in dough and the ability of dough to be shaped differently according to the baked product required (Gray and BeMiller, 2003). The appeal of bread arises from its aerated structure (Campbell & Martin, 2012). However, healthier wholemeal and fibre-enriched breads suffer from less palatable structures, as the bran particles destroy the bubbles, such that the nutritional benefits of these breads are compromised through low consumption (Campbell *et al.* 2008c). Although bread has been scientifically studied for most of the last century, a complete understanding into the entire process is still unclear (MacRitchie, 2016). This is because of the inherent complexity of the fundamental physical processes (such as volume expansion, dough density, starch gelatinisation, protein denaturation and crust formation) and of experimental and mathematical models designed to better understand baking (Mondal & Datta, 2008), making the quality of bread difficult to be comprehensively defined (Scanlon & Zghal, 2001).

This chapter explores the importance of dietary fibre, of which wheat is a major source, and discusses bread as a means of increasing dietary fibre consumption. The effects of incorporating wheat bran into bread formulations, and possible

ways to overcome these deleterious effects, are reviewed. Aeration and rheological behaviour throughout the breadmaking process are described, with a brief history of the breadmaking process and the stages carried out in the production of bread.

## **2.2 Dietary fibre and its health benefits**

According to the American Association of Cereal Chemists (AACC), ‘dietary fibre is the edible part of plants (includes cellulose, lignin and hemicelluloses) that can neither be absorbed in the small intestine or digested but has significant health benefits’ (AACC, 2001; Hartikainen & Katina, 2012; Vitaglione *et al.*, 2008). A rich source of dietary fibre is cereal bran, with wheat bran being one of the most important cereal fibre sources (Ferguson & Harris, 1997; Sidhu *et al.*, 1999; Uysal *et al.*, 2007; Vetter, 1988). Wheat bran is the outer fraction of cereal grain and is a rich source of protein, carbohydrate, vitamins and minerals, thus, addition of wheat bran to bread produces a high fibre product.

Dietary fibres are classified as either soluble or insoluble, and have specific effects on the breadmaking process (Figuerola *et al.*, 2005; Hartikainen & Katina, 2012; Jaime *et al.*, 2002; Schneeman, 1987). The differences between soluble and insoluble dietary fibre in breadmaking processes vary in regards to their effects on the water holding capacity, oil holding, swelling capacity, viscosity and gel formation, which underpins the physiological effects of dietary fibre (Femenia *et al.*, 1997; Figuerola *et al.*, 2005; Królak *et al.*, 2017).

Fibre is an important component for a healthy diet; delivering adequate fibre levels, however, is a serious challenge. Health-wise, an increase in the consumption of dietary fibre reduces susceptibility to diseases such as cardiovascular diseases, obesity, colo-rectal cancer, hypertension, diabetes and gastrointestinal disorders (Anderson *et al.*, 2009; Prosky & DeVries, 1992; Sidhu *et al.*, 1999; van der Kamp, 2004). Because of its benefits to human health, the recommended average dietary fibre intake is approximately 30-38 g per day for men and 21-25 g per day for women (Cummings & Frolich, 1993; Gordon, 2003; Laurikainen & Ha, 1998; Sidhu *et al.*, 1999; Spiller, 1993). Despite this, typical Western diets contain fibre levels less than 20 g per day (Hartikainen & Katina, 2012; Spiller, 1993). This indicates that the potential health benefits of fibre are not being enjoyed by most of the population, resulting in adverse consequences for individuals and national health services alike (Hartikainen & Katina, 2012; Katina *et al.*, 2010).

The best method for increasing the consumption of fibre is to ensure frequently consumed foods are high in fibre, as this offers consumers a healthy option with minimal effort. Bread is the most consumed food item; encouraging and facilitating consumption of high-fibre bread is therefore an effective route to increasing fibre consumption and its associated health benefits in the population. Another reason why bread is a good choice for focus on increasing fibre consumption is that it is a staple food that is cheap and readily available (Campbell *et al.*, 2001; Campbell *et al.*, 2008).

### **2.3 Bread as source of fibre**

A product is defined as 'wholemeal' if the whole grain including the husk and outer layer of the cereal are used in its production (Atkins, 1995; van Der Kamp *et al.*, 2014). Bread is produced when wheat flour, water, salt, fat and yeast are mixed, proved and baked; other ingredients can be added to enhance the taste of the bread according to the baker's preference. Wheat is the 'king of all cereals' because it is the most widely grown and has the highest international trade among all cereals in the world (Atkins, 1995; Campbell *et al.*, 2008; Kent & Evers, 1994; McGee, 1995). Since wheat bran is a by-product of wheat flour milling and bran facilitates a high fibre diet (Atwell, 2002), it makes sense for bread to be fortified with wheat bran as it is simply putting back the by-product that was previously removed (Pomeranz *et al.*, 1977; Rao & Rao, 1991). In addition to incorporating foods rich in fibre into diets, health experts have tried to encourage increased levels of fibre-rich diets by advocating the consumption of five portions of fruits and vegetables daily. The difficulties in this approach, with consumers seeing consumption of the requisite amount of fruits and vegetables as necessitating more effort, brings the subject of bread fortification back to the fore (Królak *et al.*, 2017). Bread is the most important food in the world because of its wide consumption among human beings due to varying traditional or religious beliefs from ancient times to date. Increasing bran consumption is arguably the single most important factor to increase the health of the population (Campbell & Martin, 2012). Although bread fortification with wheat bran is agreed to be one of the best ways to increase dietary fibre consumption

(Zhang & Moore, 1997), fortification of bread with wheat bran results in detrimental organoleptic and structural effects on bread (Campbell *et al.*, 2008).

Figure 2.1 shows the schematic structure of a whole grain cereal. There are three main parts to a wheat grain; the bran, the endosperm and the germ. The germ (the baby plant or embryo) is approximately 2.5% of the total kernel weight but is often separated from the flour during mixing because of its total fat content (10%); this fat content reduces the milled flour shelf-life considerably (Nebraska Wheat, 2004). Wheat germ is rich in B-vitamins, some proteins and trace minerals (Nebraska Wheat, 2004). The germ is ultimately part of the whole wheat flour but sold separately to desired customers. Wheat endosperm makes up approximately 83% of the wheat kernel and is the food supply for germinating plant, providing a source of essential energy to the germinating wheat plant (Nebraska Wheat, 2004). It contains the greatest proportion of proteins, carbohydrates, iron and vitamins (riboflavin, niacin and thiamine) (Nebraska Wheat, 2004). Wheat endosperm is also a source of white flour and soluble fibre (Nebraska Wheat, 2004). Bran, which is of utmost interest in this current work, forms the outer layer of the wheat cereal and consists mainly of non-starch polysaccharides (46%), protein and starch. The outer wheat layer (commonly known as wheat bran) is made up of the pericarp (fruit coat), testa (seed coat) and part of the endosperm known as the aleurone layer (Apprich *et al.*, 2014; Koegelenberg, 2016).

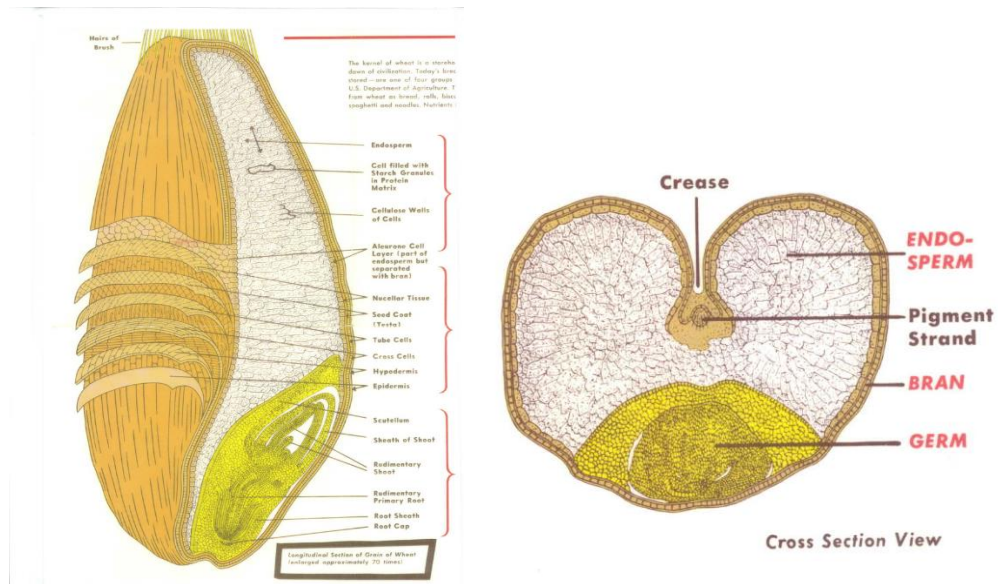


Figure 2.1: Structure of a cereal grain (Nebraska Wheat, 2004)

## 2.4 Addition of bran to bread

Cereal-based products are fortified with wheat bran in two way; either by substituting flour with bran or mixing bran with the germ and flour to make up whole-grain flour (Hemdane *et al.*, 2016; van Der Kamp *et al.*, 2014). Wheat bran is added to increase the dietary fibre levels in bread, but the addition of wheat bran generally results in a final product of inferior quality (Hemdane *et al.*, 2016; Jacobs *et al.*, 2015). Regardless of how bran is added, technological disadvantages as well as inferior end products are obtained compared to refined flour products (Hemdane *et al.*, 2016). The source of the bran has to be taken into account when studies are carried out; for instance, low grade flours with fine weatings have more detrimental effects to baked loaf volumes while the wheat pericarp has more deleterious effects on the breadmaking potential of the flour (Hemdane *et al.*, 2015, 2016). Thus, the next sections look at the effects

of wheat bran on bread and possible ways to overcome or reduces these negative effects.

#### **2.4.1 Effects of bran on bread**

Dietary fibre (such as wheat bran) when added to bread increases the nutritional properties of the resulting baked loaf but has a negative effect on the sensory attributes is observed (Cavella *et al.*, 2008; Hemdane *et al.*, 2016). The main downside to bran fortification in bread is that the final baked loaf is seen as being of inferior quality (Cavella *et al.*, 2008; Gormley & Morrissey, 1993; Laurikainen & Ha, 1998; Salmenkallio-Marttila *et al.*, 2001). The low volume, coarse texture, taste and colour of brown or wholemeal bread are disliked by many consumers (Hemdane *et al.*, 2016). Therefore, while consumers are willing, and indeed often wanting to increase their dietary fibre consumption, this is on the condition that wholemeal bread does not differ significantly in its characteristics to those of white bread (Basman & Koksel, 1991; Cauvain *et al.*, 1983; Cavella *et al.*, 2008). This highlights that consumers are more taste conscious than health-conscious (Drewnowski & Popkin, 1997), with the low volume and coarse texture of wholemeal bread being associated with staleness. This on its own is a problem, as it takes a great deal to change the preference of individuals. Furthermore, since wholemeal flour deteriorates faster than white flour because of the higher lipid content, which is susceptible to rancidity, more negative effects are observed with bran fortification in wholemeal bread than in white bread. Wheat bran has a negative effect on loaf volume, decreasing the bread quality and appeal and thus causing reluctance to consume (De Kock *et al.*, 1999). Cavella *et al.* (2008) found that functional role of dough in relation to

its rheological behaviour was dependent on fibre content; the addition of dietary fibre to dough formulations at room temperature caused an increase in the dynamic modulus as the fibre content was increased.

The deleterious effects of wheat bran have been suggested to be as a result of several factors. The first effect observed was the dilution of gluten proteins (Hemdane *et al.*, 2016; Pomeranz *et al.*, 1977); found that the decrease in volume correlated with the decrease expected from gluten protein dilution in the presence of less than 7% bran, but when higher percentages of bran were used, the decrease in volume did not correlate with the decrease in gluten protein dilution. The effects observed from bran are as a result of the physical, chemical and biochemical attributes of the bran (Hemdane *et al.*, 2016). But it should be noted that since the behaviour of wheat bran is assessed based on dough/bread characteristics, and that the characteristics and functionality of the wheat flour play a role in the overall behaviour observed. The baking potential of whole-grain bread wheat cultivars could not be predicted because the variations in wheat bran functionality surpassed the variations in wheat flour (Hemdane *et al.*, 2016; Seyer & Gélinas, 2009).

Shetlar & Lyman (1944) noted a “recent emphasis on the production of more nutritious bread” and that whole wheat bread is vastly inferior technically to white bread, for which the reasons were not completely known. At that time less work had been reported on wheat bran than on wheat germ. They hypothesised that bran has a mechanical effect, diluting gluten and disrupting films, and therefore that grinding bran more finely should improve loaf volume.

(Shetlar & Lyman, 1944) concluded that “the large volume of loaves containing fine ground bran indicates that bran must contain an ameliorating factor which increases loaf volume as well as a destructive factor which influences baking”. De Kock *et al.* (1999) stated that wheat bran resulted in both physical and chemical negative effects to bread dough and baked loaves.

When wheat bran is added to dough formulations, a decrease in water availability was observed because of the bran-water interaction. This is reported in a number of papers (Cavella *et al.*, 2008; Zhang & Moore, 1999); water extracts from bran hydration increased loaf volume. This is because the additional water added during mixing is retained in the loaf during baking, resulting in a heavier loaf but smaller loaf volume (Campbell *et al.*, 2008; Rao & Rao, 1991). The water absorption capacity was independent on bran particle size when measured using a Farinograph, as the hydration of wheat bran is dependent of the water retention capacity in nanopores (Jacobs *et al.*, 2015; Zhang & Moore, 1997). Although particle size is clearly an important factor influencing the observed effects of bran, and has been studied in many papers, mostly these do not report specific particle sizes and just compare “coarse” and “fine” particles or “coarse”, “medium” and “fine”, using these as relative terms. Exceptions include the work of (Campbell *et al.*, 2008c) who reported their coarse, medium and fine bran samples as having mean particle sizes of 1182, 585 and 210  $\mu\text{m}$ , respectively, with the medium and fine samples produce by milling the original (coarse) bran.

Washed bran and cellophane were ground to different average particle sizes and in both cases loaf volume increased as particle size decreased (Shetlar & Lyman,

1944). Shetlar & Lyman (1944) found that “a striking feature, aside from loaf volume, was the change of colour and texture as particle size became smaller and that as bran particles approached flour particle size, it became difficult to distinguish individual bran particles in the finished product, and the grain and texture were similar to those of white bread.” Unwashed bran gave larger loaf volumes than washed bran, indicating that the latter has only a diluting effect, while unwashed bran contains also a water-soluble property which is also evident in extracts of bran. The work from Shetlar & Lyman (1944) was the first to look at this topic in this way, opening an avenue for further research into the field of breadmaking by fortifying with fibre.

The use of varying bran particle sizes to improve fibre content and hopefully reduce the detrimental effects is certainly one of the most investigated subjects in cereal science. The different particle sizes used in studies are either from particle size reduction or from bran-rich milling with different particle sizes (Hemdane *et al.*, 2016). Brans from size reductions have similar overall composition while bran-rich milling streams are a mixture of different sources, hence, different chemical composition (Hemdane *et al.*, 2015, 2016). Different researchers observe that bran particle size influences the detrimental effects seen in bread, although there is a lot of disagreement on the details of the particle size (Campbell *et al.*, 2008; De Kock *et al.*, 1999; Ishwarya *et al.*, 2017; Lai, Hosene, & Davis, 1989; Pomeranz *et al.*, 1977; Zhang & Moore, 1999, 1997). Altering bran particle size did not have any effect on the bread composition (De Kock *et al.*, 1999; Seyer & Gélinas, 2009; Strange & Onwulata, 2002; Zhang & Moore, 1997). Although individuals wish to be health conscious, their taste

consciousness and preference tends to take priority when it comes to food choices (Drewnowski & Almiron-Roig, 2009; Drewnowski, 1997). There is a widespread rejection of wholemeal bread because bran disrupts the aerated structure in dough and bread (Chin, 2003; De Kock *et al.*, 1999; Federation of Bakers, 2018; Thompson *et al.*, 2008). Understanding the effects of bran particle size is therefore essential in order to minimise these undesirable effects on breads structure and palatability.

The high number of particles present in fine bran disrupts the mechanical integrity of the dough structure, and further dilutes the gluten proteins compared to the relatively fewer particles present in coarse bran (Gallagher, 1988). Fine bran particles give lower loaf volumes and a denser appearance and crumb texture than medium or coarse bran particles (Campbell *et al.*, 2008a,b,c; De Kock *et al.*, 1999; Zhang & Moore, 1999, 1997) and as bran particle size decreases, there is a decrease in the water holding capacity of wheat bran (Cadden, 1987, 1988; Campbell *et al.*, 2008c). The finer the bran particle, the lesser the time required for mixing which is probably connected to variations in water absorptions rates between particle sizes rather than the result of any effects of chemical reactions within the doughs or physical factors relating to the structure of the dough (Zhang & Moore, 1999, 1997). The use of bran with finer particle sizes was suggested in previous works because it was found that fine bran particle sizes resulted in aerated bread structures more similar to that of white bread, increasing the acceptance of bran-enriched breads (Collins & Hook, 1991; De Kock *et al.*, 1999; Hook & Collins, 1987; Lai *et al.*, 1989; Nelles,

Randall, & Taylor, 1998; Ozen & Hamit, 1997; Pomeranz *et al.*, 1977; Rao & Rao, 1991; Rasco *et al.*, 1991; Shetlar & Lyman, 1944).

Zhang & Moore (1997, 1999) found that medium size particles gave the largest final baked loaf volume, with fine particles resulting in the smallest loaves. This suggests that an optimum particle size may exist, and this may explain why some research found small particles to be more beneficial and other research showed large particles to be less damaging. These contradictory results may arise from the different particle sizes only being considered relative to each other; in each study the 'larger' particle may in fact be medium-sized. Campbell *et al.* (2008c) found that breads produced using fine bran particles had better sensory preferences than breads made from medium or coarse bran particle sizes, contrast to finding from Zhang & Moore (1997, 1999) and illustrating how the effect of particle size is dependent on the breadmaking system under study as well as on the relative sizes of the particles in the study.

Understanding the existing effects of bran in breadmaking has led to researchers finding ways to reduce or eliminate these effects to make for better high fibre breads. The next section discusses the approaches that have been tried in combating the deleterious effects of wheat bran in breadmaking.

#### **2.4.2 Overcoming effects of bran on bread**

Researchers have investigated different methods to reduce the detrimental effects of bran on bread in order to produce wholemeal bread that is similar in palatability and appeal to white bread, by adjusting the ingredients and techniques used in production.

One approach is to use flours with very high protein contents (ranging from 13-15%), addition of water and improvers (enzymes, surfactants or commercial glutens) and processing manipulations. This helps to increase gluten-starch strength and fermentation stability which lead to an increased gas retention and dough expansion, resulting in an improved bread volume and crust colour (Hemdane *et al.*, 2016, 2015; Lai *et al.*, 1989; Sanz Penella *et al.*, 2008; Sidhu *et al.*, 1999).

Milling of wheat bran into smaller particle sizes was proposed as an approach that alleviates the detrimental effects of bran (Campbell *et al.*, 2008c; Lai *et al.*, 1989; Moder *et al.*, 1984; Pomeranz *et al.*, 1977; Shetlar & Lyman, 1944), although other researchers found that smaller particle sizes gave less beneficial results (Ferguson & Harris, 1997). Another issue with grinding wheat bran was that smaller loaf volumes were produced when fine wheat bran particles were used to bake loaves but with smoother textures (Campbell *et al.*, 2008). This illustrates the challenge of defining “better” when it comes to bread, as bread quality is a function of both volume and crumb structure and altering bran particle size can have opposite effects on these two factors.

Despite the consensus that wheat bran has detrimental effects on bread the causes of these negative effects are uncertain and are of great interest among researchers (Bloskma & Bushuk, 1988). Since the presence of bran increases the rate at which water is absorbed by the dough mixture and reduces gluten network development during mixing, an obvious strategy is to increase the amount of water in the mixture. This is accepted as a requirement to give

doughs that will be handle able through the processing machinery, but the added water reduces dough strength and baked loaf volume (Dreese & Hosene, 1982; Hook & Collins, 1987; Lai *et al.*, 1989; Moder *et al.*, 1984; Pomeranz *et al.*, 1977; Rao & Rao, 1991; Zhang & Moore, 1999). There is no specified procedure to determine the amount of extra water required to obtain a dough that is more handleable and aerated. Some studies have increased the amount of water by half the percentage of wheat bran added to the formulation (Campbell *et al.*, 2008a,b,c). Increase in the amount of water was seen to increase the loaf volume and enable proper gluten interaction, but addition of too much water leads to development of a sticky dough which in turn produces an inferior loaf (Hemdane *et al.*, 2016).

Since bran dilutes the gluten network in the dough, this can be countered by introducing vital wheat gluten into the dough formulation (Collins & Young, 1986; Gan *et al.*, 1989; Hemdane *et al.*, 2016, 2015; Hook & Collins, 1987; Lai *et al.*, 1989; Pomeranz *et al.*, 1977; Rao & Rao, 1991; Sidhu *et al.*, 1999). This technique was seen to increase loaf volume and crumb texture, as well as improve the organoleptic characteristics of the bread.

Two methods were used when trying to use pre-soaking of bran as an approach to eliminate its deleterious effects; either soaking bran in a limited amount of water or in excess amount of water, with both methods noted to improve bread quality (Hemdane *et al.*, 2016). Soaking of bran in limited amount of water before adding to the dough formulation was employed to improve the quality of bran-enriched breads and overcome negative effects (Chen *et al.*, 1988;

Dreese & Hosney, 1982; Hemdane *et al.*, 2016; Lai *et al.*, 1989; Nelles *et al.*, 1998; Salmenkallio-Marttila *et al.*, 2001; Sosulski & Wu, 1988). The thinking was that, as bran absorbs the water required for dough development, pre-soaking the wheat bran would make it sufficiently hydrated for effective dough development. This technique was seen to improve loaf volume as well as produce softer loaves when compared to loaves produced from untreated bran (Hemdane *et al.*, 2016; Lai *et al.*, 1989; Nelles *et al.*, 1998). Nelles *et al.* (1998) conducted a study for the reduction in the negative effect of bran and improving bread quality by the pre-treatment of the bran by way of soaking, fermentation and heat treatment. A dough made using bran saturated with water reduced the detrimental effects usually observed from brans. Unfortunately, there are no conclusive findings on the effects of soaking bran before dough/bread production (Hemdane *et al.*, 2016).

Other ways by which the negative effects of bran can be evaded include:

- Addition of oxidants to dough formulations (Collins, 1983; Galliard & Collins, 1988; Hook & Collins, 1987; Pomeranz *et al.*, 1977; Sosulski & Wu, 1988).
- Addition of emulsifiers and fat to dough formulation (Dreese & Hosney, 1982; Pomeranz *et al.*, 1977; Rao & Rao, 1991; Shogren *et al.*, 1981).
- Addition of extra yeast to dough formulation (Collins, 1983), with this method, the proving time will have to be reduced.
- Addition of salts (Lai *et al.*, 1989).
- Addition of enzymes (Collins, 1983; Hemdane *et al.*, 2016; Lai *et al.*, 1989).

- Fermentation of bran (Hartikainen & Katina, 2012).
- Chemical treatments of bran (Hemdane *et al.*, 2016; Rasco *et al.*, 1991).
- Hydrothermal treatment of bran (De Kock *et al.*, 1999; Hemdane *et al.*, 2016; Nelles *et al.*, 1998).

These methods still have many limitations and as such more research is needed to understand the behaviour of bran on dough and thus, how to fix it. More understanding into the mechanism of bran and the cause of the detrimental effects on cereal based products is important.

## **2.5 Aeration and rheology of wholemeal bread**

### **2.5.1 Dough aeration**

For breadmaking to be understood as a series of aeration stages, the mechanism by which gas cells in the dough create the cellular structure of the bread crumb must be understood (Scanlon & Zghal, 2001). Understanding how these air bubbles nucleate in the dough during mixing is a fundamental first step; nearly 80 years ago it was seen that these air bubbles are the only nuclei available for subsequent gas growth (Baker & Mize, 1941).

The aerated structure in bread is made up of approximately 70% gas after cell growth during the proving stage of bread making (Campbell *et al.*, 2008c). The increase of bubbles in bread dough is a complex process compared to the growth of bubbles in liquids (Chiotellis & Campbell, 2003a,b). It is important to understand how bran interacts with bread and dough bubbles so as to help

bread manufacturers produce bran-rich bread that maintains an appealing aerated structure.

The mixing of wheat flour with water to form dough gives the dough the ability to retain CO<sub>2</sub> gases from yeast fermentation. This provides bread with the aerated structures that makes bread palatable and desired by consumers. This aerated structure characteristic is not observed in breads produced from any other cereal except rye, and the aerated structure is less pronounced in the latter when compared to that of wheat. Wheat is able to produce breads with fine aerated structures because of the gluten proteins present in wheat which form viscoelastic networks during dough development capable of retaining gas (Campbell *et al.*, 2008c).

Bubbles play major roles in each stage of the breadmaking process; from their entrainment during mixing, their growing during proving, and their setting the aerated structure during baking to give bread products with finer texture and structure which is more appealing to consumers (Campbell, 2015; Campbell & Martin, 2012; Dobraszczyk *et al.*, 2001). Aeration during mixing assists dough development by changing the character of dough due to its elasticity properties given by gluten proteins, which is related to dough rheology and its ability to retain gas.

Chamberlain described gases as “the neglected bread ingredients” (Dobraszczyk *et al.*, 2001). Over the past 100 years of bread research, contribution of aeration and rheology to breadmaking have been widely studied especially in regard to the rheology of bread but there is still a significant gap in the understanding of

aeration in bread. This is surprising since both play significant parts in every stage of the breadmaking process, however, aeration is inherently more challenging to study than rheology, hence its relative neglect until recent decades. Most studies have concentrated on dough rheology and development, but the relationship between dough aeration and dough rheology is not fully understood (Chin & Campbell, 2005a).

Investigating the effect of wheat bran on wholemeal bread and dough and how it affects aeration will provide a better explanation as to why the addition of wheat bran into flour makes bread less desirable, facilitating the alleviation of these damaging effects. Definitive answers as to how bran affects dough aeration and how this can be rectified have been a challenge. This is attributed to variations in research results due to three factors; variation in definition of bran (origin), natural variation in composition and physical properties and variation in breadmaking procedures and in compensations made (Noort *et al.*, 2010; Zhang & Moore, 1997).

The entire breadmaking process is a series of aeration stages (Campbell & Mougeot, 1999; Chin, 2003) (Figure 2.2). Air bubbles are created and monitored in the mixing stage, leading to bubble growth and foam structure formation and finally the production of a sponge-like structure called bread.

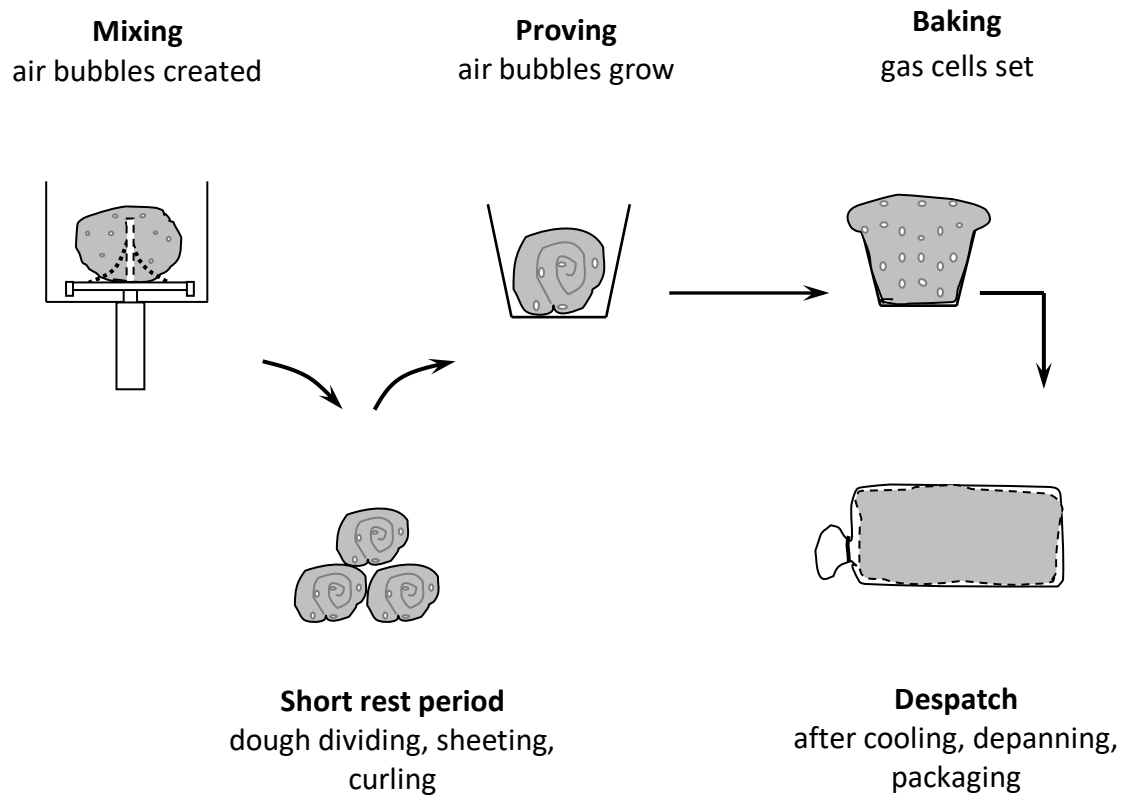


Figure 2.2: Main stages involved in a breadmaking process (the first three stages are of most importance in this research). Adapted from Chin (2003)

### 2.5.2 Bread dough rheology

Rheology is the study of flow and deformation of materials (Dobraszczyk & Morgenstern, 2003). According to Cauvain, (2015) and Elgeti *et al.*, (2015), dough rheology is defined as ‘the resistance of the dough to deformation due to its elastic properties and also its extensibility properties’. Rheology determines the extent of aeration during mixing and the growth and coalescence of gas cells during proving and baking (Campbell & Martin, 2012). Dough development occurs when the alignment of flour gluten proteins imparts the required gas retention to dough. Cauvain (2015) notes that development is an open-ended term due to the complex changes in gluten protein network that take place

during mechanical actions i.e. mixing, rounding and sheeting. The changes in gluten structure during mixing underpin dough development, by improving its ability to retain gases during the proving and baking stages to form bread with finer texture. It is not easy to measure dough development directly; instead it can be observed from the properties of dough rheology during mixing. The increase in dough resistance to deformation is used to identify the extent of dough development (Zheng *et al.*, 2000).

Viscosity and elasticity, which describe rheological behaviours of bread doughs, are mostly based on formation of a continuous protein network during mixing (Dobraszczyk, 2004; Döring *et al.*, 2015; Wieser, 2007). Rheological behaviour of dough has been studied by various methods; one of the commonly used techniques is torque profile which correlates dough rheology to dough development, and is illustrated by peak dough development (Zheng *et al.*, 2000). Peak dough development occurs when the resistance to deformation during mixing increases to a peak and can be demonstrated by the torque profile which quantifies the dough development during mixing. This property have been studied extensively (Chin & Campbell, 2005b; Hosene, 1985; Zheng *et al.*, 2000). The properties of dough rheology have been measured using Farinograph, Mixograph, Extensograph or Alveograph. These items of equipment are mixers used in flour, water and dough profiling such as flour-water absorption level, torque profiling, and dough stretching behaviour. However, Chin & Campbell (2005a) argued the relevance of these large deformation tests as it is unclear what constitutes optimum mechanical development and Dobraszczyk *et al.* (2001) noted that these techniques are

difficult to interpret due to the complexity in defining parameters such as modulus, stress and strain states of the dough.

A reason for studying dough is that it shows highly complex rheological properties as a result of the gluten network properties (Bagley, Dintzis, & Chakrabarti, 1998), modified by other dough components. An underappreciated element of dough rheology is the contribution of the bubbles (Bellido *et al.*, 2006; Chin *et al.*, 2005). The rate of disproportionation of air bubbles in dough is influenced by bubble sizes and the separation between them (Dobraszczyk & Morgenstern, 2003; van Vliet, 1999) while the presence of bubbles affects the rheological properties of the dough (Chin & Campbell, 2005a; Elmehdi *et al.*, 2004). Most research studies on dough rheology and development, tend to overlook the interaction with aeration; to get a full picture; studies into this subject area should consider aeration, rheology and dough development together. Having achieved a population of bubbles via aeration during mixing that are influenced by, and influence, the developing rheology of the dough, these bubbles are then inflated with carbon dioxide gas produced during proving.

Chiotellis & Campbell (2003a) noted that most researchers investigating bubble growth have focused on the growth of individual bubbles in liquids with a defined amount of diffusing species. de Cindio & Correra (1995) were the first to consider the existence of a bubble size distribution and CO<sub>2</sub> production rate although without experimental backing. The model used by de Cindio & Correra (1995) was somewhat complicated and was simplified by Shah *et al.* (1998) for

the growth of individual dough bubbles. This new method was observed to be slow at initial stages of proving as it was expected that bubbles would contain only nitrogen. This technique was later used for the measurement of gas retention in dough. Herrero-Sanchez (2000) extended the technique of Shah *et al.* (1998) to include the bubble size distribution of bread dough. For the use of this enhanced technique, Herrero-Sanchez (2000) assumed that CO<sub>2</sub> concentration remains constant throughout the dough mixing and proving stages and that bubbles reach their equilibrium size immediately.

Oxygen from air also contributes to dough development during mixing through chemical reaction that occurs within the dough, while nitrogen supports the initial aerated structure (Collins, 1986). The effects of oxidation on dough rheology have been investigated by mixing dough to differing levels of gas content (Chin *et al.*, 2005); yet the significant effects of the gas content on the measured bulk rheological properties is still equivocal and the real contributor to dough development and aeration has not been clarified. Hoskeney (1985) reported that nitrogen did not contribute to the oxidation process from the observation on mixing reaction. This means that oxygen plays a critical role in dough development, in addition to the presence of bubbles. This is due to the fact that only oxygen participates in the oxidation process, and hence assist dough development. Hence, the effects of gas content on dough oxidation and rheological structure is an interesting subject to investigate as it could clarify the real contribution made by oxygen during mixing stage to overall dough development.

In order to test the accuracy of this model, an experimental dynamic dough density (DDD) technique was developed (Campbell *et al.*, 2001). This was carried out by weighing a sample of yeasted dough in air and immersed in a liquid of known density (xylene); the density can be calculated from the difference between the weights. This technique was also used to measure the rate of CO<sub>2</sub> production by yeast assuming that dough is saturated, and that the CO<sub>2</sub> gas produced will inflate the bubbles. This technique was found to obtain interpretable results when measured against different temperatures, mixing pressures and yeast concentrations but it overestimated the rate at which gas enters the dough at the early stages of proving (Campbell & Herrero-Sanchez, 2001; Campbell *et al.*, 2001). Chiotellis & Campbell (2003a) were able to address the shortcomings of previous works to allow the dynamic increased in the bubble size distribution to be followed throughout the proving time. The DDD system is an integral tool used the experimental works in this current thesis.

### **2.5.3 Relationship between bread aeration and dough rheology**

Aeration and rheology interact throughout the breadmaking process (Campbell & Martin, 2012). Dough aeration and rheology are discussed in relation to the stages of breadmaking (mixing, proving and baking) in this thesis. Before bread is produced, a series of decisions have to be made by the baker such as the dough formulation, the mixer to be used and how to operate the mixer (Campbell & Martin, 2012). The type of mixer and how to operate the mixer are usually decided on before the required day while the dough formulation used is dependent on the type of flour available, market demands or prices of required ingredients and product desired (Campbell & Martin, 2012).

Figure 2.3 provides a schematic diagram on the interaction between aeration and rheology, with on the mixing stage as the control centre of bread quality (Campbell & Martin, 2012).

Dough development (labelled 1 in Figure 2.3) occurs when all ingredients are mixed and properly aerated; causing gluten network structure development through viscoelastic interactions of gluten proteins (Campbell & Martin, 2012). These viscoelastic interactions lead to gluten rheology (labelled 2) and hence lead to the changes to bulk rheology labelled, and it is the bulk rheology that influences bread aeration. Bulk rheology can be measured using a Farinograph or Extensinograph. Between stages 3 and 4, a two-way relationship is observed as the presence of bubbles also have an influence on bulk rheology (Campbell & Martin, 2012; Chin & Campbell, 2005a, 2005b; Chin *et al.*, 2005). Aeration also has an effect on dough development (from 4 to 1) by the presence of atmospheric oxygen. This shows the interaction between aeration and rheology is a circular one during the mixing stage of breadmaking.

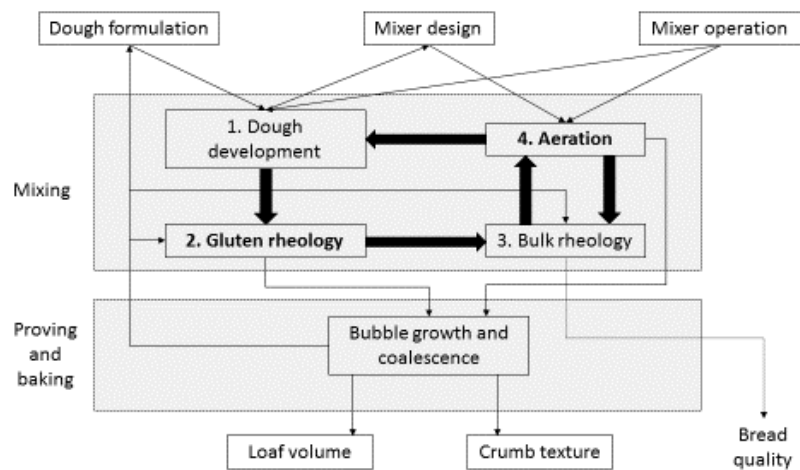


Figure 2.3: Interaction between aeration and rheology, as influenced by dough formulation, mixer type and design operation during mixing, proving and baking. Source: (Campbell & Martin, 2012)

During the proving and baking stages of breadmaking, dough behaviour is determined by gluten rheology and the aerated state of the mixed dough (Figure 2.3). The ingredients used also have major effects at these stages of breadmaking. Bubble growth and extent of coalescence affect the final loaf volume and crumb texture obtained.

#### 2.5.4 The Chorleywood Breadmaking Process

The Chorleywood Breadmaking Process (CBP) is a time-efficient commercial process used for the majority of bread production in the UK and several other countries (Cauvain & Young, 2015). Due to removal of bulk fermentation, the bubble structure created in the dough mixer directly affects the baked loaf appearance and structure (Baker & Mize, 1941; Cauvain *et al.*, 1999; Chiotellis & Campbell, 2003a). The CBP provided a major turnaround in the breadmaking industry following its introduction in the UK in the 1960s. Cauvain & Young

(2015) described the CBP as a 'no-time dough-making process which uses mechanical development'. The distinctive attribute of the CBP when compared to that of other breadmaking processes is its method of dough development. The CBP provides rapid development of the dough compared to bulk fermentation processes. According to Cauvain & Young (2015) other benefits of introducing this process to bakers are:

- Reduction in processing time
- productivity (more loaves per unit of flour, as yeast is no longer being converted to carbon dioxide during the bulk fermentation process)
- Versatility through batch processing

As with any breadmaking method, the key factor in creating a high quality, desirable finished product is ensuring that the bread is soft and light. In order to achieve these desirable qualities, it is important to ensure that appropriate gas levels are entrained within the dough. In the CBP, more so than for other breadmaking processes, because of the omission of the bulk fermentation stage, aeration of dough is critical in the production of a high-quality palatable product that is desirable to consumers (Cauvain & Young, 2015; Cavella *et al.*, 2008; Chiotellis & Campbell, 2003a).

Two major components of bread that are important throughout the breadmaking process are starch and gluten. Starch is made up of amylose and amylopectin. Amylose is a linear molecule that consists of  $\alpha$ -1,6 and 1,4 D-glucopyranosyl units, amylopectin is a branched and larger molecule. Starch granules absorb water and swell in the presence of sufficient water and this can

be reversed during gelatinisation (Goesaert *et al.*, 2005; Koegelenberg, 2016). After gelatinisation, starch polymers cool and form a crystalline state; this is known as retrogradation (Goesaert *et al.*, 2005).

Gluten is produced when gluten proteins are mixed with water. There are two groups that make up gluten proteins; monomeric gliadins and polymeric glutenins which together account for about 80% of wheat protein (Goesaert *et al.*, 2005). Because of the presence of these unique gluten proteins in wheat, bread dough development is possible, leading to a viscoelastic structure capable of expanding to retain fermentation gases to give raised bread. Gluten proteins aid in development of dough as well as determining the final loaf volume and crumb structure (Selinheimo *et al.*, 2007). This gluten network develops after the hydration of wheat flour during mixing, while breaking down covalent and non-covalent bonds (Singh & MacRitchie, 2001). For the development of quality dough for breadmaking, the ratio of gliadin to glutenin proteins has to be appropriate. While glutenin polymers form a continuous network to provide strength and elasticity to the dough, gliadin act as plasticisers holding the glutenin polymers together (Koegelenberg, 2016).

#### **2.5.5 Stages of breadmaking**

The three main stages of bread production are mixing, proving and baking; without undergoing these stages, raised bread types cannot be produced (although the flat breads are not proved). These stages involve the use of several

ingredients, with flour and water being the two most important ingredients as they influence final bread texture and crumb (Mondal & Datta, 2008).

Rheological properties of a bread dough are developed at each stage of the breadmaking process and contributes to the aeration of the loaf (Campbell & Martin, 2012). Bubbles are trapped into dough in the mixing stage of breadmaking (Campbell *et al.*, 2001), after which bubble growth and coalescence occur during proving using CO<sub>2</sub> gas produced during yeast fermentation. Finally, these bubbles are set into sponge-like structures of interconnected gases during baking (Campbell & Martin, 2012). The stages of breadmaking are further discussed below with reference to wheat bran.

#### **2.5.5.1 Mixing**

The mixing stage is the decision-making stage for the final loaf (Campbell & Martin, 2012). It is at this stage the baker decides what dough formulation to use for a particular kind of loaf and this in turn determines structure and organoleptic characteristics of the bread. The smooth elastic characteristic of a bread is determined at this stage, which aids gas retention in the following breadmaking stages (Cauvain, 2015).

Using the CBP as a point of reference, nitrogen gas from the atmosphere forms bubbles that act as nucleation sites for the CO<sub>2</sub> gas produced during the proving stage. Atmospheric oxygen along with the use of ascorbic acid enhances dough development. The gas content of dough mixed with air or nitrogen depends on the dough formulation and mixing pressure. Mixing dough under low pressures resulted in low loaf volume and improperly developed structure as it hinders

CO<sub>2</sub> gas retention (Baker & Mize, 1941); it also changes the number of bubbles per unit volume (Campbell *et al.*, 2008; Cavella *et al.*, 2008). Smaller bubble sizes are observed with high speed mixing than slow speed mixing (Campbell & Martin, 2012).

There are three main processes that occur during aeration (Scanlon & Zghal, 2001);

- Gas entrainment (gas entry into dough)
- Gas disentrainment (release of gas from dough)
- Bubble break up and foam formation

Mixing is the most important stage in the breadmaking process as control of final loaf structure begins with dough aeration, development and hydration (Anderssen, 2007; Peighambardoust *et al.*, 2010). The resistance of dough during mixing increases to an optimum level until it decreases; this point is known as over-mixing of the dough and is determined by the quality and quantity of gluten proteins (Koegelenberg, 2016). Apart from dough development, the initial water distribution and ingredient hydration occur during this stage (Anderssen, 2007; Peighambardoust *et al.*, 2010). Once dough has been developed, the proving stage is commenced.

Beginning with dough aeration, the effect of wheat bran is dependent on mixing and the particle size of the bran (Campbell *et al.*, 2008c). In regards to wheat bran and the mixing stage, bran could conceivably affect bread structure and quality by affecting aeration of the dough during mixing, affecting the size and number of bubbles created in the dough and hence the subsequent growth and

transformation during proving and baking of the bubbles. Campbell *et al.* (2008c) proposed that bran disrupted the dough surface during mixing. This increased the surface roughness and increased the quantity of air entrained within the dough; during proving however, the disruption to the structure caused by bran resulted in a decreased ability of the dough to retain gas. Therefore, instead of containing the gas during expansion, the structure ruptured allowing gas to escape and hence reducing aeration and expansion of the dough.

Mixing during the CBP occurs at high speed, taking fewer than 3 minutes to develop the dough mechanically instead of via the traditional lengthy bulk fermentation process. Pressure-vacuum mixing ensures a fine cell distribution within the dough; initial mixing at positive pressure increases oxygen availability to help develop the dough, followed by a partial vacuum being drawn near the end of mixing to remove excess air, expand existing cells and allow subdivision of cells created during final mixing, leading to a fine cell structure (Chin & Campbell, 2005a; Martin *et al.*, 2004; Shah *et al.*, 1998; Trinh *et al.*, 2013). According to Cauvain & Young (2015), since 90% of the final loaf quality is developed during the mixing stage of the CBP, the mixing is the major stage in the breadmaking process.

Dough formulation ingredients are homogenised during the mixing stage of the CBP, thus, leading to the occurrence of dough aeration, development and hydration (Anderssen, 2007; Campbell & Martin, 2012). In mixing, air bubbles are entrained into the dough, acting as nucleated sites for gas cells that grow

during proving and baking (Campbell, 1991; Campbell *et al.*, 1993; Cauvain, 2015; Chiotellis & Campbell, 2003a). Formation of the nucleation sites by nitrogen in the air is essential, as without them CO<sub>2</sub> gas generated by yeast would have nowhere to diffuse, resulting in loaves with low volumes and poor structure (Baker & Mize, 1941). Oxygen from the air also contributes to dough development by oxidising the dough, but is rapidly removed from the dough at the end of mixing due to yeast activity (Chamberlain, & Collins, 1979). This yeast activity leads to continuous gluten network interaction, as well as dough being able to retain CO<sub>2</sub> gas. The gluten network developed enables the dough to have viscoelastic properties which help prevent dough from rupturing during proving.

#### **2.5.5.2 Proving**

Although the mixing stage is the most important of the breadmaking process, in that it determines the final structure of the dough as well as enables gas entrainment; it is at the proving stage that dough rises due to CO<sub>2</sub> gas retention and bubble growth. The proving stage is the heart of the breadmaking process because it is the link between the bubbles created during mixing and the baked loaf; this is through the production of CO<sub>2</sub> by yeast fermentation (Campbell & Martin, 2012). Thereby, causing the development of more defined aerated structures in the final baked loaf.

Aeration during mixing and the final baked loaf have a complex competition for the available CO<sub>2</sub> gas dependent on bubble size and partial pressure (Campbell & Martin, 2012) and the coalescence of bubble during the last stage of proving

and early stages of baking (Campbell & Martin, 2012). This process is complicated by the variability of bubble sizes and their high surface areas for mass transfer; as well as the portioning of the generated CO<sub>2</sub> between the liquid phase and the bubbles. Mathematical models have been designed (Chiotellis & Campbell, 2003a; de Cindio & Correra, 1995; Rathnayake *et al.*, 2018) to measure some factors during the proving stage. These factors include; variation in CO<sub>2</sub> gas within a dough, the amount of CO<sub>2</sub> gas lost during proving and the rate of bubble growth close to the surface (Campbell & Martin, 2012). These mathematical models have been validated by measuring the growth and loss of gas of a dough sample (Campbell & Martin, 2012; Chiotellis & Campbell, 2003b; Ktenioudaki *et al.*, 2009) or by use of non-invasive X-ray and CT-microscopy (Bellido *et al.*, 2006; Córdoba, 2010; Jensen *et al.*, 2014; Koksel *et al.*, 2016).

This leads nicely to dough rheology. A number of researchers have done works on dough rheology by characterising bubble inflation rheometry, using the Dobraszczyk/Roberts dough inflation system (Dobraszczyk, 2004; Dobraszczyk & Morgenstern, 2003; Dobraszczyk *et al.*, 2003). Using this equipment, it was found that bubble inflation correlates with bubble failure strain and baked loaf volume from flours of varying breadmaking capabilities (Campbell & Martin, 2012; Dobraszczyk, 2004; Dobraszczyk *et al.*, 2003). These findings confirmed the works of Van Vliet *et al.* (1992) which suggested that strain hardening of wheat flour dough is the reason for stability of bubbles in doughs.

A technique called the Dynamic Dough Density system was developed in 2001 by Campbell *et al.* that enables change in dough density to be measured over a

period of time until dough reaches its maximum expansion capacity at which stage the dough starts to lose CO<sub>2</sub> gas to the system.

As bread has been identified as an appropriate means of increasing bran/fibre consumption, understanding the behaviour and interaction of bran during the proving stage might help in finding appropriate methods to overcome the negative effects of bran on bread doughs.

Bran could affect bubble growth and coalescence during proving by adversely affecting the dough structure to a point that the surface ruptures and gas escapes, rather than allowing the bubbles to expand. This would considerably reduce the gas retention within the dough and increase coalescence by the breaking down of gas cell walls (Zghal *et al.*, 2002).

#### **2.5.5.3 Baking**

The baking stage is the final step where dough formulations are put in the dry heat of an oven for a prescribed period at a specified temperature to produce a loaf which has been carefully created to achieve desired characteristics. Baking causes critical physical, chemical and biochemical changes to the dough. This process also enhances the aerated structure within the dough; as it is being baked it transforms the foam structure produced in the proving stage into a sponge structure containing a porous interconnected network of fine gas cells separated by thin walls (Campbell & Martins, 2012). A number of events contribute to aeration occur during baking (Campbell & Martin, 2012):

- Increased temperature resulting in deactivation of yeast, destroying enzymes and microorganisms;

- Further dough expansion with temperature increase;
- Volume increase and dehydration of dough with increase in temperature;
- Crust formation encourages dough coalescence and structure formation;
- Compression of bubbles near bread crust due to expansion;
- Starch-gluten matrix set causing rupture of bubble walls and creating interconnection rendering crumb porous leading to loss of leavening gases and their replacement by air;
- Firming of gas-liquid interface, which is now the defining component of the mechanical properties of the aerated structure;
- Gluten network development due to the presence of  $\alpha$ -amylase in wheat bran causing an improved crumb structure and loaf volume (Packkias-Doss *et al.*, 2019).

Knowing the relationship between wheat bran and the baking stage of the breadmaking process helps understand how to improve the effects of wheat bran on dough and bread. Bran could affect baking by physically disrupting the gluten films that form the structure of the dough, thus failing to retain the gas during the final expansion as the loaf is baked. This disruption is particularly significant during baking, as it is at this point that the structure is stretched to a maximum as the expansion occurs. The addition of bran results in the need for extra water to be added to dough formulations. This additional water remains in the dough through to the baking stage and results in a heavier, denser loaf being produced and increases starch gelatinisation which in turn

reduces gas retention during baking (Dreese & Hosney, 1982; Rodgers & Hosney, 1982).

## **2.6 Summary**

Although an increase in consumption of dietary fibre is advised by health researchers and nutritionists, it is of great challenge to encourage individuals to consume enough fibre in order to achieve health benefits. Wheat bran is one of the richest sources of dietary fibre and in wholemeal breads can increase fibre consumption but producing acceptably palatable wholemeal and high fibre breads has been a continuous challenge for researchers. The addition of wheat bran to dough formulations disrupts the aerated structure of the bread, leading to a final loaf of low volume and dense characteristics. Addition of wheat bran to bread leads to serious negative organoleptic changes such as textural changes, decrease in loaf volume, unfavourable crust texture and colour as well as an unpalatable taste. The effects observed from bran are based on the physical, chemical and biochemical characteristics of the bran type. Particle size is one of the major factors influencing the effects of bran in bread. A number of approaches to overcome the negative effects of bran have been implemented. Dough development, aeration and rheology are all interlinked within the mixing, proving and baking stages; from the creation of bubbles to the growth of these bubbles and finally setting of the sponge-like structure that makes up a loaf of bread. Bran influences each stage of the breadmaking process, such that a full understanding how to produce acceptable wholemeal breads requires understanding the effect of bran at each stage of the process.

Arabinoxylans are a soluble fibre component of wheat bran that could be extracted as a functional bread ingredient. Having established in this chapter a general understanding of the breadmaking process and the issues over bran incorporation in bread, the next chapter introduces arabinoxylans as a potential fibre additional to bread, leading to the objectives for the current research.

## Chapter 3. Arabinoxylans and bread

### 3.1 Introduction

Arabinoxylans (AX) are hemicelluloses, the second most naturally occurring polysaccharide after cellulose and an important structural component of plant cell walls (Biliaderis *et al.*, 1995; Koegelenberg, 2016). AX consists of a linear chain of xylose with side chains of arabinose. Arabinoxylans are a novel fibre source which could be a potential beneficial food ingredient, particularly in the bakery industry (Courtin & Delcour, 1998, 2002). However, AX-based ingredients are not currently commercially available. The recent emergence of biorefineries has given a context in which AX could be commercially produced, offering a new class of functional food ingredients (Campbell *et al.*, 2019; Du *et al.*, 2009; Martinez-Hernandez *et al.*, 2018; Misailidis *et al.*, 2009).

The importance of dietary fibre for human health has been established, while its consumption still presents an ongoing challenge. AX are potentially a promising source of fibre in bread, that could enhance bread quality while contributing to the consumption of soluble fibre. This chapter discusses the structure and classification of AX, as well as the usefulness of AX in breadmaking industry.

### 3.2 Classification and structure of arabinoxylans

Arabinoxylans (AX) are branched polymers found in the outer layer and endosperm of cereal cell wall that form the major hemicellulose component in the non-starch polysaccharides content of all grain cell wall (Izydorczyk &

Biliaderi, 1995; Saulnier *et al.*, 1995; Koegelenberg, 2016; Schooneveld-Bergmans *et al.*, 1999). Arabinoxylans are made up of two pentose sugars, arabinose and xylose, as illustrated in Figure 3.1. The source from which AX are extracted determines the composition of the extract. Compositional variation ranges between 11-25% wheat bran content and 12-14% total distillers dry grains with solubles (DDGS) (Pedersen *et al.*, 2014).

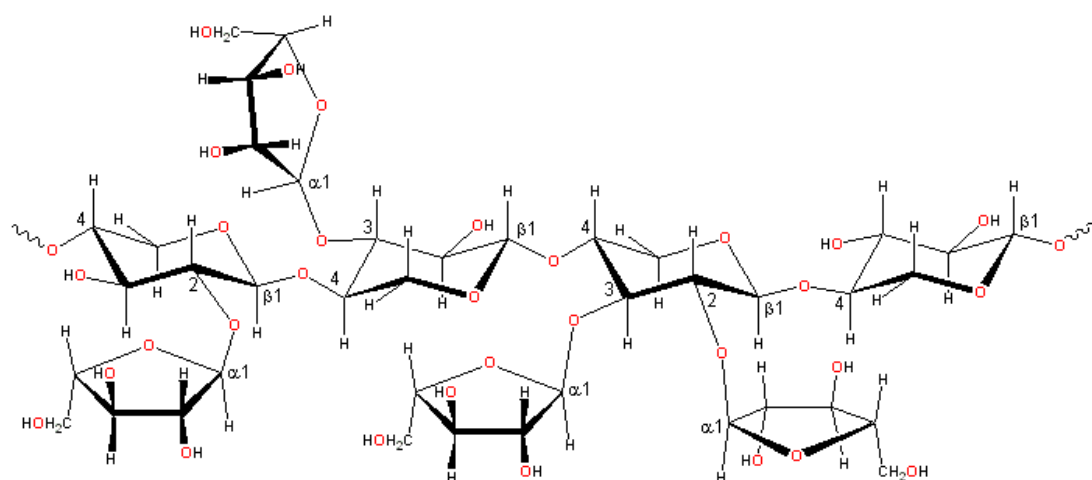


Figure 3.1: Structure of Arabinoxylan

AX molecules are categorised under the broad term of dietary fibre (both soluble and insoluble types) and are thought to have beneficial roles in human nutrition and health; such as reducing the symptoms of constipation and lowering the risk of high cholesterol levels, diabetes, atherosclerosis and colorectal cancer (Morris *et al.*, 1977; Plaami, 1997; Willett, 1994). Arabinoxylans have also been found to influence the quality of baked products bread, such as loaf volume, crumb texture and staleness characteristics, due to their physiochemical properties such as high viscosities and large water-holding capacities (Biliaderis *et al.*, 1995; Courtin & Delcour, 2002; Izydorczyk &

Biliaderi, 1995; Skendi *et al.*, 2011) and also their effect on the formation and properties of dough and bread (Anderson *et al.*, 2009).

Arabinoxylans have high water holding capacity of approximately 3.5 to 10 times their own weight depending on their solubility and source (Hemdane *et al.*, 2015; Meuser & Suckow, 1986). This water-holding capacity of AX accounts for almost 30% of the water binding capacity of wheat flour and has a significant effect on the dough handling properties and bread quality and yields (Baillet *et al.*, 2003; Courtin & Delcour, 2002; Meuser & Suckow, 1986; Wang, Van Vliet, & Hamer, 2005). This high-water holding capacity of 30% is an attribute of Water Extractable AX (WEAX), the second class of AX being Water Unextractable AX (WUAX). The two classes of AX from wheat are Water Extractable AX (WEAX) and Water Unextractable AX (WUAX). WEAX accounts for 25-30% of AX while WUAX accounts for 70-75% of AX (Courtin & Delcour, 2002; Meuser & Suckow, 1986).

### **3.3 Arabinoxylans and bread**

With the great need for continuous production of one of the world's most consumed foods, the production of breads with improved nutritional and functional benefits is a major target for not only the food industry (and the people in it) but also for the consumer. Incorporating arabinoxylans into wholemeal bread is another way of improving its health benefits in this ever-evolving consumer-driven market. Although AX have positive health benefits, however, there are also some negative effects of adding AX to wholemeal bread

due to the functionality and properties of AX, the effects (positive and negative) of AX on wholemeal bread are obtained from the same properties. This high water absorption is attractive to bakers, allowing more water in bread formulations, impacting on bread quality parameters, including loaf volume, crumb texture and staling characteristics (Biliaderis *et al.*, 1995; Skendi *et al.*, 2011). At the same time, the water absorption capacity of AX in dough formulation can produce dough which is viscous and difficult to handle because of limited amount of water (Izydorczyk & Biliaderi, 1995).

### **3.3.1 Arabinoxylans as an ingredient in bread dough**

The three main parts of a wheat grain are the bran, the endosperm and the germ. 24% of wheat bran is composed of arabinoxylans, thus wheat bran is recognised as a good source of AX. This 24% AX found in wheat bran is part of the thick and complex xylans cell walls that protect the wheat kernel. For this reason, AX are proposed as very good sources of dietary fibre. Dietary fibre has a range of effects on bread dough, these range from dough hardening (reduction in extensibility properties) to the general disruption of dough gluten network (Collar *et al.*, 2007; Gómez, *et al.*, 2003; Wang *et al.*, 2002). Because of the high-water holding capacity of AX, an increase in the water absorption of the bread doughs fortified with AX are expected. This could lead to a possibility of sticky doughs being formed, making handling much more difficult (Collar *et al.*, 2007). AX influence bread dough by affecting water balance and rheological properties (Roels *et al.*, 1993; Skendi *et al.*, 2011).

The quality of bread can be affected both negatively and positively depending on the experimental properties and setup of the AX used in fortification of the bread (Roels *et al.*, 1993). The potentially beneficial role played by AX offers the possibility of increasing the healthiness of wholemeal bread, providing consumers with a standard healthy and tasty loaf. Addition of AX extracts from cereal to bread has been an area of interest among researchers for quite some time, although proper understanding of the interactive behaviour between bread and AX has not been determined (Bell, 2015; Courtin & Delcour, 2002; Hosney, 1984; Izydorczyk & Biliaderi, 1995; Jankiewicz & Michniewicz, 1987; Li *et al.*, 2002; Meuser & Suckow, 1986; Rattan *et al.*, 1994; Roels *et al.*, 1993; Wang, Van Vliet, & Hamer, 2005). AX are highly viscous solutions with a water holding capacity which increases the interest of their study (Cawley, 1964; Izydorczyk *et al.*, 1991; Izydorczyk & Biliaderi, 1995; Jelega & Hlynka, 1972). Although different studies agree on the impact of AX on the rheological properties of bread dough and finished baked loaf, the findings are mixed and inconclusive (Denli & Ercan, 2001; Wang *et al.*, 2004). The mixed results observed from previous research could be as due to differences in the types of AX and their origins as well as the method in which extraction was carried out and nature of the AX (WEAX or WUAX) (Courtin & Delcour, 1998). The molecular weight (MW) and level of impurity of the AX also are likely to account for variations in results obtained by other researchers (Courtin & Delcour, 1998).

Researchers have provided the four following hypotheses on the effect of AX to bread dough:

- Positive functional effects are observed with the addition of WEAX to bread dough as a result of viscosity increase (Cawley, 1964).
- Courtin & Delcour (1998) and Roels et al. (1993) hypothesized that water holding capacity of AX has an effect on characteristics of dough.
- A gas holding network could be developed in dough as a result of gelling influences on viscosity and water holding capacity of AX (Neukom & Markwalder, 1978).
- Finally, the interactive phenomena between AX and the gluten protein present in dough are responsible for observed functional effects (Udy, 1956).

AX have an impact on bread quality parameters which include the loaf volume, crumb texture and staling characteristics (Bell *et al.*, 2015; Biliaderis *et al.*, 1995; Rattan *et al.*, 1994; Skendi *et al.*, 2011), mainly due to the ability of WEAX to form viscous solutions and WUAX to absorb and retain water (Bell *et al.*, 2015; Saulnier *et al.*, 2007).

### **3.3.2 Functionality and Effects of AX in bread**

Since AX have functional properties which can be exploited for either food or non-food uses, AX have the possibility of being of great economic value (Campbell *et al.*, 2019; Courtin & Delcour, 2002; Du *et al.*, 2009; Maes & Delcour, 2002; Martinez-Hernandez *et al.*, 2018; Misailidis *et al.*, 2009). The physicochemical properties of arabinoxylans make them a promising candidate to be added to bread as a functional ingredient, and their effects on finished bread products have been studied widely over the last few decades (Biliaderi &

Izydorczyk, 2006). Arabinoxylans are multifunctional molecules with much functionality which can be added to wholemeal bread for further improvement (Saulnier *et al.*, 2007).

The physicochemical properties of AX are dependent on the functionality of AX (Sasaki *et al.*, 2004). The characteristics of AX with functional properties on bread dough include; foam stability, molecular weight, viscosity, water solubility, water holding capacity and oxidative crosslinking and gel foaming capacity (Sasaki *et al.*, 2004). Foam stability increases with molecular weight as a result of increase in viscosity. An increase in viscosity is observed as the concentration and molecular weight of AX increases (Saulnier *et al.*, 2007). There is a relationship between the water holding capacity of AX and the water solubility; because AX have the ability to be water soluble, they have a high-water holding capacity; this in turn affects the texture of dough and bread. This water holding characteristic of AX reduces the amount of water available in a dough formulation for proper dough development (Rao *et al.*, 2007), thus, affecting the rheological properties of dough and preventing gluten protein network and producing dough which is viscous and hard to handle (Bell, 2015).

Döring *et al.* (2015) characterised the effect of AX on protein microstructure at different levels between 0- 10% concentration on the microstructure of wheat and rye dough formulations. This was done using a Modified Glutomatic mixing system and found that addition of AX at a concentration of 2.5% reduced the elasticity of the dough. This led to the assumption that adding about 2.5%AX could have a positive effect on the final volume and crumb structure of a baked

loaf as long as dough hydration was accounted. Wang *et al.* (2003) on the other hand studied the effect of the interaction of water unextractable solids (WUS) on dough properties and gluten quality. It was found that the high-water binding capacity of WUS prevented water to be available for hydration during the breadmaking process. Hence, addition of an extra amount of water might help improve the gluten quality and thus, enhance dough development.

In the case of the crumb structure of bread, AXs are found to have both positive and negative effects depending on the type and origin of the AX. Improved crumb structure was observed with addition of WEAX while addition of WUAX was either found to have no effect or a negative effect on crumb structure (Courtin & Delcour, 2002; Michniewicz *et al.*, 1992; Rouau *et al.*, 1994). The issue with this is, WUAX has a higher AX content in wheat flour (70-75%) while WEAX has a lower AX content in wheat flour (25-30%) limiting the positive effects observed in wholemeal bread and dough. The functionalities of AX are all intertwined and thus result in similar effects. Further research with different AX concentrations has to be carried out for better understanding and utilisation of AX. AX have a higher water holding capacity to flour and hence it is suspected that a smaller amount of AX will be required to replace a percentage of flour as compared to wheat bran (Wang *et al.*, 2002).

An increase in dietary fibre contents in food has been encouraged by health experts in recent years but although people are somewhat willing to increase fibre intakes, addition of fibre to food causes less preferred versions of food products. This is because the richest dietary fibre foods are cereals and addition

of cereal bran (specifically wheat bran) to food reduces the organoleptic characteristics of the food. In the case of this research, addition of wheat bran to bread dough competes with the flour for available water and causes improper dough development. Lack of adequate amount of water for dough development prevents gluten protein network development and proper development of aerated structures during mixing and yeast fermentation. For production of wholemeal bread that is both healthy and tasty, the detrimental effects of bran have to be completely alleviated to maximise the beneficial effects of bran on wholemeal bread. A number of researchers have carried out works to help understand the effects of wheat bran on already baked loaf but there is a gap in studies of the effects of bran on dough. To properly understand the effects of bran, studies should be based on interactions of bran with wheat dough instead of baked loaf. The Dynamic Dough Density system developed by Campbell *et al.* (2001) is a worthwhile technique to be used in studying the effects of bran on wholemeal dough during the mixing and proving stages of breadmaking. This is because the Dynamic Dough Density system has the ability to mimic aeration of dough during mixing as well as the expansion capacity during proving.

As noted in Chapter 1, the main objective of the current research is to improve knowledge on bread aeration and rheology as affected by fibre, specifically wheat bran and arabinoxylans. The Dynamic Dough Density (DDD) system has been identified as a new technique that gives a sensitive indication of factors affecting the ability of doughs to expand and retain gas, while dynamic oscillatory rheometry is relevant to understand effects of fibre on dough rheology. Addition of fibre to bread formulations always raises the issue of how

much additional water to add; a further objective is to seek a suitable method for quantifying the amount of water required for fibre-enriched bread dough formulations. Thus, the objectives for the current research were:

- To confirm the relevance of the Dynamic Dough Density system and to apply it to understand effects of fibre on gas retention during proving;
- To investigate approaches for compensating for fibre in the dough formulation through increased water addition;
- To investigate effects of fibre on dough rheology;
- To apply these studies to doughs prepared in a high-speed dough mixer relevant to the Chorleywood Bread Process.

### **3.4 Summary**

Arabinoxylans are a fibre component of wheat bran that could become commercially available as bread ingredients via co-production in biorefineries, offering quality benefits while increasing the fibre content of breads and their health benefits. Generally, AX and other fibres have complex effects throughout the breadmaking process and understanding these effects in order to produce healthy breads that retain their palatability is an ongoing challenge. However, in recent years' new bread research techniques have become available that can shed new light on the interactions between aeration, rheology and fibre during breadmaking. One of these is the Dynamic Dough Density (DDD) system, which was used in the current work to investigate effects of bran and AX. Prior

to this, in order to demonstrate and evaluate the value of the DDD technique, it was applied to study another topic of commercial interest; the effect of retardation on dough expansion, which is described in the next chapter.

## **Chapter 4. Effects of ethanol and retardation on dough expansion**

### **4.1 Introduction**

Refrigeration of doughs is often carried out to facilitate the timing of the baking of products by removing the direct link with when the dough is mixed. Retarding is a specialised form of refrigeration in which humidity levels are kept high in order to avoid surface loss of moisture leading to a hard skin and poorer quality, and is often applied to doughs containing yeast (Cauvain, 2015). However, baked product quality can deteriorate following retarding. In the current study, doughs were formulated with small amounts of ethanol, to compare their behaviour with that of retarded doughs in which ethanol may have accumulated. The effects of ethanol and of retardation were analysed using the Dynamic Dough Density (DDD) system, which is a sensitive indicator of dough expansion behaviour under conditions that mimic proving (Campbell *et al.*, 2001; Campbell *et al.*, 2008; Campbell *et al.*, 2008b). The retardation experiments demonstrate the usefulness of the DDD test, prior to applying it to bran and AX studies. The work was done in consultation with CSM Bakery Solutions, who provided materials and guidance, and helped with interpretation of the findings.

Experiments carried out in this chapter were also used to introduce and validate the DDD system for further studies throughout this thesis.

## **4.2 Retardation of bread doughs**

Bread production using more efficient methods like retarding of doughs has provided effective guidance and processing in the development of the breadmaking industry. Dough retardation has been in practice since the 1950s, to help minimise the overall production process time of breads. By decreasing the temperature of a bread dough, the yeast activity within that dough is simultaneously reduced. This phenomenon is known as dough retarding and is done using an equipment called the dough retarder (Cauvain, 2015). This process is used more commonly in European countries than in the UK.

Irrespective of the kind of bread being produced, the dough can be retarded as long as the retarding and proving conditions are used as this process does not improve the quality of the end product. Breadmaking processes that involve the use of bulk fermentation present a different challenge compared to doughs that do not require bulk fermentation (no-time breadmaking), such as CBP. Two major challenges are found with retarding bread doughs that require bulk fermentation. The first is that, since the amount of yeast required is a very important part of dough development, so any changes made to the yeast levels will consequently cause changes in bulk fermentation or dough temperature to suit the production of the desired final product (Cauvain, 2015). The second major challenge is the amount of gas produced and present in a bulk-fermented dough. A change in the amount of gas present in a dough changes the final bread product obtained after retarding (causing the production of a bread different from the intended desired product).

Bread doughs are poor conductors of heat, the size of the dough being retarded determines the way the dough will behave during and after retardation. A retarded small dough piece will have an even distribution of temperature across the sample while a large dough sample being retarded will result in either the skinning of the outer layer of the dough or occurrence of white spots (Cauvain, 2015). This is due to moisture loss from the surface of the dough over time.

In regards to retarding temperatures, the initial cooling and the storage phase temperature have significant effect on the final baked loaf (Cauvain, 2015). Dough weight loss during the storage phase is another effect influenced by retarding temperatures. At low temperature conditions, dough fermentation occurs continuously with retardation. This may result in the final product having an intense acidic flavour which is undesirable. In the case of no-time breadmaking, there is no reason to decrease the dough temperature especially if improvers are being used as this may lead to the inhibition of the oxidizing agents and thus, a drastic reduction in the gas retained within the dough (production of an undesirable final product) (Cauvain, 2015). This can lead to an uneven expansion of bread dough during proving.

The current work prompted by a query from CSM Bakery Solutions, who wished to understand better why retarding resulting in poorer bread quality. They had hypothesised that the yeast, which continues to be slowly active even at retarding temperatures of typically 4°C, produces ethanol which affects subsequent bubble stability during proving and hence baked product quality. We identified that the Dynamic Dough Density system would be an appropriate

way to investigate this hypothesis and to demonstrate the sensitivity and value of this technique.

### **4.3 Introduction to the Dynamic Dough Density (DDD) system**

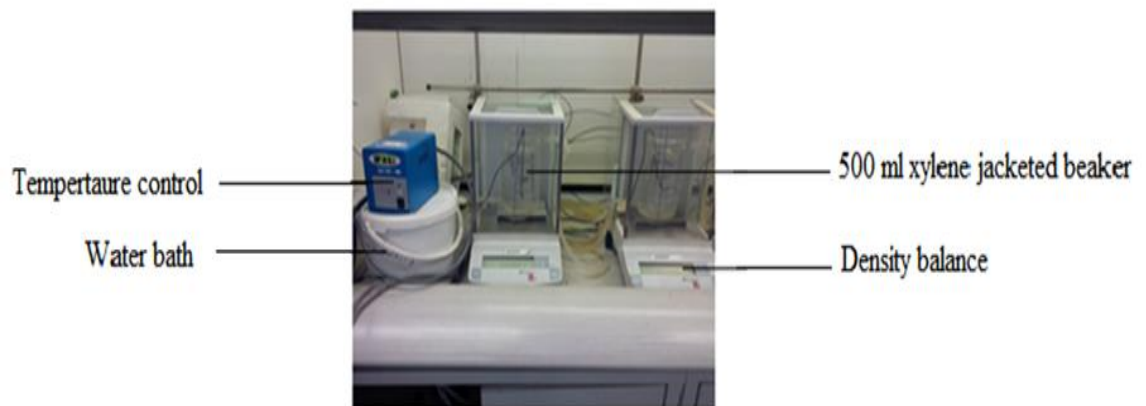
The Dynamic Dough Density technique follows the changing density of a yeasted dough sample; as the yeast produces carbon dioxide gas, the dough expands and the density changes. The functional property of dough that is of interest is its ability to expand and retain gas; the maximum expansion, as indicated by the minimum density achieved by the dough, is therefore a measure of this quality of the dough (Campbell *et al.*, 2001; Campbell *et al.*, 2008). The DDD technique is quite sensitive and is therefore a useful technique for investigating the effects of ingredients or processing conditions on dough quality.

For the current experiments, four density measurement systems were used. A single density measurement system comprises an analytical balance (Ohaus Adventurer 65 g / 0.1 mg) with a jacketed beaker, a double-cup sample holder and a J-type thermocouple wire, as illustrated in Figure 4.1 and Figure 4.2. The double-cup is equipped with an anti-float cap and is used to weigh the sample both in air and immersed in the liquid (xylene) contained in the beaker. Xylene was purchased from Fisher Scientific (Loughborough, UK) with a density of 0.86059 g/cm<sup>3</sup> at 38°C. The thermocouple junction is placed below the double cup and towards the radial centre of the beaker. The water bath is maintained at 40°C and water circulated through the jackets of the beakers, to give a xylene

temperature of  $\sim 38^{\circ}\text{C}$ . The changing weight of the dough piece and the xylene temperature are recorded every 10 seconds by a computer programme written in LabVIEW 7.0 (National Instruments, UK). The DDD system is placed in a fume hood to avoid health and flammability hazards associated with xylene.



*Figure 4.1: DDD double cup*



*Figure 4.2: Dynamic Dough Density system*

## 4.4 Materials and methods used in the current work

### 4.4.1 Materials

Dough samples were prepared using strong white flour, salt, yeast, fat, water and ethanol. Preliminary studies were undertaken using commercial strong white bread flour, and with no added sugar in the formulation. Following discussions of these results with CSM in which there was a concern the results were influenced by the yeast depleting the sugar during retardation, the study was repeated using flour and improver supplied by CSM, and with added sugar. Tables 4.1 and 4.2 show the ingredients used in dough preparation and their sources.

*Table 4.1: Preliminary ingredients and sources*

<b>Ingredients and percentage on flour weight</b>	<b>Details</b>
Strong white bread flour (100%)	1.5 kg bag, Sainsbury's, London, EC1N 2HT
Salt (1.6%)	Sainsbury's cooking salt, Sainsbury's, London, EC1N 2HT
Water (62%)	Distilled water, research laboratory, University of Huddersfield
Yeast (4%)	Fast action dried yeast, Sainsbury's, London, EC1N 2HT
Fat (5%)	500 g Trex vegetable fat, Princes Limited, Liverpool, L3 1NX
Ethanol (0-2% replacement of water)	Absolute, analytical reagent grade, Fisher Scientific, Loughborough, LE11 5RG

Table 4.2: CSM ingredients and sources

Ingredients and percentage on flour weight	Details
Wheat flour (100%)	T550, CSM Bakery Solutions
Salt (1.6%)	Sainsbury's cooking salt, Sainsbury's, London, EC1N 2HT
Water (59%)	Distilled water, research laboratory, University of Huddersfield
Yeast (3.5% and 7%)	Fast action dried yeast, Sainsbury's, London, EC1N 2HT
Improver (3%)	CSM Bakery Solutions
Ethanol (0-2% replacement of water)	Absolute, analytical reagent grade, Fisher Scientific, Loughborough, LE11 5RG

For the preliminary studies using commercial flour from Sainsbury's, doughs were formulated on the basis of 63% water absorption, less 1% to facilitate sample handling for the Dynamics Dough Density (DDD) system for preliminary studies (Campbell *et al.*, 2008). When using the wheat flour and improver sent by CSM bakery, 59% distilled water was used for experimental work at the request of the company. For studies of the effect of ethanol, ethanol concentration was varied by replacing 0 to 2% of water weight in preliminary studies and 0 to 4% in the final experiments.

Tables 4.3 and 4.4 show the amount of water and ethanol in each dough formulation. For studies of dough retardation, doughs were prepared in the same way but omitting the ethanol.

Table 4.3: Ethanol concentrations and amounts in dough formulations

Ethanol level (%)	Ethanol level (g)	Water level (g)
0.0	0.0	31.0
0.4	0.1	30.9
0.8	0.3	30.7
1.2	0.4	30.6
1.6	0.5	30.5
2.0	0.6	30.4

Table 4.4: CSM ethanol concentrations and amounts in dough formulations

Ethanol level (%)	Ethanol level (g)	Water level (g)
0.0	0.0	29.5
0.5	0.2	29.3
1.0	0.3	29.2
1.5	0.4	29.1
2.0	0.6	28.9
2.5	0.7	28.8
3.0	0.9	28.6
3.5	1.0	28.5
4.0	1.2	28.3

It is standard practice in the DDD test to use twice the standard yeast level, to speed up the test (Campbell *et al.*, 2008c). In the preliminary tests, 4% yeast was used, in line with previous works in the lab. For subsequent studies using CSM's flour and formulation, initially 3.5% yeast was used (as this was the standard amount of yeast used by CSM bakery). However, for some unknown reason the DDD profiles took much longer than expected. Trials were repeated using CSM's flour at yeast levels of 7% following normal practice of DDD tests (i.e. the use of double the yeast level). Double the amount of yeast is used to facilitate the activation of the yeast while imitating the proving stage of breadmaking, thus predicting the expansion rate of the dough.

#### **4.4.2 Dough preparation in the Minorpin mixer and sampling for DDD analysis**

Doughs based on 50 g flour were prepared using the Minorpin mixer (Henry Simon, Ltd, UK) shown in Figure 4.3, which has four pins in the rotating head and three on the base. In the case of preliminary studies, dry ingredients were put into the mixer first and mixed for 1 minute, then fat and 31 g of water or the ethanol-water equivalent were added and mixed for 7 minutes to develop the dough. With the CSM samples, dry ingredients were mixed for 1 minute and then 29.5 g or ethanol-water equivalent added to the mixer for an extra 7 minutes to develop the dough. Experiments were carried out twice using the CSM flour; first with 3.5% yeast and then with 7% yeast. Dough temperatures at the end of mixing were measured and ranged from 26.3-29.5°C. After mixing, the dough was retrieved from the mixer, placed on a bench between two metal rods of 12 mm diameter and rolled flat using a rolling pin. A cylindrical cutter of 21 mm diameter was used to cut two samples from the dough piece, each weighing approximately 5-6 g. Each sample was then swirled in a spherical flask for 30 s to strengthen the outer surface of the dough and eliminate points of weakness (Campbell *et al.*, 2008). For the investigation of the effect of ethanol, the samples were placed into the DDD system as described below, with measurements recorded from 3 minutes after the end of mixing. For the investigation of the effect of retardation time, the samples were placed in beakers covered with cling film, to avoid moisture loss, and placed in a refrigerator at 4°C for the required time before being retrieved and placed in the DDD system.



*Figure 4.3: Henry Simon Minorpin mixer (Henry Simon Limited, England)*

## **4.5 Investigations**

### **4.5.1 Effect of ethanol on dough expansion**

To investigate the effect of ethanol concentration on dough expansion in the DDD system, eight replicate data points were obtained for six ethanol levels over a two-day experimental period. On the first day, two dough samples were prepared for each of the six ethanol concentrations (0, 0.4, 0.8, 1.2, 1.6, and 2%), to give a total of 12 dough samples, prepared in a random order. For each dough, two samples were retrieved as described above and placed in two of the four DDD systems. On the second day the trial was repeated in the reverse random order to that used on the first day (the pair of DDD systems used in each case was not that used on the first day, such that overall each formulation was tested

twice over all four DDD systems). Thus, for each ethanol concentration, four dough samples were prepared over two days, and two samples from each dough tested, to give a total of eight data points for each ethanol level.

#### **4.5.2 Effect of retardation time on dough expansion**

To investigate the effect of dough retardation time, a four-day experimental plan was prepared in order to test dough samples that had been retarded at 4°C (a refrigerator was used in the absence of a retarder) from 0 to 18 hours at 1 hour intervals, a total of 19 conditions. Each time was tested twice, in an order dictated by the logistics of the timing, with two samples tested each time, to give a total of four data points for each retardation time. A dough sample was mixed, rolled flat to a thickness of 12 mm, and seven samples cut from the dough piece using the 21 mm cylindrical cutter. Each sample was swirled for 30 s in a spherical flask and then placed in a beaker covered with cling film and placed in the fridge. A second dough was immediately mixed, and seven more samples retrieved; the timescale between the mixing of the two dough samples was 10 minutes. When the retardation time to be tested was reached, a sample from the first mix was retrieved from the fridge and placed in one of the DDD systems, then 10 minutes later a sample from the second mix was placed in second DDD system. To cover all 19 retardation times from 0-18 hours, with four replicates for each time, required a total of 12 dough samples giving 84 samples, of which 76 (4×19) were tested. Dough samples were mixed either first thing in the morning (around 8.00 am) to allow retardation times of 0-9 hours to be tested (because after 4 hours the experimental time increased from the usual ~50 minutes to ~2 hours; above 4 hours of retardation, the samples were run on

a 2-hour basis over the 4 days of analysis in order to get four replicates for each hour), or in the evening (around 10.00 pm) to allow times of 10-18 hours to be tested (this was done in 2 hours interval over the 4 days). Figure 4.4 shows part of the Excel spreadsheet used to schedule the tests.

When a dough sample is placed into the fridge at 4°C or taken from the fridge and placed into the xylene at 38°C, it takes time for its temperature to change. The temperature profile was measured approximately by placing a dough sample on the end of a temperature probe and monitoring the change over time, to get a feel for the time associated with temperature change relative to the retardation and DDD profiling times.

#### **4.6 Statistical analysis**

From each DDD profile the minimum density and the time to reach the minimum density were determined. Analysis of variance (ANOVA) was carried out using Microsoft Excel. The ANOVA (at a 95% confidence interval) measures the differences in the results within all each sample group (Sainsbury's, 3.5% CSM and 7% CSM) to determine whether addition of ethanol to each dough formulation causes any effects.

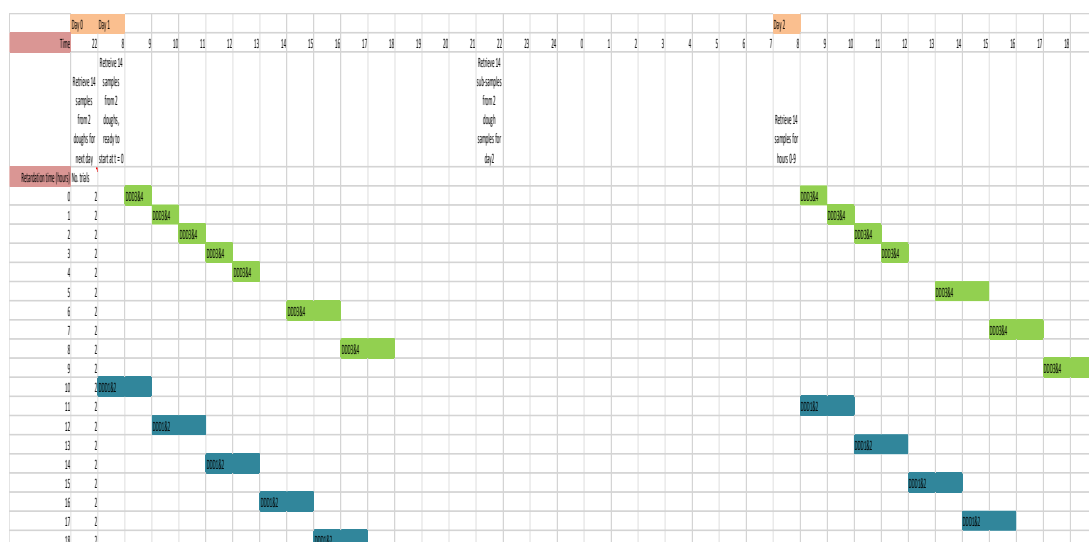


Figure 4.4: Part of the spreadsheet used to schedule DDD tests for different retardation times

## 4.7 Investigations

### 4.7.1 Effect of ethanol on dough expansion

Figure 4.5a plots the dynamic dough density profiles averaged from eight trials against time for the preliminary investigation using Sainsbury's flour, in which ethanol level was varied from 0-2%. Figure 4.5b and c show the results for the subsequent trial using the CSM flour and formulation, including an improver containing sugar and with the ethanol levels varying from 0-4%. Figure 4.5b shows the results from using 3.5% yeast, and Figure 4.5c the results from using 7% yeast.

In the case of Figure 4.5a, the samples exhibited typical DDD profiles in which density decreased to a minimum, with no sudden losses of gas, indicating reasonably stable dough samples. Minimum density was reached after around 2000 s. The profiles are not dramatically different with the addition of ethanol.

By contrast, Figure 4.5b, shows a longer time to reach minimum density, around 4000-6000 s. suspecting that this was down to too low a yeast level, the trial was repeated with twice the yeast level; as shown in Figure 4.5c, this had the effect of reducing the time to minimum density to around 2500-4000 s. In both cases, also in contrast to Figure 4.5a, there appears to have been an effect of ethanol level on the shape of the DDD profile. In part this is because the second investigation extended to higher levels.

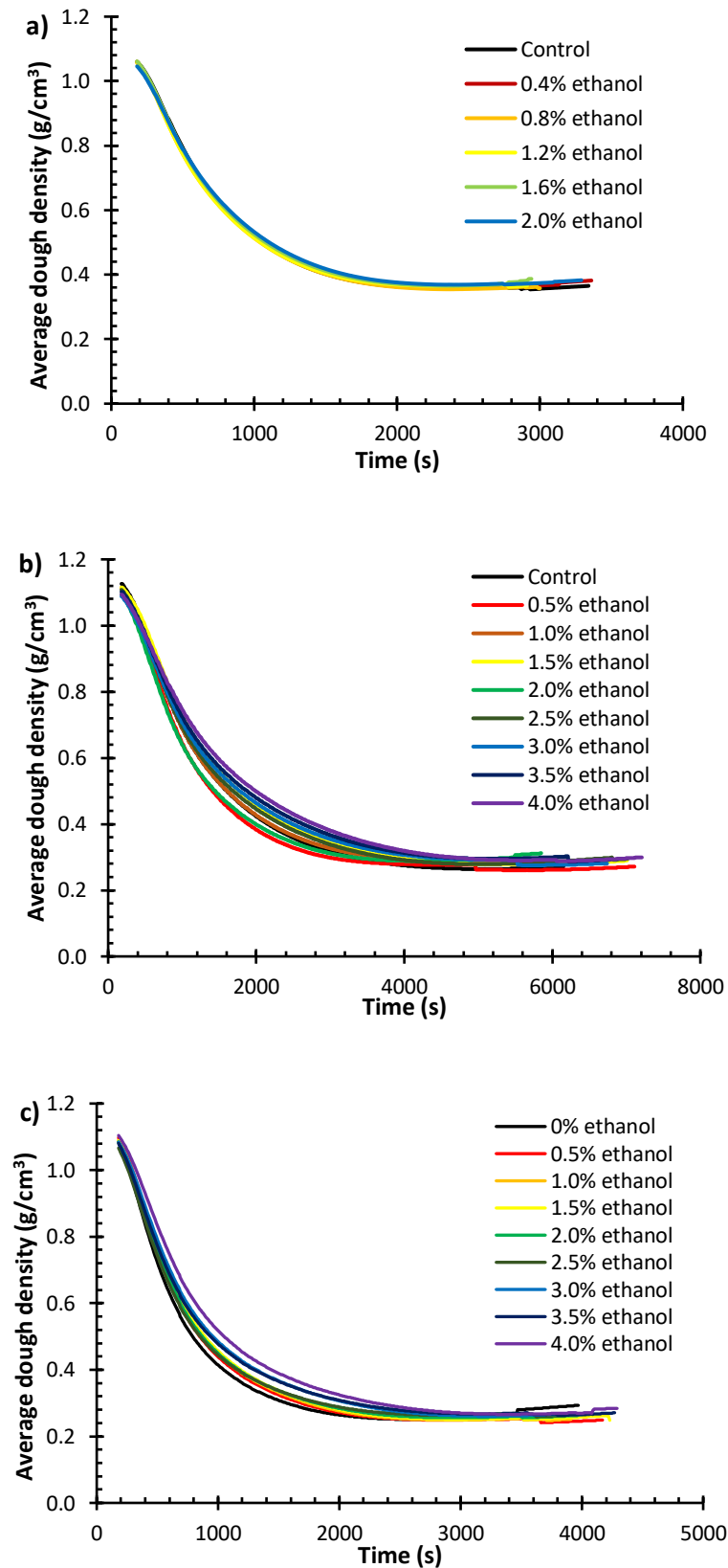


Figure 4.5: Average dough density of different ethanol-dough formulations over time a) Preliminary studies using Sainsbury's flour; b) CSM flour with 3.5% yeast; c) CSM flour with 7% yeast

Figure 4.6 shows the minimum densities for the eight replicates for each ethanol level of the Sainsbury's flour dough, CSM flour (3.5% yeast) and CSM flour (7% yeast). While the experiments carried out using Sainsbury's flour ranged from 0-2% ethanol, experiments carried out using CSM flour had ethanol levels up to 4%. Each point is averaged from eight samples and the error bars are  $\pm 1$  standard deviation of the mean.

Clearly, the doughs prepared from the CSM flour achieved lower minimum densities (i.e. higher expansion) than the doughs prepared from the Sainsbury's flour. In itself this is not a meaningful finding, as the investigations were carried out several months apart, and with very different formulations that were not intended to be comparable. In particular, the CSM formulation contained added sugar, in order to avoid any effect of sugar depletion on the results. Beyond that, the intention behind the two formulations was to provide confirmation of patterns and to see if the broad patterns were influenced by sugar addition.

The CSM doughs with 7% yeast achieved lower minimum densities than those with 3.5% yeast. This is in line with previous unpublished work from our labs which indicates that higher yeast levels lead to higher maximum expansion in the DDD test. The minimum density/maximum expansion occurs when the rate of gas production by yeast fermentation equals the rate of loss of gas from the surface of the dough piece (Campbell & Herrero-Sanchez, 2001; Campbell *et al.*, 2001, 2008; Chin & Campbell, 2005b; Shah *et al.*, 1998). Higher yeast levels shift the balance towards higher rate of gas production, such that more expansion is achieved before the gas loss equals the gas production.

Considering the Sainsbury's flour dough, there is some variability in the results, but in general there appears to be an upward trend in the results observed. A fitted trend line (not shown) had  $R^2$  value of 0.4369, implying a correlation coefficient of 0.66 for a sample size of 8, which is significant at the 5% level of confidence. ANOVA also indicated significant differences between the treatments with  $p = 0.026$ . Thus, the effect of ethanol appeared to be to increase the minimum density, in other words to decrease the maximum expansion achieved by the dough. It is known that in general ethanol accumulation decreases the growth rate of yeast and associated rate of  $\text{CO}_2$  production (Brown *et al.*, 1991; Ingram & Buttke, 1984), which is consistent with the findings here and offers an explanation, that addition of ethanol inhibited  $\text{CO}_2$  production and hence slowed the rate of growth of the dough piece and hence the maximum expansion achieved. Figure 4.6 shows an increase in minimum density with the addition of 0.4% ethanol compared with the zero (control) ethanol control, but a large decrease with 0.8% ethanol. This is probably not significant and down to random variation, but it is conceivable that small amounts of ethanol could influence dough behaviour in non-linear ways. This means that the potency of ethanol at lower concentrations maybe stronger than at higher concentrations in bread doughs, thus, having more of an effect at lower levels than at higher levels.

CSM doughs with 3.5% yeast and with 7% yeast both showed the same upward trends. In this case, with the wider range of ethanol levels and increased number of data points, the statistics were more conclusive: for 3.5% yeast,  $p$  value=0.117,  $R^2 = 0.185$  and for 7% yeast,  $p$  value=  $8.15 \times 10^{-7}$ ,  $R^2 = 0.817$ ). Thus, the presence of

ethanol significantly reduces the ability of doughs to expand. The likely mechanism explanation is that the ethanol inhibits the rate of production of CO<sub>2</sub> by yeast.

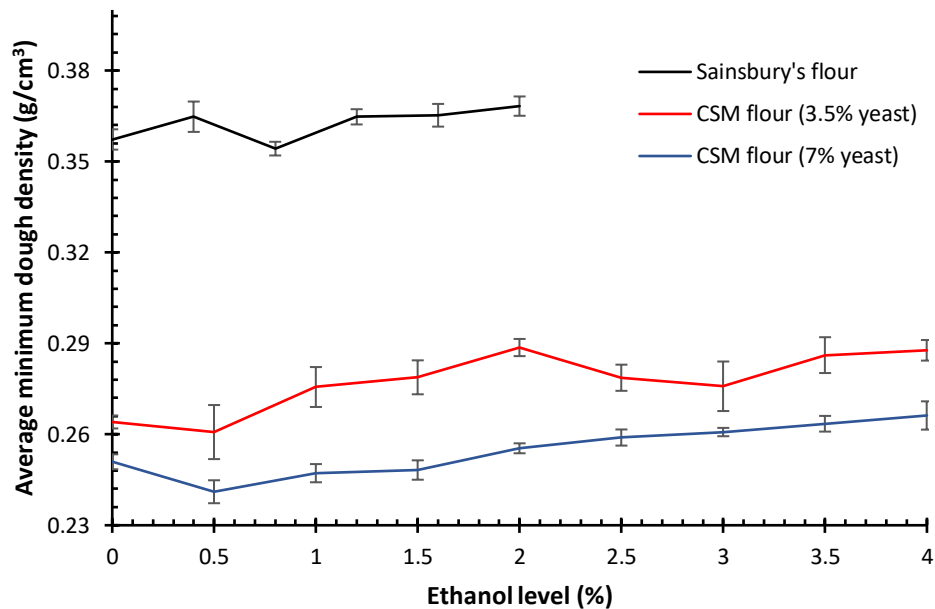


Figure 4.6: Average minimum dough density against ethanol levels

Figure 4.7 shows the average time to reach minimum densities for all three flour types and at different ethanol levels. Each point is an average of eight data points (replicates), and the error bars are  $\pm 1$  standard deviation of the mean. As noted above, with 3.5% yeast, the CSM doughs took much longer to reach the minimum, possibly because of a problem with the yeast activity. Doubling the yeast level to 7% gave much shorter times, comparable with those from the Sainsbury's dough.

Although minimum density was increased with the addition of ethanol for the Sainsbury's flour, the time to reach the minimum was unaffected, as indicated by both the correlation coefficient close to zero, and by ANOVA ( $p = 0.936$ ,  $R^2 = 0.0074$ ). For CSM dough with 3.5% yeast, although there appears to be a small upward trend, the variability in the middle of the data (red line Figure 4.6) made this not significant ( $p = 0.117$ ,  $R^2 = 0.185$ ). For the CSM doughs with 7% yeast, however, the upward trend was clearer and statistically significant ( $p = 8.24 \times 10^{-12}$ ,  $R^2 = 0.7565$ ), and apparently steeper at the higher levels, inhibiting the production of gas by yeast and slowed the expansion of the doughs. Although the effect on time to minimum density was not evident at the lower ethanol levels, taken together with the results in Figure 4.6, the picture is consistent with a mechanism in which ethanol slows gas production by yeast and hence increases the time to minimum density and decreases the extent of dough expansion.

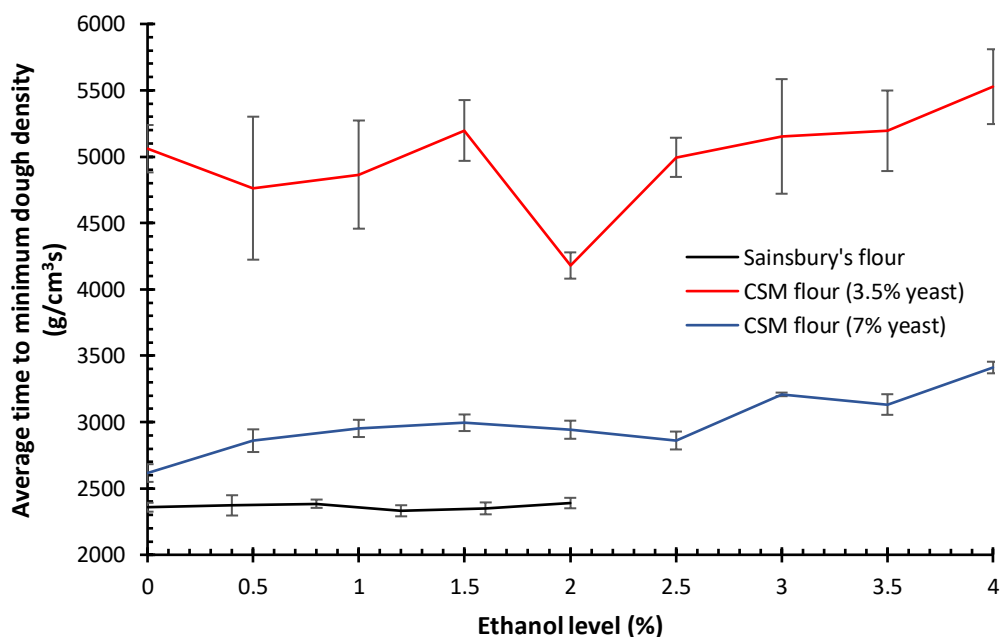
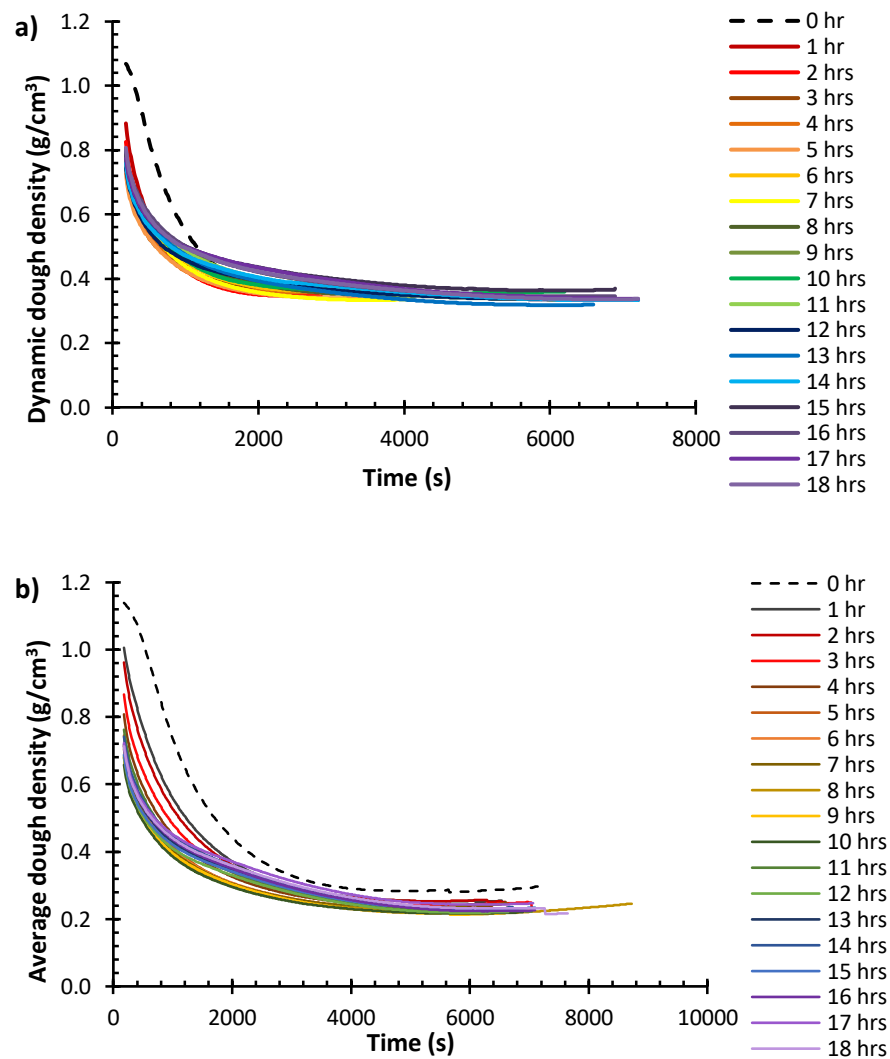


Figure 4.7: Time to minimum density versus ethanol level

#### 4.7.2 Effect of retardation time on dough expansion

Figure 4.8 shows the Dynamic Dough Density profiles for dough samples retarded at 4°C for up to 18 hours for Sainsbury's flour, CSM flour with 3.5% yeast and CSM flour with 7% yeast. In contrast with the ethanol study, in this case retarding the dough samples had dramatic effects on the density profiles for all three trials. Compared with the control dough (unretarded dough), retarded dough samples showed much lower initial densities and faster initial growth, with growth slowing subsequently, more so for dough samples retarded for longer times. The initial reduction in density is predominantly due to production of CO<sub>2</sub> by yeast during retarding, particularly during the initial period when the dough sample is still relatively warm for some time after being placed in the refrigerator. The results after only 1 hour of retarding show that the density decrease was substantial (0.882 g/cm<sup>3</sup> at 1 hr compared to 1.068 g/cm<sup>3</sup> at 0 hour), indicating substantial production of gas in that time as the dough sample cooled. In addition, the coolness (at a temperature of about 11°C from a dough temperature of about 27°C) of the sample would have decreased its initial density when it was taken out of the fridge and placed into the DDD system. This explains the more rapid initial decrease in dough density compared with the control; the gas in the dough would have been expanding as the dough warmed, decreasing its density, and gas would also be coming out of solution as the dough warmed, also contributing to a rapid decrease in density. This is more evident in Figure 4.9, which plots the changing gradient of the density profiles for the first 2000 s for Sainsbury's flour and 3000 s for CSM flour 3.5% yeast and 7% yeast. This clarifies that for the control dough at 0 hours, the slope of the

density profile is initially low and increases before decreasing, whereas for the retarded doughs, the rate of change of density is high initially then decreases over time. The decrease is more rapid for doughs retarded for longer; from Figure 4.9, for the 1 and 2 hour doughs, the curve stays steep and negative for longer than for the other doughs. This behaviour was uniform in all three experiments.



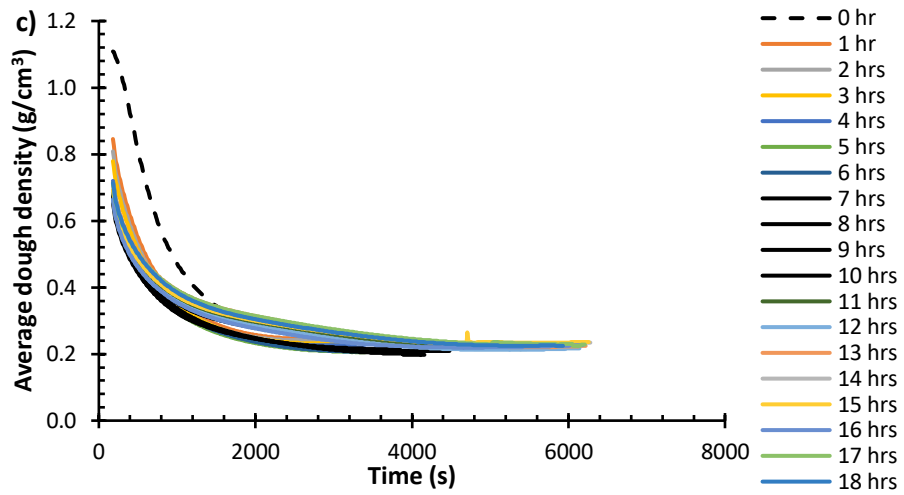
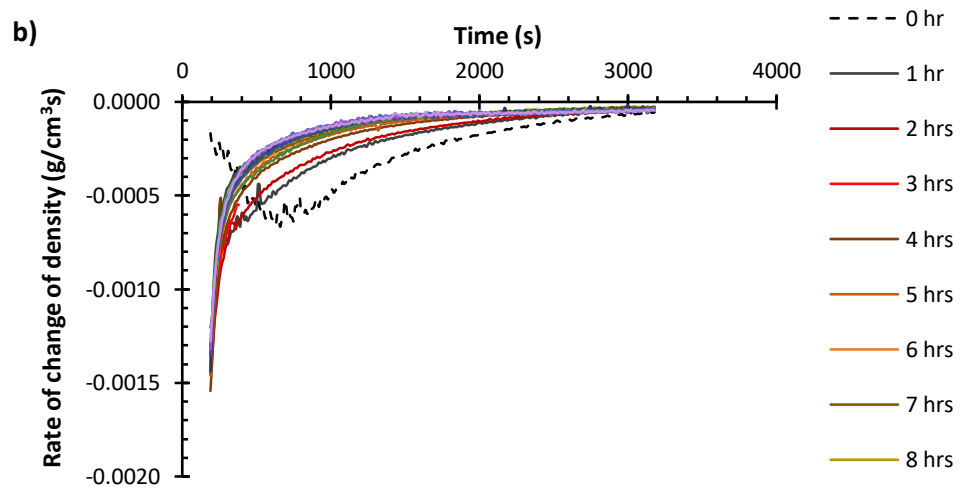
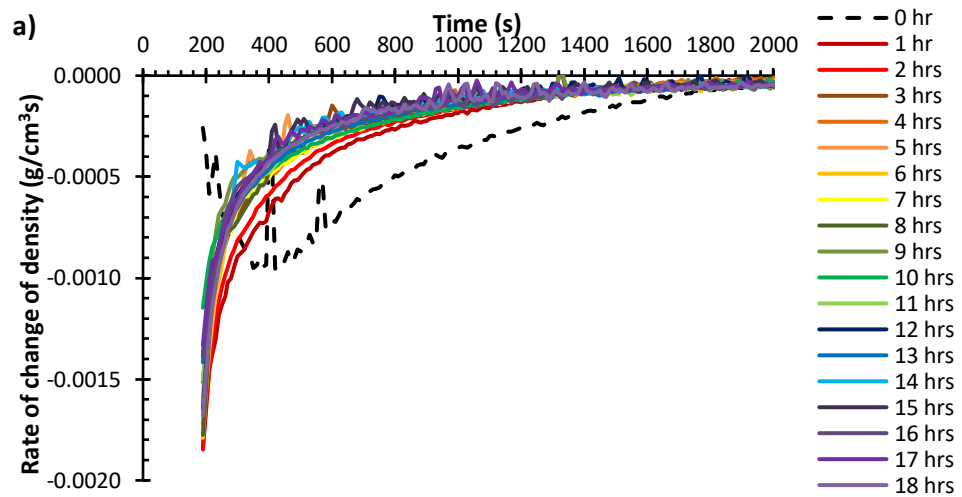


Figure 4.8: Average dough density of different retarded-dough formulations over time a) Preliminary studies using Sainsbury's flour; b) CSM flour with 3.5% yeast; c) CSM flour with 7% yeast



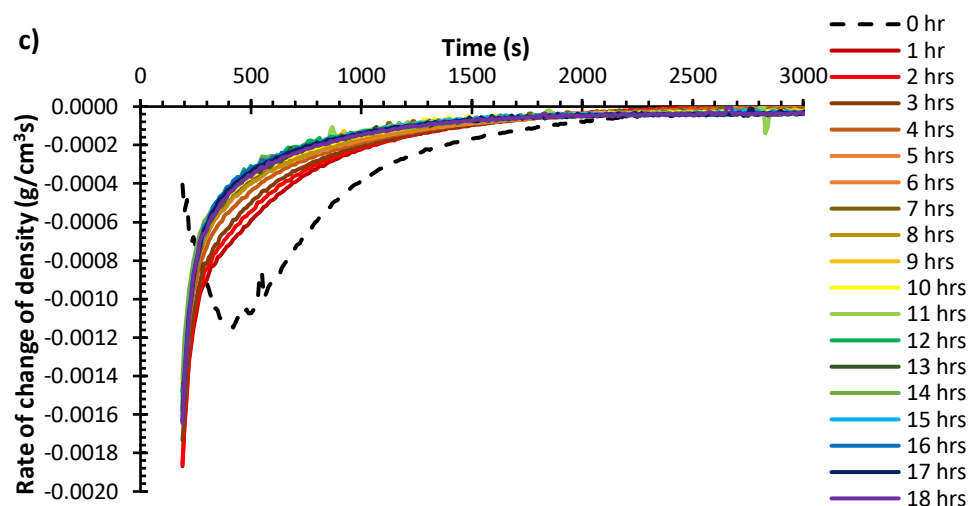


Figure 4.9: Rate of change of dough density versus time for doughs retarded for different times a) Preliminary studies using Sainsbury's flour; b) CSM flour with 3.5% yeast; c) CSM flour with 7% yeast

Figure 4.10 shows the initial dough density when the dough sample was retrieved from the fridge and placed in the xylene, for each retardation time. Clearly there is a decline in density between the control dough sample and the retarded samples. As noted above, after 1 hour the dough density was lower due to  $\text{CO}_2$  production in the fridge as the dough sample cooled down. The initial density for the Sainsbury's doughs and CSM doughs with 7% yeast decreased for the first 5 hours while for the CSM doughs with 3.5% yeast, a continuous decrease for about 9-10 hours was observed. The added sugar present in the CSM improver allowed the yeast to produce  $\text{CO}_2$  for longer in the case of the CSM doughs with 3.5% yeast while CSM doughs with 7% yeast behaved similarly to the Sainsbury's doughs. This could be because the increased yeast levels for CSM doughs with 7% yeast in relation to the amount of sugar present in the dough formulations indicating either that there was minimal further  $\text{CO}_2$  production, or that any further  $\text{CO}_2$  produced did not migrate into bubbles but

remained dissolved in the liquid phase. Consistent behaviour was observed among all three trials.

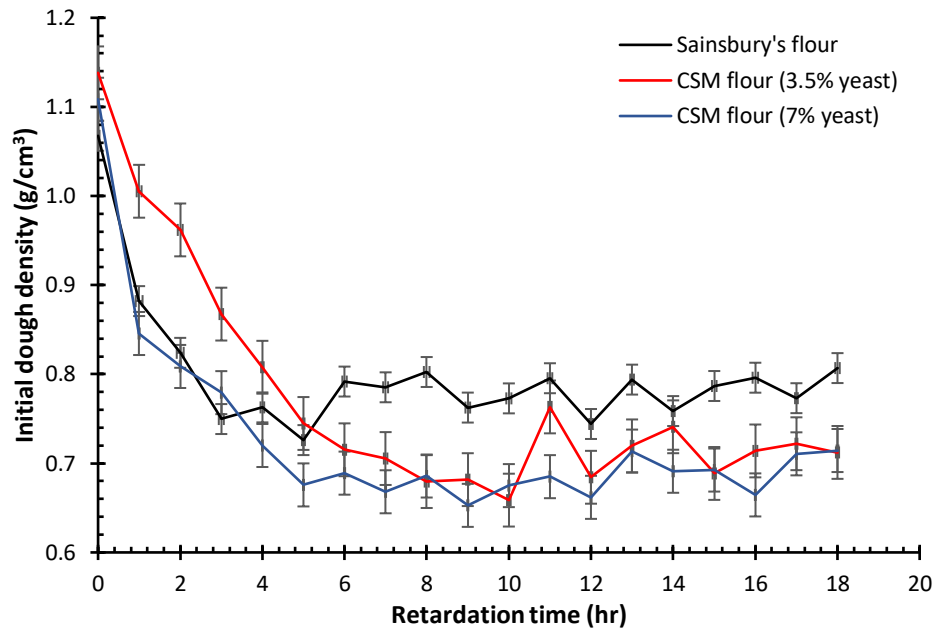


Figure 4.10: Initial dough density versus retardation time

Figure 4.11 shows the initial slope of the dough density curves of Sainsbury's flour, CSM flour 3.5% yeast and CSM flour yeast. The initial rate of change of density indicates the rate at which the gas phase increases due to thermal expansion of the gas combined with gas coming out of solution as the dough warms on being placed in the DDD system. As noted above, the initial rate of change of density was much higher for the 1- and 2-hour doughs than for the control dough, as a result of bubbles expanding and CO<sub>2</sub> coming out of solution as the dough warmed. Interestingly, there is evidence of a slight increase in the slope (i.e. less negative, so less steep) as retardation time increased; doughs retarded for longer appeared not to grow quite so quickly on removal from the fridge and placing in the xylene. Possibly the CO<sub>2</sub> started to diffuse more from

the dough sample after longer times, such that these doughs had less dissolved  $\text{CO}_2$  available to come out of solution on warming.

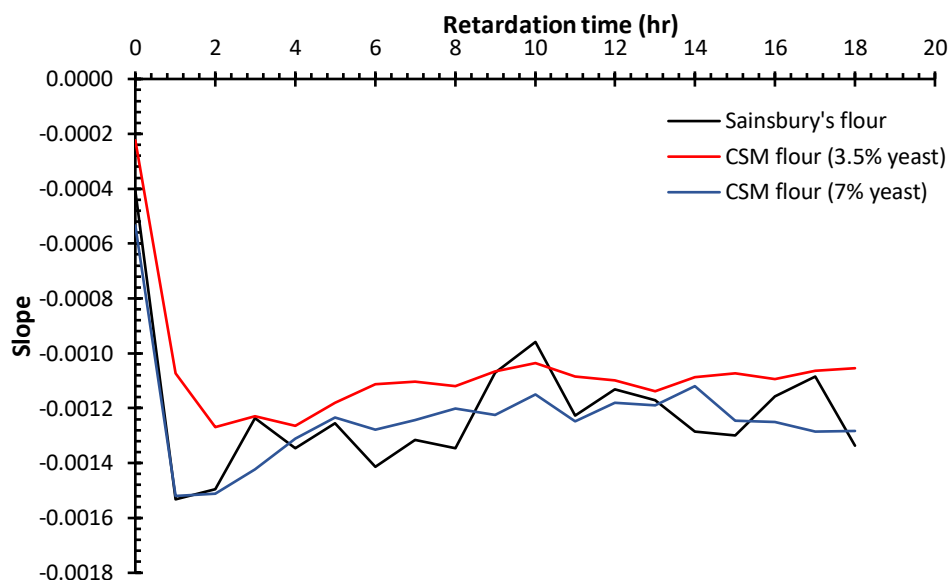


Figure 4.11: Initial slope of the dough density curve versus retardation time

Figure 4.12 shows the rates of temperature change of a dough sample being placed into the fridge at  $4^{\circ}\text{C}$  and of a dough sample taken from the fridge at  $4^{\circ}\text{C}$  and placed into the xylene at  $38^{\circ}\text{C}$ . The centre of a dough sample placed in the fridge was still at around  $10^{\circ}\text{C}$  after 1 hour and took over 5 hours to cool down to  $4^{\circ}\text{C}$ . Thus, the cooling time was long relative to the shorter retardation times, and yeast activity might be expected to be significant, although as noted above, as the dough cools and  $\text{CO}_2$  becomes more soluble in water, the activity does not appear as a change in the initial density of the dough after retarding. This was carried out only for Sainsbury's flour to give an idea of how the temperature of the dough changes over time in the refrigerator.

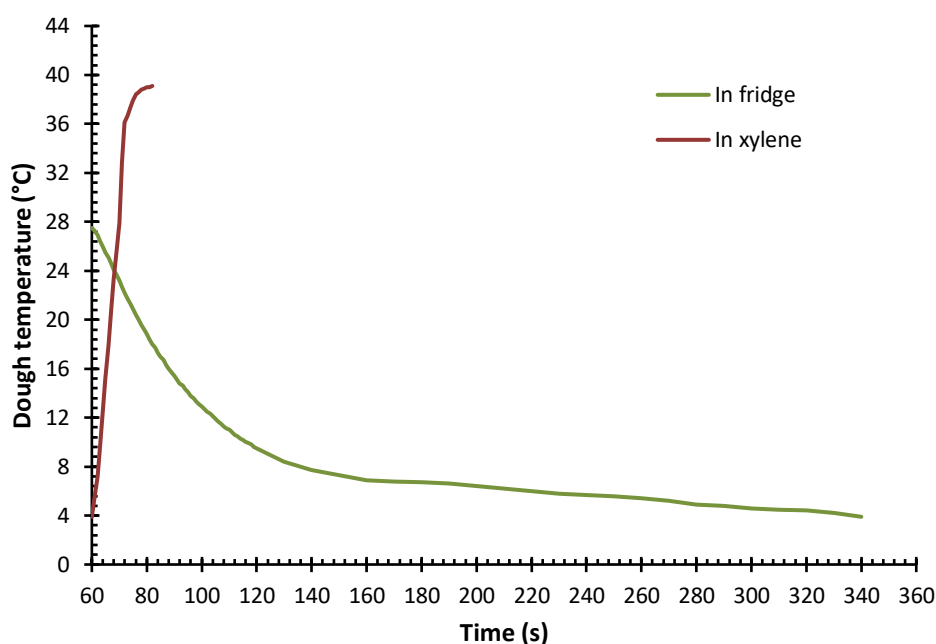


Figure 4.12: Dough temperature change in fridge (green) and in xylene (red)

A dough sample placed in xylene warmed much more rapidly, due to higher heat transfer coefficients associated with contact with liquid. Even so, the timescale for the centre of the dough piece to reach 38°C was of the order of 30 minutes, which is long relative to a typical DDD test time of 45 minutes, so the warming of the dough piece would have affected the DDD profiles. The effect would be much the same for the samples retarded for more than 5 hours (as these had all reached 4°C in the fridge), while for the 1-hour sample, for example, it was not so cool when retrieved from the fridge, and might be expected to warm slightly more rapidly when placed in the xylene. This may explain the apparent dip at 1 hour in Figure 4.8a.

Figure 4.13 shows the average minimum density for the eight replicates data for Sainsbury's flour, CSM flour with 3.5% yeast and CSM flour with 7% yeast for each retardation time. As for the ethanol study, the CSM doughs showed much

higher expansion (lower minimum densities) than the Sainsbury's doughs. However, in contrast to the ethanol results, in which higher ethanol levels gave less expansion, in this case longer retardation times appeared to give higher expansion of the doughs. This suggests that the mechanism by which retardation affects dough expansion is different to that by which ethanol affects expansion, and that the effect of retardation is not due to the accumulation of ethanol.

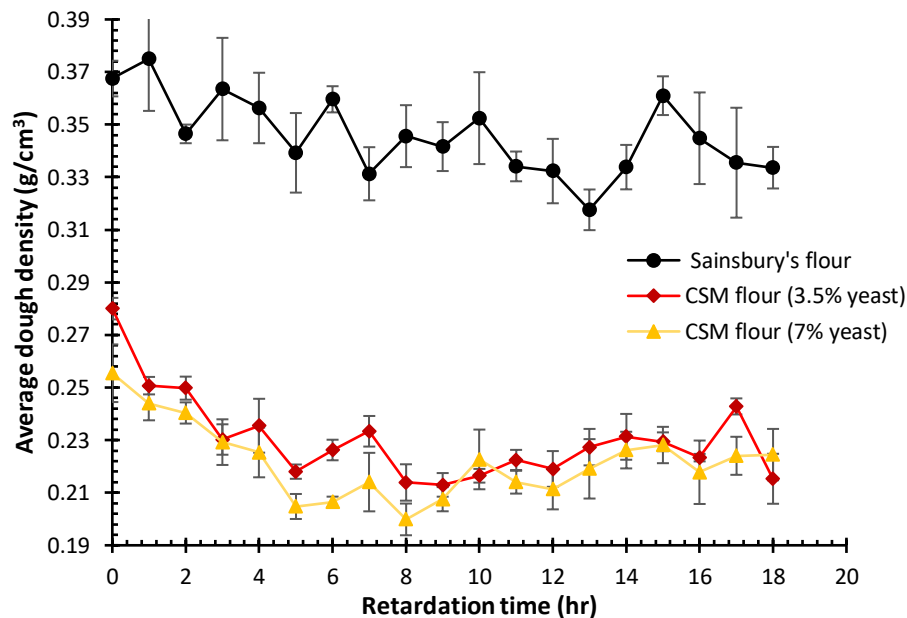


Figure 4.13: Average minimum dough density versus retardation

In contrast to the results obtained from the effect of ethanol on dough, significant differences in dough expansion occur as dough samples are retarded for longer. For Sainsbury's flour, fitting a straight line gives an  $R^2$  value of 0.3682, which is significant at the 5% level of confidence for a sample size of 19. This suggests that a linear relationship is reasonable for describing the results obtained; as retardation time increases, minimum density decreases. ANOVA

gives a  $p$ -value= 0.043, confirming that the differences between different retardation times are significant. CSM flour with 3.5% yeast had a smaller  $R^2$  value of 0.2376, while CSM flour with 7% yeast had an even smaller  $R^2$  of 0.1242, neither of which is significant at the 5% level. However, this is because in this case the minimum density decreased and then appeared to increase at longer retardation times, such that a linear model does not describe the results obtained effectively. ANOVA looks instead at whether there are significant differences between groups (retardation times in this case), rather than the overall trend; for the 3.5% and 7% yeast trials, ANOVA gave  $p$ -values of  $1.89 \times 10^{-9}$  and  $3.83 \times 10^{-5}$ , respectively, showing that the differences were highly significant, even if the relationships were not well described by a decrease that continued linearly for the longer retardation times.

The effect of retardation on dough using the DDD system showed an increase in the expansion capacity as dough samples were left to retard for longer. For the Sainsbury's flour, the increase was relatively linear over the full 18 hours, while for the CSM flour with both yeast levels, the increase was quite steep for the first 8 hours or so, after which it appeared to level off or reverse

Figure 4.14 shows the effect of retardation on the average time to reach minimum density for each corresponding retardation time of Sainsbury's flour, CSM flour with 3.5% yeast and CSM flour with 7% yeast. Clearly, retarded doughs took a lot longer to reach minimum density. It might be speculated that this is in part due to the time for a dough sample to warm up and the yeast to get going when placed into the DDD system, and for the early retarding times

this is probably true. But beyond 5 hours, the dough samples were all at much the same temperature in the fridge (Figure 4.12), but the trend of increasing time to minimum density continues. Therefore, the time for the dough to warm is not the reason for the longer time to reach minimum density. It seems more likely that it is due to a reduction in yeast activity as a result of retarding, such that the yeast produces  $\text{CO}_2$  more slowly. However, previous experience indicates that slower production of  $\text{CO}_2$  (e.g. by lowering yeast level) alters the balance between production and loss of  $\text{CO}_2$  in the DDD system to give less expansion. The higher expansion seen in the current work (Figure 4.13), despite the slower expansion, suggests a rheological change to the dough during retarding. However, the contrast with the ethanol results above suggests that the change is not due predominantly to ethanol production.

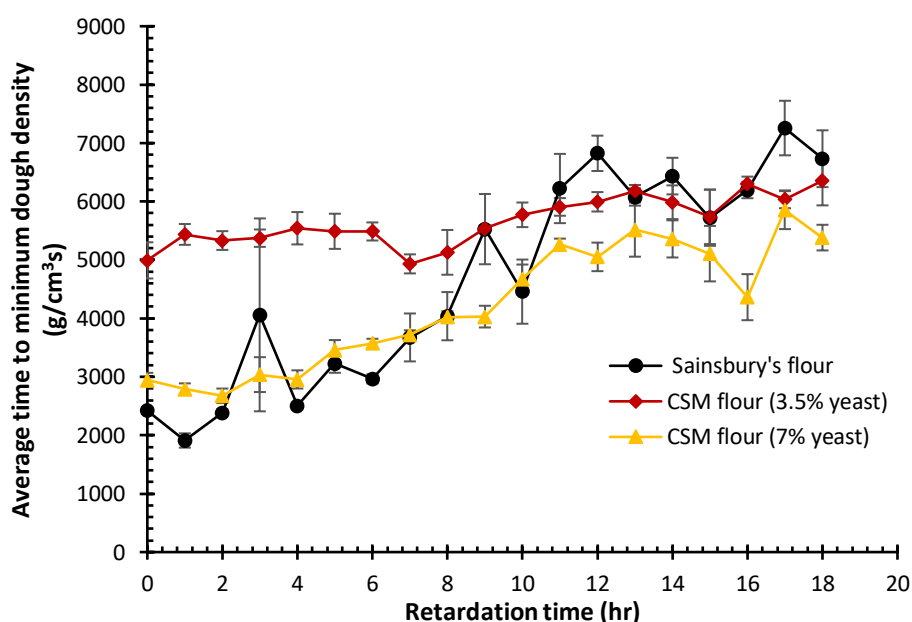


Figure 4.14: Comparison between the times to minimum density for all three experimental trials

Interestingly, the CSM doughs with 3.5% yeast initially took a lot longer to reach minimum density, as expected from the ethanol work. However, after retarding for 17 hours, the time to minimum density appears to be much the same, despite the different initial yeast levels. This suggests significant yeast production during retarding, such that the initial differences in yeast level become less pronounced.

#### **4.8 Summary**

It was hypothesised that retardation of doughs causes ethanol accumulation, which affects subsequent growth of the dough piece and the resulting bread quality. The hypothesis was tested by comparing the growth of dough pieces that had been spiked with ethanol, at up to 2% (for initial trials) and 4% (final trials) of the water, with doughs that had been retarded at 4°C for up to 18 hours, using the Dynamic Dough Density system to monitor the growth of the dough pieces. Addition of ethanol decreased the maximum dough expansion but did not greatly affect the time to reach the maximum expansion. By contrast, retarding of doughs increased both maximum expansion and the time to reach the maximum. This suggests that the effect of retardation on dough growth and bread quality is not due to accumulation of ethanol, but rather to changes in dough rheology during retardation. The study demonstrated that the DDD test is a sensitive indicator of formulation and convenient test for studying effects on dough expansion under conditions that mimic proving, and potentially useful for studying the effect of bran and fibre.

A major challenge with dough research when bran or fibre is added is determining the amount of water required for optimum dough development, as bran and fibre absorb a lot of water. The Solvent Retention Capacity test is a promising test that can help with this problem while providing more information on the interaction between flour and fibre during investigations. The next chapter discusses the Solvent Retention Capacity test as a method of determining the water absorption capacity of fibre-rich dough formulations.

## **Chapter 5. Dough water absorption using the Solvent Retention Capacity method**

### **5.1 Introduction**

Deciding on the amount of water required for the mixing and formation of an acceptable dough is a major challenge in the breadmaking industry. Various methods have been used in the determination of the adequate amount of water required for dough formulations. Of these methods, the use of a Farinograph is the most common but the absence of this equipment in current work led to the investigation of a less expensive method, the Solvent Retention Capacity (SRC) test. In this test, the water absorption capacity of a flour sample, its gluten quality, damaged starch levels and pentosan functionalities are determined by interacting the flour with using four distinct solvents. However, the SRC test has been developed principally for understanding the contributions of the components of white flours to water absorption. It is unclear whether the test and its interpretation are applicable to wholemeal or fibre-enriched flours. With the increasing importance of wholemeal breads, exacerbated by the perennial issue of how much water to add to doughs, it was timely in the current work to investigate whether the SRC test could give an objective basis for understanding the effects of fibre on water absorption and how water should be adjusted when fibre is added to dough formulations.

## **5.2 The problem of determining water requirements in bread dough formulations**

A major challenge when making bread dough is determining the accurate amount of water needed in the dough formulation (Cauvain, 2012). The most common method of determining the water absorption is with the use of a Brabender Farinograph, which measures the torque on the blade during mixing, giving an indication of the resistance of the dough to mixing as the dough develops (Conforti & Johnson, 1992; Migliori & Correra, 2013). Initially the flour and water provide little resistance, but as they combine the resistance increases to a peak as the gluten proteins hydrate and align, then decreases as the gluten network becomes overworked and begins to break down. The amount of water in the dough formulation affects the peak resistance. The Farinograph therefore gives a basis for defining the water absorption of a flour as the amount of water required to give a specified value of peak resistance, typically 600 Brabender Units (which are arbitrary units that indicate torque during mixing).

The Farinograph is thus an empirical rheometer used to measure dough resistance during the mixing (Conforti & Johnson, 1992). The Farinograph uses a Z-blade kneading mixer that measures the mechanical resistance by mixing flour and water into a dough mixture and gives a torque curve, from which the arrival time (time required to reach 500 BU), peak time (time required to reach the maximum), departure time (the time at which the curve drops down to the 500 BU line), stability time (the interval between the arrival and departure time) and mixing tolerance index (the difference from the curve at peak and the value 5 minutes after the peak) can be determined. However, while the Farinograph

is suitable as a practical instrument for determining water absorption and investigating other factors that affect dough development, it is limited in giving basis for understanding the origins of factors that affect water absorption.

With the limitations surrounded with the use of a Farinograph, the Centrifugation Method offers a simpler, more rapid technique for determining water absorption (Sosulski, 1962). In 1946, Finney & Yamazaki carried out experiments that established a link between the loaf volume of hard red spring wheats and the water absorption capability of the flour. This was done by suspending flour in a lactic acid medium and applying centrifugal force. Similar work was carried out by Maes & Pirotte (1955) to find out the water absorption of flour. These two set of works were based on mixing of 1.5 g flour with an excess of water inside a zeroed centrifuge tube and mixed vigorously four times with a 10-minute rest time in between (Sosulski, 1962). Absorption was calculated as the change in weights of the flour from dry particles to a swollen mixture after a centrifugation at 3,250 rpm for 25 minutes. Modifications were made to this method by Sosulski (1962) while investigating 'the usefulness of the centrifuge method in selecting for flour absorption in plant breeders' samples of hard red spring wheats'. This was done by investigating the factors that might affect centrifugal absorption. The amount of flour used was increased from 1.5 g to 5 g for the new investigations. During the investigation, it was found that an increase in the amount of water (20 ml to 40 ml) used to mix flour did not show any significant difference to the absorption capabilities of the flour irrespective of the amount of flour mixed into solution. This was observed by mixing 1.5 g of flour in a 15 ml centrifuge tube and 5 g flour in a 50

ml centrifuge tube. Interestingly, it was observed that increasing the number of mixes between rests and also the rest time reduced the percentage centrifuge absorption progressively.

One major difficulty with this method was ensuring a consistent absorption pattern for individual mixes and duplicates of a batch dough. Sosulski (1962) tried evaporating excess water in the centrifuge tubes with blotting paper and attempting to dry the internal excess water with the use of infrared light. This did not reduce the variability of results between duplicates. With this not working as hoped, Sosulski attempted to evaporate the excess water with the use of an oven at different temperatures (50°, 55° and 60°C) and different times (15, 20 and 25 minutes). Of these parameters, oven-drying at 50°C for 25 minutes showed the highest correlation for absorption. Above 50°C, yellowing of the dough samples was observed and at times below 25 minutes, some water was still observed to be dripping which were dried up with a blotting paper. The final method, which was thereafter known as the 'Centrifugation method' involved the addition of 5 g flour and 30 ml of distilled water into a 50 ml centrifuge tube, stirred into solution with a stirring rod and shaken vigorously for 30 seconds initially preventing any flour from sticking to the sides of the tube with a 10-minute rest in between for the flour to absorb the water and then mixed vigorously for 20 seconds with 10-minute rest for the next seven consecutive times. After this time, mixtures were centrifuged for 25 minutes at a speed of 2300 rpm, the supernatant decanted and oven dried for 25 minutes at 50°C. This was done in four replicates. The percentage water absorption was calculated by adding the increase in weight of flour and weight of flour used

(both in g) subtracted by 5 and multiplied by 20. Although comparison between results from Sosluski's centrifugation method and results using a Farinograph for the same samples did not give a good correlation, the centrifuge test was said to be a good predictor for Farinograph and baking absorption. This Centrifugation test was trialled as it is one of the oldest alternatives to the Farinograph method for water absorption determination and a precursor to the Solvent Retention Capacity test, proposed by Slade & Levine (1994) as a more detailed, time efficient approach to determining not just the water absorption capacity of flours but the total functionality of wheat flours. This method has now been studied extensively for years and is an approved AACC method.

### **5.3 The Solvent Retention Capacity Method**

Building on work by Finney (1984), Slade & Levine (1994) used an acid-water retention capacity test to measure flour behaviour and found that hard wheat flours correlated highly with the loaf volume of baked breads. Earlier in 1956, had Yamazaki carried out experiments using alkaline water retention capacity and reported a high correlation with cookie doughs. The Alkaline Water Retention Capacity (AWRC) test introduced by Yamazaki (1956) was eventually approved and made a AACC international method (56-10.02 2010) (AACC, 2010).

The Solvent Retention Capacity (SRC) test is a quick and inexpensive method of determining the functionality profile of flour. Although originally created for soft wheats, the use of this method for hard wheat analysis, has been increased,

including for wheat bran/arabinoxylan type experiments (Döring *et al.*, 2015; Li *et al.*, 2012).

As the crucial reason for the study of the ability to control moisture content in baked goods is to extend the shelf life of the product while maintaining an acceptable quality product (Slade *et al.*, 1991; Slade & Levine, 1994), the flour functionality of each product type requires a different type of optimisation for different extents of functional contributions for major flour components (Kweon *et al.*, 2011). Glutenin, damaged starch and arabinoxylan component functionality play very important roles in the total water absorption of the flour which is important for the preparation of doughs, with that each component having a unique water holding capacity (WHC) (Kweon *et al.*, 2011). While soft wheat products require flours with a low WHC, hard wheat products require flours of high water-holding capacity (Slade & Levine, 1994). According to Levine & Slade (2004), arabinoxylans have a negative effect (deleterious) on soft wheat products like cookies and crackers and a positive effect on hard wheat products like bread according to the water absorption rate of the flours. This means that a soft wheat cookie can have the characteristics of bread (that is more form-like) than the “crispy” structure of a cookie or cracker.

The SRC test was developed on the basis of the Hildebrand solubility parameter together with the swelling values and is used to measure the solubility parameters of polymers (Slade & Levine, 1994). This shows that small particles sizes (less than 500  $\mu\text{m}$ ) will dissolve easily in an excess amount of water, but large particles (more than 500  $\mu\text{m}$ ) entangle instead of dissolving. The length,

volume or weight of these polymeric particle can be estimated numerically by the degree of interaction between the different materials (Hildebrand solubility parameter). SRC is based on energetics (like thermodynamic polymer-solvent capacity), not kinetics (like mobility constraints for poor plasticizers). This test is a solvation test for flours and works by using an excess amount of solvents and is based on the swelling behaviours of individual polymeric networks in each solvent. The SRC test gives information on the degree of dough network development and solvent compatibility (Sears & Darby, 1982) and this information is used to estimate the functional contributions of each polymeric flour component (Kweon *et al.*, 2011). The principles of SRC will be defied if rheological vigorous mechanical shakers like the RVA are used instead of manual shakers (Dang & Bason, 2006) unless for a case like the uniaxial shear where gentle mechanical shakers are used (Kweon *et al.*, 2011).

The SRC test aids in the measure of four unique characteristics of flours, using four distinct solvents: water, lactic acid, sodium carbonate and sucrose. The reason for using four different solvents was because water alone cannot express the entire functionality of a flour type (Kweon *et al.*, 2011). Thus, the other three solvents help understand the contribution of one flour component as compared with the contribution of the flour to just swelling in water (Kweon *et al.*, 2011). These three distinct solvents are individually better and more compatible for each specified flour polymer (Slade *et al.*, 1991; Slade & Levine, 1994). Dilute aqueous lactic acid solutions exaggerate the functionality of glutenins in flour polymers (and doughs), dilute aqueous sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) solution is responsible for the solvent-accessible amylopectin in damaged starch, and

concentrated aqueous sucrose solution is responsible for the solvent-accessible pentosans/arabinoxylans (Kweon *et al.*, 2011). This method was originally designed for investigating the functionality of North American wheat flours (Duyvejonck *et al.*, 2011) and expands further on the Alkaline Water Retention Capacity (AWRC) test. The reason for using three distinct solvents (lactic acid, sodium carbonate and sucrose) along with water was that at room temperature, the functional components (glutenins, damaged starch and pentosans) of the flour contribute simultaneously to the degree of water absorption (Kweon *et al.*, 2011; Kweon *et al.*, 2014).

#### **5.4 Materials and methods used in current work**

SRC was carried out with the use of four solvents (water, 5% w/w lactic acid, 5% w/w sodium carbonate and 50% w/w sucrose). Each solvent gives a distinct interpretation of the flour-fibre samples used. Water provides the absorption capacity of flour, that gives an insight into the optimum amount of water required to produce dough samples. Lactic acid measures the glutenin quality and functionality of each flour-fibre formulation, while sodium carbonate gives an insight into the extent/amount of damaged starch present in the formulations and sucrose measures the pentosan variation. Arabinoxylans, a focus of the current work, are pentosans (polymers of five-carbon sugars) and were thus expected to mostly affect the response of the sucrose solution.

For these sets of experiments, 100% white breadmaking flour substituted with 0%, 5%, 10% and 15% w/w wheat bran (fine and coarse) and 0.5%, 1.5% and 2.5%

w/w wheat bran arabinoxylans and sugarcane bagasse arabinoxylans were used to carry out the SRC test.

The amount of water needed to be added to flour to create a suitable dough for breadmaking is a key parameter of interest to the baker and is called the “Water Absorption”. It is of particular relevance when bran. The SRC test is a solvation assay for flours that is based on the enhanced swelling behaviour of individual polymer networks in selected single diagnostic solvents. The 4-solvent SRC technique included water-SRC, 5% w/w lactic acid SRC (La-SRC), 50% w/w sucrose SRC (Su-SRC) and 5% w/w sodium carbonate ( $\text{Na}_2\text{CO}_3$ -SRC) which were used individually with flour in order to determine the water holding capacity, gluten strength, arabinoxylan functionality and amount of damaged starch, respectively. All solvents were prepared 24 hours before experiments were carried out.

Following the approved methods of the American Association of Cereal Chemists (AACC International Approved Method 56-11.01, 2010), 50 g centrifugal tubes were weighed with each corresponding cap before 5 g flour or 5 g of flour/wheat bran or flour/arabinoxylan were weighed into the tubes. 25 g of selected solvent (distilled water, 5% w/w lactic acid, 50% w/w sucrose or 5% w/w  $\text{Na}_2\text{CO}_3$ ) was added, each tube was left to dissolve for 20 minutes while being shaken at the 5, 10, 15 and 20 minutes for approximately 5 seconds. Samples were transferred immediately into a centrifuge (Eppendorf 5702 series) at 1000 *g* for 15 minutes. Supernatant was then decanted, and tube drained at 90° angle for 10 minutes on a paper towel. Weight of sample tubes after draining

(tubes with pellet) alongside corresponding caps were measured and recorded. All sample tests were carried out in triplicates. The SRC value for each solvent was calculated using:

$$\%SRC = \left\{ \left[ \left( \frac{\text{tube, cap, gel weight} - \text{tube, cap weight}}{\text{flour weight}} \right) - 1 \right] \left( \frac{86}{100 - \text{flour moisture content}} \right) \times 100 \right\} \quad (5.1)$$

The gluten performance index (Kweon *et al.*, 2009; Kweon *et al.*, 2011) and arabinoxylan performance index were also calculated to determine the gluten and AX functionality in regards to water SRC. (Kweon *et al.*, 2014) designed a new parameter called the gluten performance index (GPI). The GPI parameter indicates the overall glutenin performance and functionality with other strong networks and is calculated as the lactic acid SRC divided by the sum of sodium carbonate SRC and sucrose SRC.

$$GPI = \frac{LaSRC}{SCSRC + SuSRC} \quad (5.2)$$

API is a function of AX based on the SRC solvents, calculated as:

$$API = \frac{SuSRC}{LaSRC + ScSRC} \quad (5.3)$$

## 5.5 Effect of SRC solvents on high fibre formulations

The effects of bran and AX at different levels and, for the bran, particle sizes were investigated using the 4-solvent SRC test, which indicates the water

absorption levels of flour/fibre formulations and the gluten strength, arabinoxylan functionality and the extent of damaged starch.

#### **5.5.1 Effects of percentage bran and particle size of bran on water absorption**

Figure 5.1 shows the effects of fine and coarse bran on the water SRC for both Sainsbury's and Allinson flours. In general, the Allison flour required less amount of water for dough formation than the Sainsbury's flour (with an apparent anomaly with 5% coarse bran), reflecting the higher protein content of the Sainsbury's flour. Adding fine bran tended to increase the water-SRC, with both flours showing a consistent upward trend as bran level increased from 0 to 15%. In the case of coarse bran, adding 5% appeared to decrease the water SRC compared with the Sainsbury's flour Control, while further addition of bran increased in water-SRC, while for the Allinson flour there was a steady upward increase in water SRC as bran level increased. Overall, fine bran increased water SRC more than coarse bran at all levels of addition and for both flours.

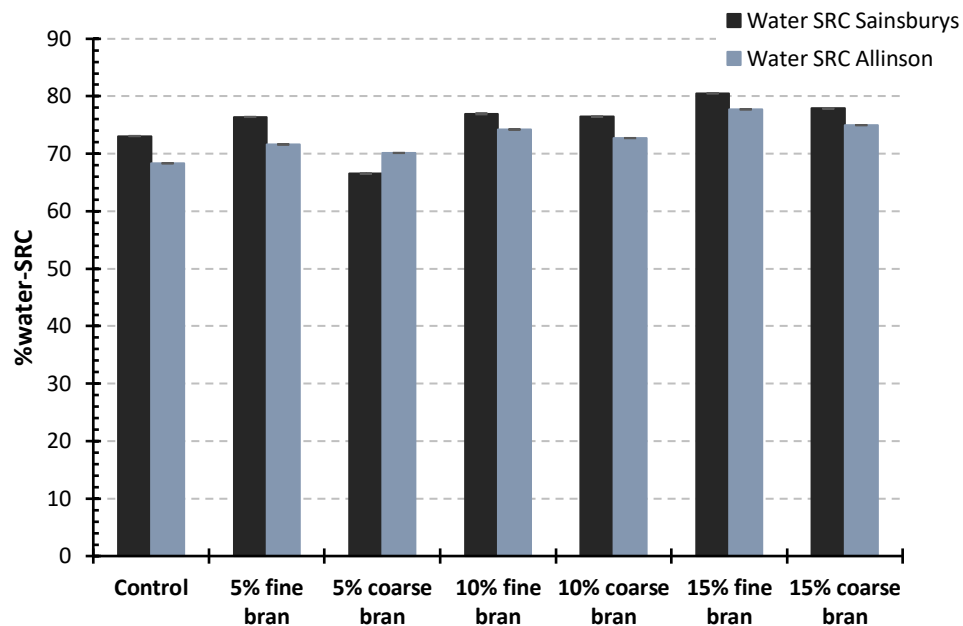


Figure 5.1: Water absorption capacity of each flour-bran formulation using the SRC method using two flour types

Campbell *et al.* (2008b,c) and Zhang & Moore (1999, 1997) note that wheat bran has a higher water absorption capacity than plain flour and that the particle size of the bran has a major role to play in the competition of water in a dough formulation. The SRC test is not exactly equivalent to the traditional Farinograph water absorption, but the water-SRC data supports the general finding that fine bran increases water absorption more than coarse bran, as fine bran particles are able to absorb water more rapidly than coarse bran particles.

Figure 5.2 shows the 5% lactic acid SRC results for the flour-bran formulations. Lactic acid SRC measures the glutenin quality and functionality of the flour (Kweon *et al.*, 2009; Slade & Levine, 1994) and dough formulations. Clearly, the control dough of both flour types had the highest glutenin functionality of 116% (Sainsbury's flour) and 111.5% (Allinson flour), respectively. Addition of bran

decreased the La-SRC, indicating that the bran interfered with gluten formation, but with no consistent difference between the fine and coarse bran. Bran-enriched dough formulations made from Sainsbury's flour showed to have a higher glutenin functionality than bran-enriched bread doughs made from Allinson flour (with an exception for 15% coarse bran), in line with the results for Water SRC. According to Kweon *et al.* (2011), the La-SRC tests should give the highest value of the 4 solvents. Kweon *et al.* (2011) said a typical bakers flour range at 14% moisture should have a La-SRC value >140 and for all dough formulation, less values were observed. It should be noted that previous studies were carried out using soft American wheat flour without bran addition.

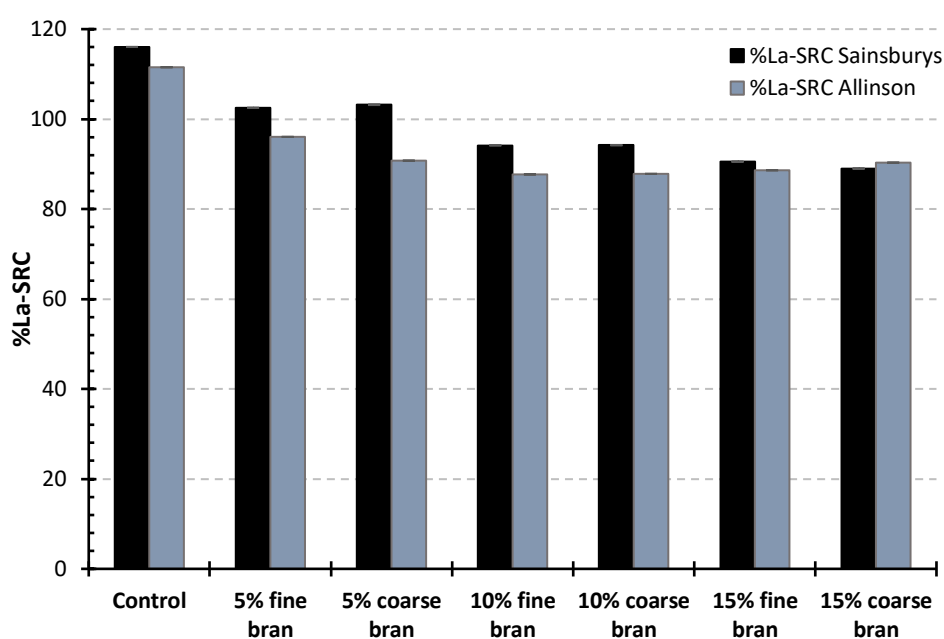


Figure 5.2: Gluten quality and functionality of each flour-bran formulation using the SRC method

Figure 5.3 shows the equivalent  $\%Na_2CO_3$ -SRC data, which indicates the extent damaged starch in a flour (Kweon *et al.*, 2009). Once again lower values were obtained for Allinson flour than for from Sainsbury's flour. However, in contrast

to La-SRC, here the addition of bran gave a large increase, with fine bran having a much larger effect than coarse bran. It is not obvious why bran should influence a measure that supposedly indicates the presence of damaged starch; the results suggest that bran particles in some ways mimic starch granules in their uptake of solvents, particularly if the bran particles are small.

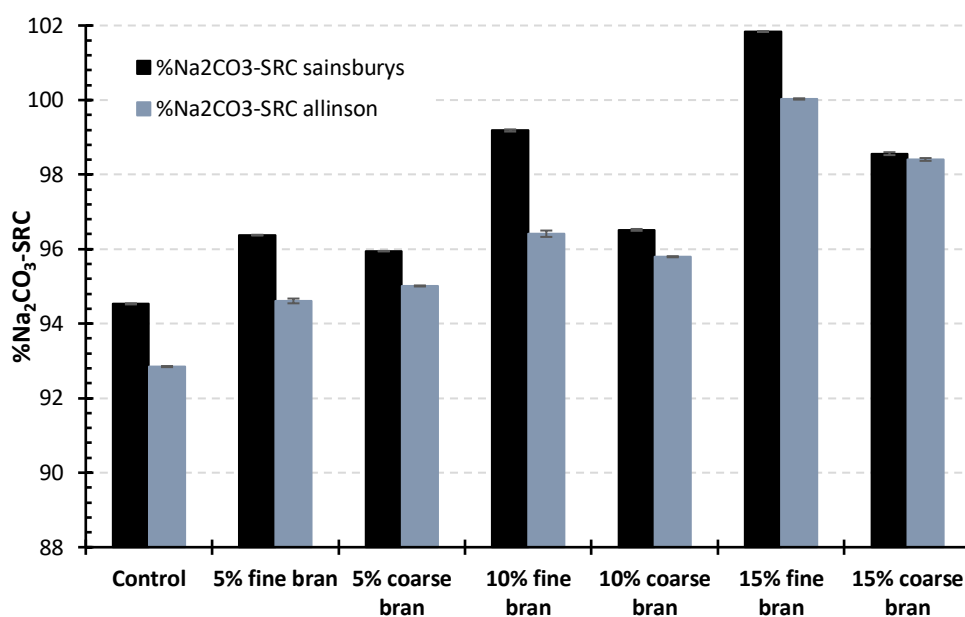


Figure 5.3: Amount of damaged starch in each flour-fibre formulation using the SRC method

Finally, Figure 5.4 shows the %Su-SRC data, which is considered to indicate pentosan functionality. Again, Sainsbury's flour gave higher values than Allinson flour. Once again, there is a strong effect of bran particle size. fine bran tended to give an increase in Su-SRC at the higher levels of addition, while coarse bran gave a very clear decrease. This pattern was consistent for both flours.

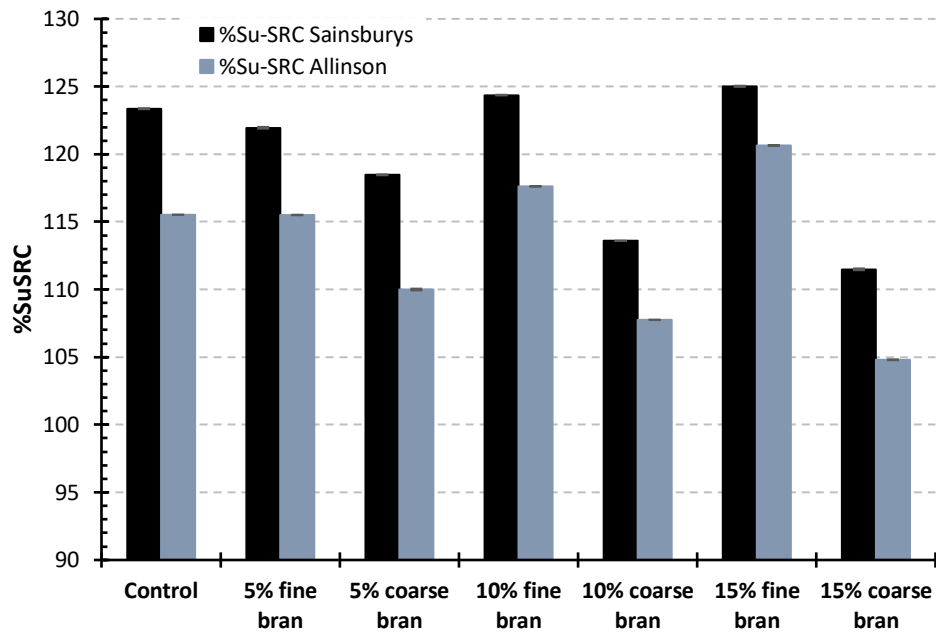


Figure 5.4: Pentosan variation in all flour-fibre formulation using the SRC method

The Su-SRC solution is very viscous as 50% sugar is being used to make the solution, this might be a reason for the high values obtained. The baker's flour range according to Kweon *et al.* (2011) should be between 105-115% and this was observed with results obtained from Allinson flour, but not Sainsbury's flour as the range was exceeded by all samples except 15% coarse bran. This could either be as a result of the type of flour used (hard wheat) while most studies previously carried out were done using soft wheat Canadian flour.

Figure 5.5 presents the data to allow direct comparison effects of all four SRC solvents for the formulations with Sainsbury's flour; Figure 5.6 shows the same for Allinson flours. Clearly, from both Figures, Water-SRC increased with the addition of bran, and a higher effect is observed with fine bran than with coarse bran, in agreement with previous works using other approaches to measure water absorption (Zhang & Moore, 1999, 1997). Both fine and coarse bran-

enriched samples showed of a decrease in La-SRC with the addition of bran, for both flours, while  $\text{Na}_2\text{CO}_3$ -SRC show the opposite behaviour, with no difference between fine and coarse bran. However, Su-SRC showed the greatest effect of bran particle size, with fine bran giving an increase, and coarse bran a decrease, for both flours.

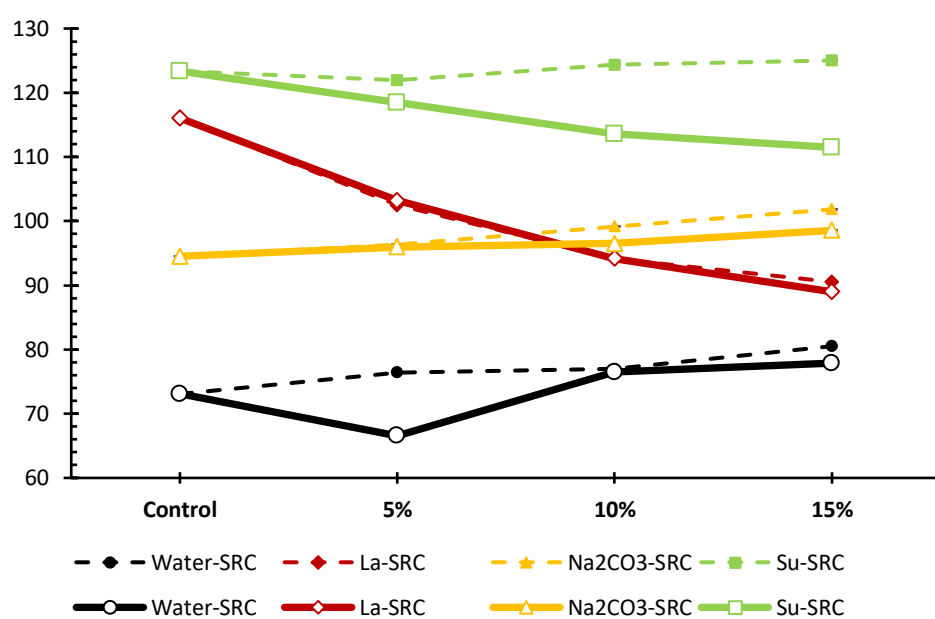


Figure 5.5: Comparison of SRC results from both bran sizes with Sainsbury's flour

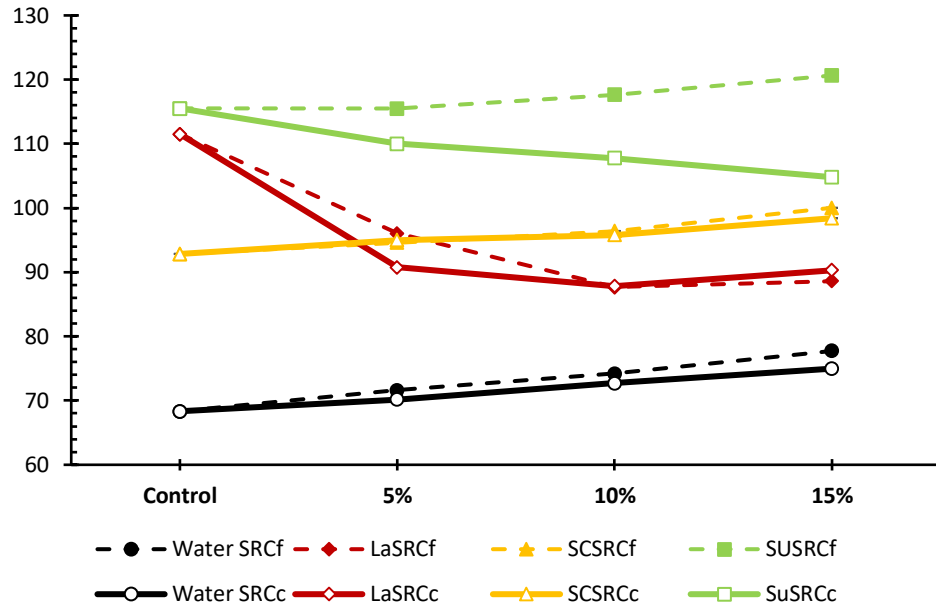


Figure 5.6: Comparison of SRC results from both bran sizes with Allinson flour

The results are very consistent for both flours and show that addition of bran affects the four solvents of the SRC test in different ways, and that the effects are influenced by particle size. These results show that the SRC test is responsive to effects of bran level and particle size, but because the SRC test has not been investigated in detail previously for flour/bran formulations, detailed and conclusive interpretation is not possible. However, it is clear that the responses of these solvents of fibre addition provides clues about the interaction of the fibre with flour components and with water and give a basis for understanding how bakers should adjust water levels in dough formulations in response to fibre addition.

Although there are no previous studies on flour-fibre testing using this method, the result obtained for the control sample follows works by Kweon *et al.*, (2009). Wholemeal flour analysis using the SRC method was investigated by Ram *et al.*

(2005) and compared with white flour to determine if this method will be good for predicting Farinograph water absorption (FWA). Similar SRC values obtained by Ram *et al.* (2005) for water (67.2 to 83.7%) and sodium carbonate (74.0 to 111.7%) were within the same range while lactic acid and sucrose of current work were observed to have higher values than works of (Ram *et al.*, 2005). It should be noted that while (Ram *et al.*, 2005) used wholemeal flours, investigations carried out in this current work used manually fortified samples.

The raw SRC data can be interpreted differently by combining the data to calculate the gluten performance index (GPI) and arabinoxylan performance index (API) using equations 5.2 and 5.3.

Figure 5.7 shows the gluten performance index of both flour types. Clearly, both flour types showed a decrease in gluten functionality when bran was added, with a greater decrease for fine bran, again illustrating how bran interferes with gluten development, and more so when the bran is present as numerous small particles instead of a few large particles.

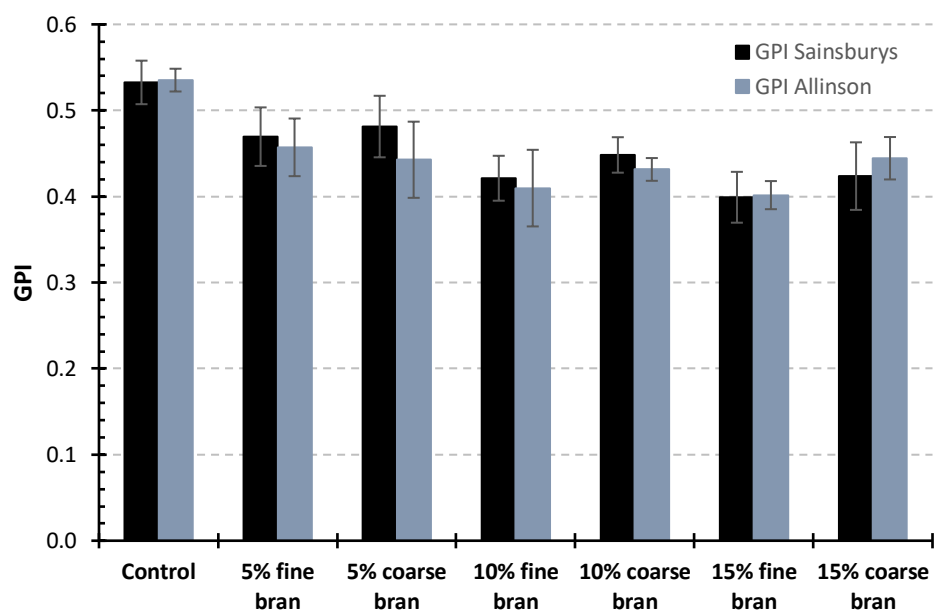


Figure 5.7: Gluten performance index for both flour types

### 5.5.2 Effects of type and percentages of arabinoxylan extract on water absorption (using two different flour types)

Figures 5.8- 5.11 show the individual results for the effect of SRC solvents on AX-enriched samples using wheat bran AX (WBAX) and sugarcane bagasse AX (SCBAX). Also, Figures 5.12 and 5.13 compares the responses of each SRC solvent for the two flour types. Figure 5.14 shows the Arabinoxylan performance index of samples from both flour types.

The SRC test is not exactly equivalent to the traditional Farinograph water absorption; the water-SRC data indicated excessively high water absorption capacities that would lead to the production of dough samples which were difficult to handle due to stickiness. This stickiness was determined by preparing doughs with resulting % water and manually handling each sample.

However, the value of the SRC test in indicating the contributions to water absorption arises from the individual components.

Figure 5.8 shows the effect of water-SRC on AX (WBAX and SCBAX) enriched sample formulations. As found previously for the bran formulations (Figure 5.1), the Allison flour gave lower water-SRC values than the Sainsbury's flour. Both types of AX increased the water-SRC values by similar amounts for both flours, demonstrating the high water holding capacity of AX (Courtin & Delcour, 2002). Water is the main reference of the SRC method because it has the ability to hydrate and swell the functional flour components to varying degrees. Water is also associated to the total water holding capacity of all flour constituents (Gaines, 2000; Kweon *et al.*, 2009). Water SRC values are linked to the overall WHC contributed by the flour functional components including glutenin, damaged starch and pentosans/arabinoxylans (Kweon *et al.*, 2011), where 'water holding capacity (WHC)' is typically expressed as grams of water/grams of dry component and is approximately equivalent to a flour's water-SRC value (Kweon *et al.*, 2011; Slade & Levine, 1994). WHC is an important functional parameter related to the processing and finished products of baked goods (Kweon *et al.*, 2011).

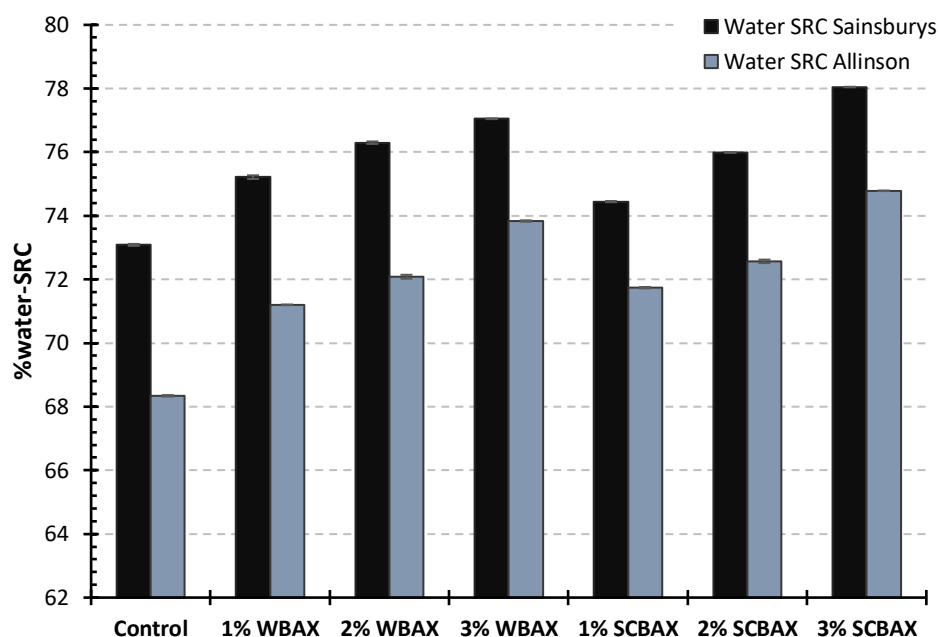


Figure 5.8: Water absorption capacity of each AX-flour formulation using the SRC method

Figure 5.9 shows the effect of the two types of AX (WBAX and SCBAX) and two types of flour (Sainsbury's and Allinson) on the 5% lactic acid solution. Lactic acid SRC measures the glutenin quality and functionality of the flour and dough formulations. As with bran, addition of AX decreased La-SRC, indicating that AX interferes with gluten formation, with SCBAX having a more damaging effect than WBAX.

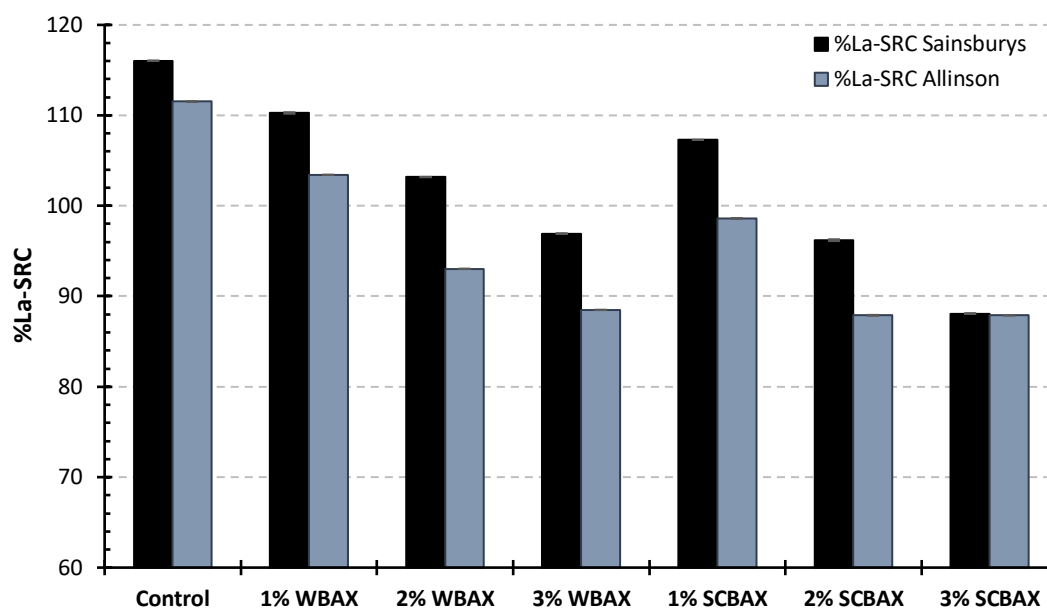


Figure 5.9: Gluten quality and functionality of each AX- enriched (WBAX and SCBAX) formulation using the SRC method

Kweon *et al.* (2011) observed a typical bakers flour range at 14% moisture should have a La-SRC value >140, higher than the values seen in the current work. It should be noted that previous studies were carried out using soft American wheat flour.

Figure 5.10 shows the data for %Na<sub>2</sub>CO<sub>3</sub>-SRC, which indicates the extent of damaged starch in a flour. As with bran, AX increased %Na<sub>2</sub>CO<sub>3</sub>-SRC, with wheat bran AX having a greater effect than sugarcane bagasse AX, although overall the results were somewhat variable. An increase in the concentration of WBAX using Sainsbury's flour increased the Na<sub>2</sub>CO<sub>3</sub>-SRC. In the case of WBAX using Allinson flour in the formation, there was an increase between 1% WBAX and 2% WBAX then a decrease at 3% WBAX (95.1% - 96.9% - 96.4%). 1% SCBAX of Sainsbury's flour seemed to give a very larger increase which is out of line with the other data and probably erroneous; the other data seem to indicate a

much lower effect of SCBAX compared with WBAX. As this is the first time the SRC test has been used to explore effects of AX, it is not possible to interpret these observations fully, but the results demonstrate that the %Na<sub>2</sub>CO<sub>3</sub>-SRC test responds to AX addition. As %Na<sub>2</sub>CO<sub>3</sub>-SRC is supposed to indicate damaged starch, it is not obvious why AX should have an effect on this parameter; it seems likely that the relation with damaged starch is true in purely white flour formulations, but no longer holds so strongly in fibre-rich formulations.

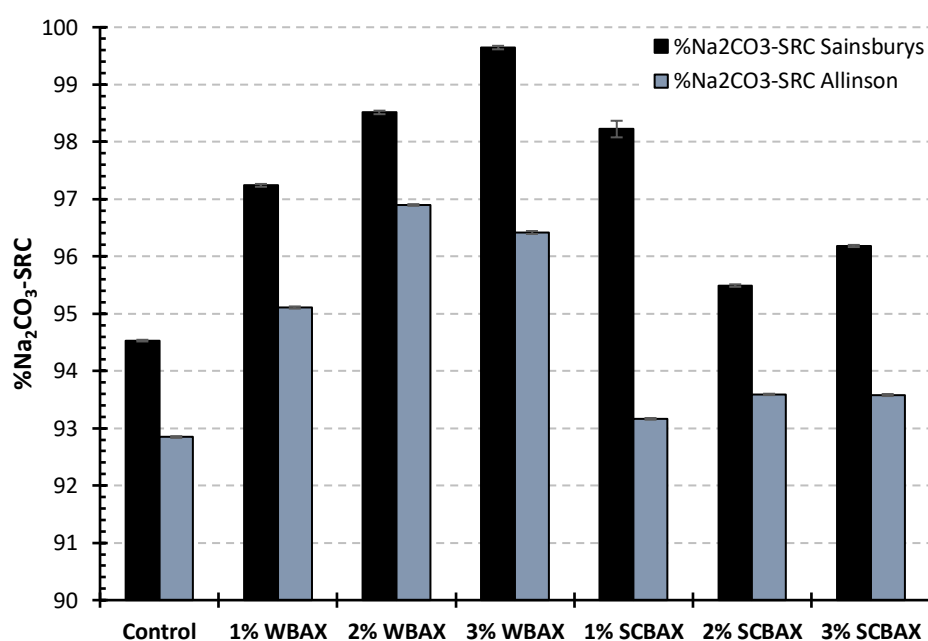


Figure 5.10: Amount of damaged starch in each AX-enriched formulation using the SRC method

Figure 5.11 shows the %Su-SRC data, which reflects the influence of pentosan; as arabinoxylans are pentosans, this measure was expected to show a significant response. It will be recalled that in the case of bran, opposite effects were observed for fine and coarse bran, with fine bran giving an increase in Su-SRC and coarse bran a decrease. The addition of AX gave consistent decreases in Su-SRC for both AX types and both flours, with WBAX once again giving a stronger

response that SCBAX. Bran contain AX; these findings suggest that bran exhibits some counteracting effects on Su-SRC, with AX promoting a decrease, but other factors related to particle size able to counteract this to give an increase if the bran is sufficiently fine.

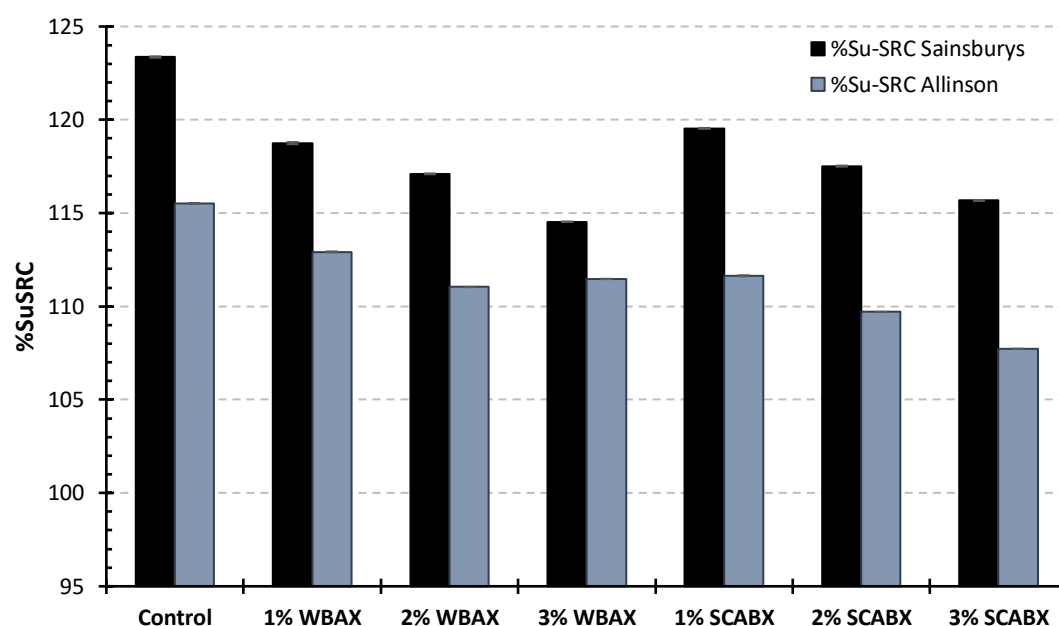


Figure 5.11: Pentosan variation in all flour-AX formulation using the SRC method

Although Kweon *et al.* (2011) claim that the best way to determine AX functionality is using sucrose, Duyvejonck *et al.* (2011) found the use of water to be a better approach for the determination of AX functionality in flours. This led to the conclusion that WE-AX plays a role in Su-SRC of flours. On further investigation, it was found that the higher value of AX found from water SRC was obtained from the supernatant and not from the 'dough' mixture. Hence, works from Kweon *et al.* (2011) are still very valid and are further supported by this current research.

Figures 5.12 and 5.13 summarise the solvent retention capacity values for all four solvents and, both arabinoxylan samples for Sainsbury's and Allinson flour, respectively. In general, consistent trends were observed, with SCBAX giving a stronger negative response than WBAX for La-SRC, indicating greater interference with gluten formation, while WBAX gave a stronger increase in  $\text{Na}_2\text{CO}_3$ -SRC than SCBAX. These differences relate to the different compositions and structures of the two AX types, with WBAX having a much higher degree of arabinose substitution than SCBAX. Fully understanding the interaction between AX structure and the four solvents would require a much more extensive investigation; however, the current work has demonstrated that these solvents are responsive to AX and give clues and guidance about how to adjust dough water levels to account for addition of AX.

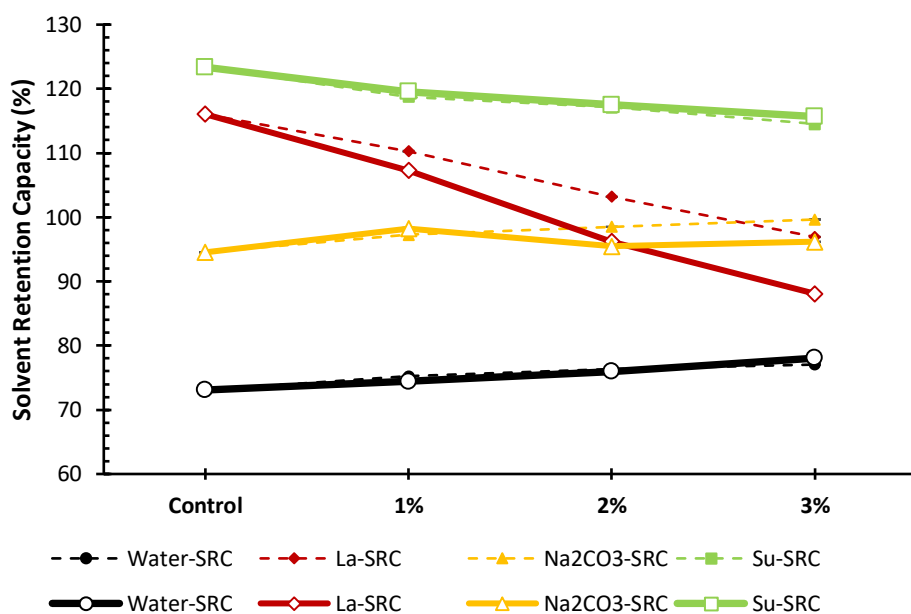


Figure 5.12: Average SRC results for both WBAX (thin line) and SCBAX (thick line) at different concentrations using Sainsbury's flour

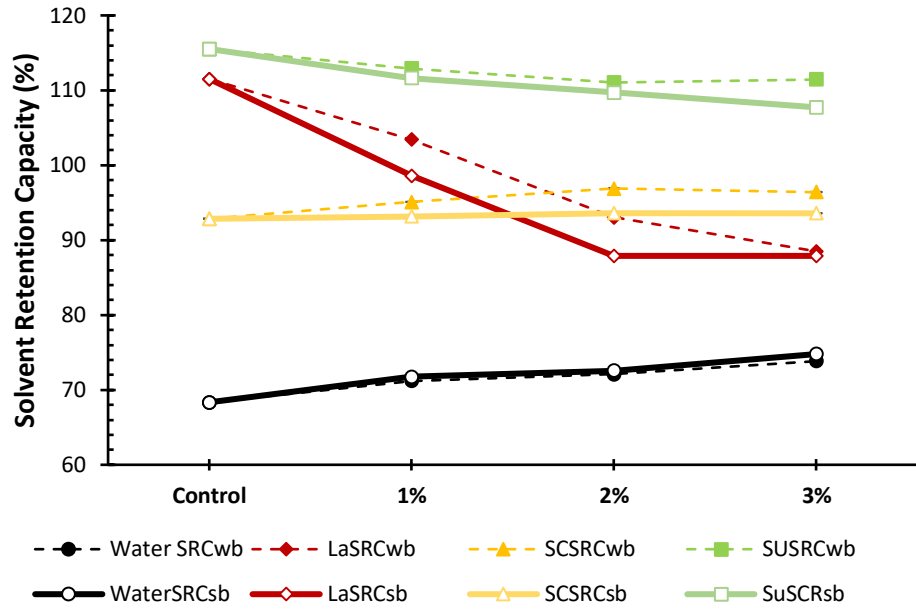


Figure 5.13: Average SRC results for both WBAX (thin line) and SCBAX (thick line) at different concentrations using Allinson flour

Figure 5.14 shows the arabinoxylan performance index (API) of both flour types and different concentrations (1%, 2% and 3%) of both AX types. In general, addition of AX increased the API as expected.

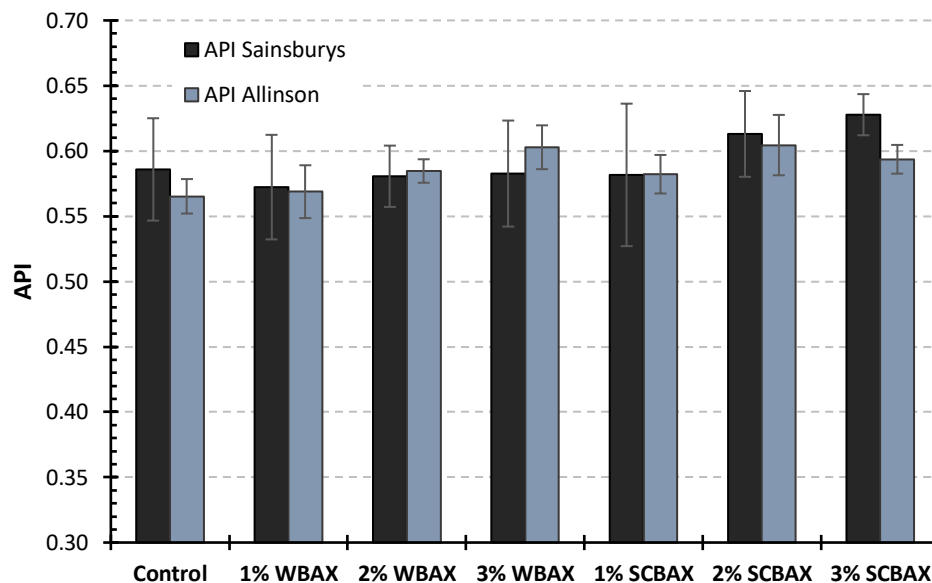


Figure 5.14: Average arabinoxylan performance index for both AX types and both flour samples

The SRC test is designed to exaggerate effects of flour components that interact with water and other solvents, such that the water levels it reports cannot be directly taken as the water level to use in actual dough formulations; the SRC results have to be translated to actual water levels suitable for use by bakers, based on specific local studies. While the above work shows that the SRC test is sensitive to bran and arabinoxylans and can give information about their interactions in dough formulations, another approach was investigated using the DDD system, to try to get a direct indication of the water adjustment to make when bran is added to a dough formulation.

### 5.5.3 Dynamic dough density at different water levels

The Dynamic Dough Density (DDD) system discussed in section 4.3 was another method used in trying to determine the amount of water required for each dough formulation. The DDD system measures the maximum expansion

of dough, which led to the thought that the DDD system might be a possible method for dough water absorption determination. The idea was that on addition of bran (or other fibre), the water level could be adjusted to give equivalent expansion to a control dough.

Different dough formulations (control, 5% wheat bran, 10% wheat bran and 15% wheat bran) were mixed with seven different % water level. Control dough samples were mixed with % water levels ranging from 58% - 64%, 5% wheat bran samples were tested with % water levels ranging from 60.5% - 66.5%, 10% wheat bran samples were tested with % water levels ranging from 63% - 69% and 15% wheat bran samples were tested with % water levels ranging from 65.5% - 71.5%. Sainsbury's flour was used for the tests in this section. Experiments were carried out on a small scale and all dough formulations were based on 50 g of flour, mixed in the MinorPin mixer. These % water level range were decided on based previous works by Campbell *et al.* (2008c) which stated that the % water required for bran enriched doughs and bread was half the % of bran used to enrich the formulation added to the % water required for a control dough formulation. The lower the minimum density, the higher the maximum expansion (and vice versa), it is an inverse relationship. All experiments were carried out in four replicates. Each dough sample was analysed using the DDD system and the maximum expansion calculated.

Figure 5.15 shows the effects of varying bran and water levels on maximum dough expansion. Clearly, adding bran decreased the ability of doughs to expand in agreement with studies by Campbell *et al.* (2008c). Although water

level had relatively little effect on the expansion capacity of the control dough, increasing water levels restored to some extent the ability of doughs containing bran to expand. Thus, for example, dough containing 5% bran could expand to a similar degree to the control dough if the water level was increased to 65%. However, at higher levels of bran addition, doughs were unable to expand to similar levels to the control at any water level. Thus, this approach proved not to give a basis for deciding the appropriate water adjustment when bran is added to a dough formulation.

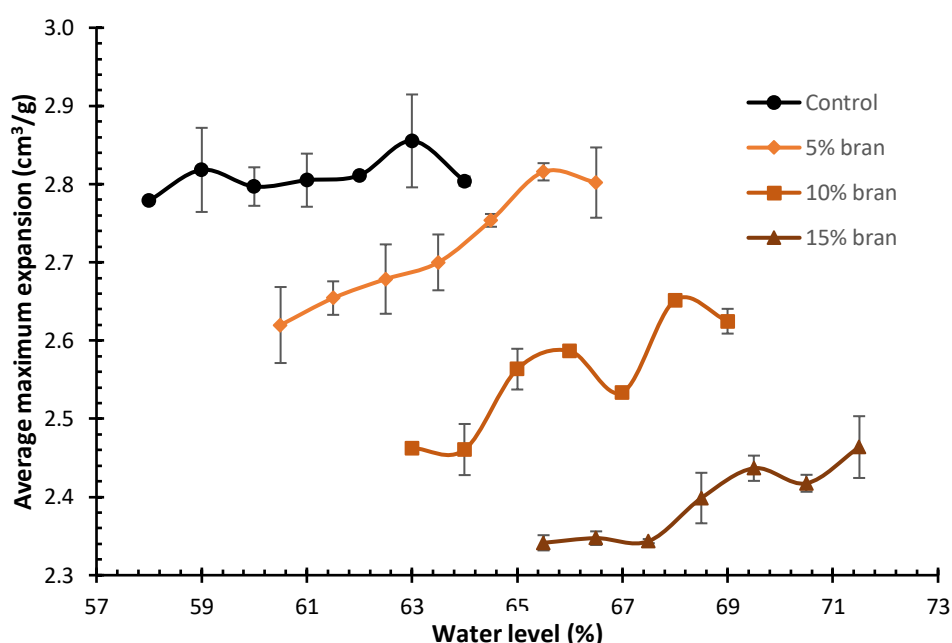


Figure 5.15: Average maximum expansion for different dough formulations at varying % water levels using the Dynamic Dough Density

Neither the SRC test nor the DDD test was able to give an unambiguous and objective basis for adjusting water absorption in dough formulations in response to bran or fibre addition. Thus, the current work continued to use guidance from the literature, as seen in the following chapters.

## 5.6 Summary

Predicting the amount of water required in a dough formulation is one of the most difficult problems with bread studies. Although the use of a Farinograph is still the most common ways of determining the adequate water absorption level of dough formulations, other methods for determining the right amount of water for dough formulations have been proposed over the years. These methods include the Centrifugation test, the Alkaline Water Retention Capacity test and, the Solvent Retention Capacity (SRC) test.

The SRC test investigated in the current work because it provides information about four distinct features of each formulation. The SRC-test was carried out using the 4-solvent method (water, 5% w/w lactic acid, 5% w/w sodium carbonate and 50% w/w sucrose) to determine the effects of bran and AX on the water required in a dough formulation and on, the resulting functionality of glutenins, damaged starch and pentosans. Experiments were carried out on both wheat bran-enriched dough formulations and arabinoxylan-enriched dough formulations.

Adding bran increased the overall water absorption and also increased the SRC element that is understood to relate to damaged starch, while the indicators of, glutenin quality and variation in pentosans decreased as the with increased bran levels. The effect of bran on Su-SRC, which indicates pentosan functionality, was affected by bran particle size, with fine bran increasing the measure while coarse bran decreases it. The SRC test provided initial indications to the

expected behaviours to be obtained from further investigations; although levels indicated by SRC are exaggerated relative to the actual water levels required in dough formulations. Fine bran showed more of an increased effect than coarse bran with all comparing properties except gluten quality, where both samples showed similar behaviour. There was a decrease in the gluten performance index (GPI) as the bran level increased. This exaggeration could be as a result of the difference in the breed of wheat used in the original development of the SRC test (soft wheat) compared to the breed of wheat used in the current study.

Wheat bran AX and sugarcane bagasse AX had higher water absorption capacities irrespective of the flour type used compared to the control dough, with a greater increase for sugarcane bagasse AX. Wheat bran AX and bagasse AX both showed a decline in gluten quality but opposite behaviours with amount of damaged starch with wheat bran AX increasing and bagasse AX decreasing. The average arabinoxylan performance index for both AX samples, showed similar behaviours of a slight increase as the level of AX increases.

The DDD test was investigated as an alternative basis for determining water adjustment in response to bran or fibre addition. The idea was that water could be adjusted to give equivalent expansion. Addition of bran decreased the expansion capacity of doughs, and increasing water restored the expansion capacity to some extent. However, at levels of bran addition of 10 or 15%, doughs were unable to expand as much as control doughs at any level of water addition.

Particle size and fibre source are two characteristics that pose detrimental effects on bread and dough; affecting both dough aeration and rheology. The

next chapter discusses the effect of fibre (wheat bran and arabinoxylans) on dough expansion, dough rheology and dough microstructure.

## **Chapter 6. Effects of fibre on dough expansion, rheology and microstructure**

### **6.1 Introduction**

This chapter provides an in-depth study into the measurement of the expansion capacities of dough samples fortified with either wheat bran or arabinoxylans. Previous literature on the subject is discussed leading to the specific method used in this study; Dynamic Dough Density system. The materials and methods used in obtaining a uniform particle size of wheat bran used for studies throughout this work, and the compositional specification of the arabinoxylan, white flours and wheat bran, are described. The effects of the level and particle size of wheat bran as well as the effects of type and level of arabinoxylan extracts on dough expansion were studied using the Dynamic Dough Density system. The rheological behaviour of dough samples with varying levels and particle sizes of wheat bran were studied using oscillatory rheometry. Dough samples were also studied using scanning electron microscopy to understand the effect of fibres on the microstructure of the fibre enriched dough samples.

### **6.2 Expansion capacity of doughs - Methodology and applications with major focus on the Dynamic dough density system**

Preparing a dough is as easy as applying a work input in the form of mixing to suitable proportions of wheat flour and water; without adding anything else, these two ingredients can make a basic dough (although for a raised bread, a leavening agent, usually yeast, needs to be added, while salt is the fourth main

ingredient of bread doughs, affecting flavour, yeast action and protein properties). Mixing of flour and water leads to the formation of a viscoelastic property which has gas cells present due to the mixing process. The mixing stage is the only opportunity for gas cells to be formed (Baker & Mize, 1941), after which the gas cells change in size and number during proving and set in a foam form during baking. Dough expansion occurs during the proving phase as yeast fermentation occurs, producing carbon dioxide gas that diffuses into bubbles in the dough making the dough piece expand. According to Gandikota & MacRitchie (2005) 'the baking process can be simply thought as the formation of a cell structure in dough, its manipulation by subsequent operations and some means of causing expansion'. The ability of the dough to expand and retain gas is its key functional property, arising from the viscoelastic network formed by the gluten proteins when mixed with water. Measuring dough expansion therefore gives a measure of this key functional property of dough.

Initially, Bungenberg de Jong (1956) came up with the idea of using a vacuum during a study of dough expansion. This work was carried out on whole and defatted flour doughs to study the expansion capacity of the formulated dough samples. This method was adopted by MacRitchie (1976) and findings were in agreement with Bungenberg de Jong (1956) that the use of vacuum allows dough expansion to be quantified. Similar vacuum expansion works were carried out by Bell *et al.*, (1981) to test if the shortening on bread dough volume had any beneficial effects using high temperature oven baking conditions. This was observed not to be the case as dough expansion was observed at low temperatures to cause same volume increment as high temperature conditions.

Apart from the use of a vacuum to measure dough expansion, Dobraszczyk *et al.*, (2003) developed a technique using the Stable Micro Systems dough inflation system to determine the dough rheology parameters under conditions of strain, similar to baking expansion conditions (Gandikota & MacRitchie, 2005). Prior to this study Van Vliet *et al.*, (1992) had done works to show that the property of strain hardening is a very important requirement for the ability of dough to expand during baking (Gandikota & MacRitchie, 2005).

Gandikota & MacRitchie (2005) constructed a new apparatus capable of expanding a dough in a controlled manner while measuring the degree of expansion (dough height) accurately. This investigation was carried out to find out the usefulness of the method in predicting flour baking potentials and to determine the usefulness of the proposed technique in obtaining fundamental information about timing and the effects on natural and added ingredients during processing. This method was used specifically to investigate the effect of bromate on the breadmaking process. This experiment was carried out with a vacuum pump connected to a pressure chamber where doughs were placed after moulding and the increased dough height measured. Provided the applied vacuum was adequately high, expansion of dough was observed.

Mixing is a very important stage of the breadmaking process as it is at this stage a baker has the most control and the initial air bubbles are created which provide nucleation sites for bubble growth during proving (Chiotellis & Campbell, 2003b). A more recent method of measuring the expansion capacity of bread dough was proposed by Campbell *et al.*, (2001), measuring the change

in dough density over time under conditions mimicking proving. (Campbell *et al.*, 2008a,b,c) developed the technique further and demonstrated its relevance for studying effects of wheat and oat bran on dough expansion and bread volume. The dynamic dough density (DDD) technique is sensitive and is therefore a useful technique for investigating the effects of ingredients or processing conditions on dough quality.

### **6.3 Materials and methods used in present work**

This section details the materials, equipment and methods used to investigate the effects of wheat bran and arabinoxylans on dough expansion during proving. It looks particularly at the effects of particle size in the case of wheat bran and type and concentration in the case of arabinoxylans using two flour types.

### **6.4 Fibre milling and particle size determination**

Commercial wheat bran was obtained from the Biorenewables Development Centre (BDC), York, UK and was used for all studies in this research. Wheat bran obtained from BDC was of a coarse particle size. To obtain a fine bran sample of the same composition, the coarse bran was milled using a Retsch grinder ZM 1000 mill (RETSCHE laboratory instruments and services, UK) at a speed of 10,000 rpm and a screen aperture of 0.5  $\mu\text{m}$ . Arabinoxylan samples (wheat bran arabinoxylan and sugarcane bagasse arabinoxylan, which had been produced by the BDC in an earlier collaboration described by (Campbell *et al.*,

2019)) were also milled into finer particle sizes with the use of the Retsch mill. The wheat bran arabinoxylans (WBAX) material received from the BDC was in very large, hard chunks that needed to be milled for sampling and analysis and for incorporation into dough formulations. This was done using a Retsch grinder ZM 1000 mill (RETSCH laboratory instruments and services, UK) at 10,000 rpm using a screen of 1 mm. Figure 6.1 shows the WBAX sample before and after milling. After milling, WBAX samples were put in plastic storage bags to prevent absorption of moisture. Milling was done to achieve particle sizes that could be comparable to that of flour and also to compare the effect of particle size on dough expansion.



*Figure 6.1: Coarse bran (left) and Fine bran (right)*



*Figure 6.2: Wheat bran arabinoxylan (WBAX) before (left) and after milling (right)*

Sieve analysis was used to determine the particle size distributions of both the coarse and fine wheat bran samples. This was done using the Endecotts Ltd. mechanical sieve shakers (model E.V.S.1) and sieves with stainless steel mesh (ranging from 2 mm to 75  $\mu\text{m}$ ). 100 g of each sample was put in the sieves and placed on the mechanical shaker for 15 minutes at a vibration intensity of 30%, after which the weight of particles remaining in each sieve was measured using an Ohaus balance. The sample particle size is determined based on 50% particle passage through the sieve mesh and this happened at 500  $\mu\text{m}$  screen. Triplicate data were obtained for both samples.

#### **6.4.1 Weighing Equipment**

Flour, wheat bran, AX, water and yeast were weighed to an accuracy of 0.0001 g using the Precisa 125A balance. Salt, sugar and fat were measured using Ohaus Adventurer weighing scale to an accuracy level of 0.001 g.

#### **6.4.2 Compositional specification**

Apart from incorporating fibre (bran, WBAX and SCBAX) into bread dough to enhance its nutritional composition, separate analyses were carried out on these three samples to get more information about the samples outside being rich in fibre. These aids understanding the effects of samples when added to bread dough. The analyses carried out included; protein content determination, moisture content determination and viscosity of the samples (for only the AX samples). All experiments in this section were carried out using only Sainsbury's flour. Viscosity of AX was done to better understand the samples and

compositional analysis of only Sainsbury's flour was done because the compositional specification of Allinson flour was provided by the manufacturer.

#### **6.4.2.1 Moisture content**

Moisture content was analysed using two methods; the oven method of moisture determination and use of the Mettler Thermogravitational Analyzer (TGA) method. In both methods, samples were analysed in triplicate and an average taken for final interpretations. Samples were weighed to a 0.0001 g precision.

The oven-drying method was used to dry samples and determine the moisture content of each sample. Approximately 2 g of sample was measured using a Precisa 125A balance and put in the oven (Genlab oven, Genlab limited, UK) for 30 minutes at a temperature of 130°C after which samples were placed in a desiccator to cool and then weighed again. This process was repeated until there was no weight change for the empty crucibles (this usually took around 2 hours), after which crucibles containing samples were put in the oven for 60 minutes at 130°C and then put in the desiccator to cool for 30 minutes and weighed. The process was repeated until no further weight loss. Measurements were carried out in triplicates. The percentage moisture was calculated by dividing the mass before heating with the difference between the mass before and after heating and multiplying by 100.

$$\%Moisture = \frac{w_0 - w_1}{w_0} \times 100 \quad (6.1)$$

where  $w_0$  and  $w_1$  are the weight of sample before and after heating (in grams), respectively.

#### **6.4.2.2 Protein content**

The Kjeldahl method of nitrogen determination was used in obtaining the protein contents of both samples. This method is a three-stage experiment (digestion, distillation and titration). Measurements were all carried out in triplicates.

For the Gerhardt Kjeldahl digestion stage, 1.25 g of each sample was put into numbered Kjeldahl tubes along with two Kjeltabs (5 g each) and 20 ml conc.  $\text{H}_2\text{SO}_4$  and a few anti-bumping agents (used to prevent bubbles from forming when digestion starts). A blank solution containing all the ingredients needed for the analysis except a sample was also prepared and digested. Due to the use of conc.  $\text{H}_2\text{SO}_4$ , this stage was carried out in a fume cupboard. Tubes were placed in the digester rack and the empty section of the rack filled with empty tubes before digestion starts. The drip tray was then removed from the apparatus and the exhaust funnel sat inside the tubes to prevent evaporation of the solution. The water pump was then turned on to provide little flow to the digester. After all this was set-up, the digester was turned on and PR<sub>1</sub> and H<sub>5</sub> displayed. The display of these indicated that the digester will run program 1 which had five steps, then the run button was pressed to start the digestion process. This process took 1 hour 20 minutes to run. A greenish blue solution was obtained at the end of the digestion time, which indicated the sample has completely digested. Tubes were brought out of the rack and left to cool before the next stage was carried out.

For the next stage, the Gerhardt Kjeldahl vapodest distillation unit was used. This system takes about 5 minutes to set up. The steam inlet tube was put into

the digestion tube on the left-hand side of the machine and a conical flask containing 50 ml of 3% boric acid and a few drops of mixed indicator 5 (to collect the distillate through the outlet tube) to the right. The protect door was closed shut as heat is emitted during the experiment. To the machine, a water source, NaOH source and steam were connected and were dispensed in this order during the distillation process. The NaOH button was held down for a few extra seconds for solution to turn completely black. This process took approximately 4 minutes after which a clear green solution was obtained. This step was carried out the same way for all the samples.

Finally, the solutions obtained in the conical flask were titrated against 0.1 M HCl including the blank and used to calculate the average titre of the samples. The average titre obtained, and the blank titre value were used to calculate the %N of the samples.

$$\%N = \frac{\text{Sample titre (ml)} - \text{Blank titre (ml)} \times \text{Normality of HCl} \times 14 \times 100}{\text{Weight of sample (mg)}} \quad (6.2)$$

The %N, the value was multiplied against the conversion factor (F) of the sample to obtain the % protein content of the samples.

$$\% \text{ Protein content} = \%N \times F \quad (6.3)$$

For wheat bran, a conversion factor of 5.7 was used (AACC, 2010).

#### **6.4.2.3 Viscosity of AX Samples**

A liquid can either be categorised as being fluid or viscous and this is determined by the consistency of a liquid. Therefore, in order to characterise the AX samples as either fluid or viscous material, a viscosity test was carried out. The Bohlin Gemini rheometer was used characterise the viscosity of

solutions in the samples at different concentrations. 1-5% concentrations of both samples were left to stir overnight using hotplate stirrers and magnetic stirrers with samples heated at 40°C for 2 hours. Samples were then poured into centrifugal tubes, weights balanced and centrifuged for 15 minutes at 4400 rpm. After centrifugation, the supernatant was carefully taken and placed evenly on the Peltier. A cone plate with geometry of 2° 55 mm (2° cone angle and 55 mm diameter) was used for these experiments because of the surface area of the sample solutions. For effective use of the rheometer, the Bohlin software available on the computer had to be of a specific setting and pressure switch set at 2-bar. Of the four options presents in the software for analysis, viscometry was the experiment selected to be carried out. The shear rate for the analysis was set to a rotation speed ranging from 0.01 to 1000 /second at a temperature of 20°C. The gap size between the cone plate and Peltier for these experiments was 70 µm (Mezger, 2014). After the setup of the software, the latch to which the cone plate was attached was unlocked to allow spinning of the sample and thus, determination of results.

#### **6.4.3 Dough preparation**

Dough samples were prepared using two types of white flour (Sainsbury's flour and Allinson flour), 1.5% sugar, 1.6% salt, 5% fat, 4% yeast and water (ingredients found in Table 6.1); all percentages based on flour weight. Dough sample formulations were mixed in a Minorpin mixer (Figure 4.3). Wheat bran (fine and coarse) as well as arabinoxylans (wheat bran and sugarcane bagasse) were substituted for white wheat flour at different percentages. Arabinoxylan samples were used initially in dry powder form after being milled and later

dissolved overnight in water before being added to dough formulations. For the dissolved AX samples, part of total amount of water required for the dough preparation was used to prepare AX solutions (Table 6.2). The total amount of flour or flour-fibre mix (for example 47.5 g flour + 2.5 g bran) used to prepare dough samples for these set of experiments was 50 g. This excluded other ingredients also used in the preparation of each dough type. Yeast solutions were also prepared and that further the reduced the amount of available water left.

For these early investigations, only small amounts of dough samples were required, which were prepared using a Minorpin mixer (Henry Simon, Ltd., UK). The Minorpin mixer has four pins in the rotating head and three in the base and can mix dough based on up to 60 g flour but 50 g was used in this research. To prepare doughs in the Minorpin mixer, dry ingredients were put into the mixing bowl along with fat, mixed for one minute to aerate the dry ingredients, then water and yeast solution were added. When putting in the dry ingredients into the mixing bowl, care was taken to ensure that salt and yeast do not come into direct contact as the salt inactivates yeast activity. Once all ingredients were in the mixer bowl, the machine head was lowered and the switched turned on. The mixer requires about 8 minutes to develop a dough.

In order to take samples for DDD analysis, dough was placed on a clean surface between two steel rods and a clear plastic rolling pin to smooth dough to a uniform thickness. Using a cylindrical steel cutter, two dough samples were cut and placed in flat-bottom flask and swirled for 30 seconds before it was placed

on the outer double cup to get the weight of dough in air before being immersed in xylene for further analysis. The swirling was done to strengthen the outer surface of the dough and enhance rheological properties. After the dough has been mixed, a timer is set for 3 minutes (time estimated for previous steps to be carried out), after which dough immersed in xylene should have started the density and voidage analysis which can be seen on the desktop of the computer. The dough temperature ranged from 25-29 °C depending on the time of mixing. Tables below show the ingredients used with respective sources; the different fibre ratios used as well as the water calculations for arabinoxylan experiments.

*Table 6.1: List of ingredients and their sources*

<b>Ingredients</b>	<b>Details</b>
Strong white bread flour	1.5 kg bag, Sainsbury's, London, EC1N 2HT 16 kg bag, Allinson flour, Amazon, UK.
Salt	Sainsbury's cooking salt, Sainsbury's, London, EC1N 2HT
Water	Ultrapure water, research laboratory, University of Huddersfield
Yeast	Fast action dried yeast, Sainsbury's, London, EC1N 2HT
Fat	500 g Trex vegetable fat, Princes Limited, Liverpool, L3 1NX
Wheat bran	Biorenewables Development Centre, York, UK
WBAX and SCBAX	Biorenewables Development Centre, York, UK

Figure 6.3 shows the arabinoxylan extracts received from the Biorenewables Development Centre (BDC). The WBAX received from the BDC was very hard and rock-like while the SCBAX was powder-like and easier to handle, but the

WBAX needed to be milled before samples taken for analysis or dough formulations.



Figure 6.3: WBAX (left) and SCBAX (right) samples received from BDC

More water was required in fibre enriched doughs to maintain appropriate dough rheology and handling properties (Table 6.2). The additional water required after dough fortification (as seen in Table 6.2) was calculated as half the percentage of fibre added to the total percentage of water required by the control dough, following the practice of (Campbell *et al.*, 2008a,b,c). This means for example, the total amount of water required for 5% wheat bran was 61.5% control dough water plus 2.5% (half the percentage of wheat bran) which is 64% (32 g). In the table below (Figure 6.2), wheat bran referred to both fine and coarse samples while AX referred to WBAX and SCBAX. The adjustments in Table 6.3 for AX samples was used only for the dry powder experiments All calculations were made based on the total amount of wheat flour (50 g) and the control dough water content was based on the different trials and manual handling. Both bran particles sizes and types of AX were used for experiments through this chapter unless stated otherwise in a given section.

Table 6.2: List of ingredients and the amount of water required for dough formulation

<b>Dough formulation</b>	<b>Quantity of flour used (g)</b>	<b>Quantity of fibre used (g)</b>	<b>% water required</b>	<b>Water required (g)</b>
Control	50.000	0.000	61.000	30.500
5% wheat bran	47.500	2.500	63.500	31.750
10% wheat bran	45.000	5.000	66.000	33.000
15% wheat bran	42.500	7.500	68.500	34.250
0.5% AX	49.750	0.250	61.250	30.625
1% AX	49.500	0.500	62.500	30.750
1.5% AX	49.250	0.750	61.750	30.875
2% AX	49.000	1.000	62.000	31.000

The above experiments were performed using AX in the form of a dry powder. However, it was considered that the AX may perform differently if it dissolved in water. For dissolved AX trials, solutions were made based on the total amount of water (61%) of the control dough and on the fact that some of the total water needed to be used in preparing yeast solutions. Control dough formulation was made up of:

- Flour weight = 50 g
- Water = 30.5 g (61%)
- Salt = 0.8 g (1.6%)
- Yeast = 2 g (4%)
- Sugar = 0.75 g (1.5%)
- Fat = 2.5 g (5%)

The 2 g of yeast comes from 25 g of yeast solution (which is 80 g suspended in 920 g water). The other 23 g of water is made up to 30.5 g by using 7.5 g to swish out the beaker.

For the experiments solubilizing the AX first, double the yeast concentration was used in preparing yeast solution (160 g was suspended into 840 g water);

this was so that there would be enough water to dissolve the AX for all experiments. Of this, 12.5 g would contain 2 g yeast + 10.5 g water. This leaves 20 g water to dissolve the AX in.

Table 6.3: Water calculations for dissolved AX experiments

	Flour (g)	Dissolve (g)	In water (g)	Actual mass of solution (g)
<b>Control</b>	50.000	0.000	20.000	20.000
<b>0.5% WBAX</b>	49.750	0.250	20.125	20.375
<b>1.0% WBAX</b>	49.500	0.500	20.250	20.750
<b>1.5% WBAX</b>	49.250	0.750	20.375	21.125
<b>2.0% WBAX</b>	49.000	1.000	20.500	21.500
<b>0.5% SCBAX</b>	49.750	0.250	20.125	20.375
<b>1.0% SCBAX</b>	49.500	0.500	20.250	20.750
<b>1.5% SCBAX</b>	49.250	0.750	20.375	21.125
<b>2.0% SCBAX</b>	49.000	1.000	20.500	21.500

Solutions were prepared in stock and stirred overnight for all eight samples required for experiments. Altogether, each solution was prepared as below.

- 120 g water + 6 × the AX level, i.e.:
- 120.75 g water + 1.50 g WBAX
- 121.50 g water + 3.00 g WBAX
- 122.25 g water + 4.50 g WBAX
- 123 g water + 6.00 g WBAX

and

- 120.75 g water + 1.50 g SCBAX
- 121.5 g water + 3.00 g SCBAX
- 122.25 g water + 4.50 g SCBAX
- 123 g water + 6.00 g SCBAX

#### 6.4.3.1 Preparation of Yeast Solution

In the dough expansion experiments, it was necessary to hydrate the yeast before adding it to the dough. 80 g of yeast was added to 920 g of water at 30°C and mixed in a 2 L bottle with a magnetic stirrer for approximately 30 minutes (until the yeast was completely dissolved). Once fully dissolved, the quantity of solution corresponding to the required mass of yeast was removed and added to the mixer. The remainder of the total water requirement was added separately.

Due to the extra water absorbed by fibre, fibre-enriched doughs required higher water volumes which diluted the yeast concentration in the final dough. To try to maintain comparable gas production rates, extra yeast was added to fibre-enriched doughs to give the equivalent yeast concentration to bran-free doughs. This enabled direct comparisons between the dynamic dough profiles to be made. The calculations for the quantities of mixture and fresh water used presented in Table 6.4 where  $x$  is the weight of yeast to be added to the fibre-enriched doughs.

Table 6.4: Table used to calculate quantity of yeast required in fibre-enriched doughs before dissolving yeast

Ingredients	Control dough	5% wheat bran	10% wheat bran	15% wheat bran	0.5% AX	1% AX	1.5% AX	2% AX
Flour (g)	50.00	47.50	45.00	42.50	49.75	49.5	49.25	49.00
Fibre (g)	0.00	2.50	5.00	7.50	0.25	0.50	0.75	1.00
Water (g)	30.50	31.75	33.00	34.25	30.63	30.75	30.88	31.00
Yeast (g)	2.00	$x$	$x$	$x$	$x$	$x$	$x$	$x$
Salt (g)	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Sugar (g)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Fat (g)	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Total (g)	86.55	$85.80 + x$	$87.05 + x$	$88.30 + x$	$84.68 + x$	$84.80 + x$	$84.93 + x$	$85.05 + x$

30.5 g of water is required for a 50 g dough formulation. After preparing a 1000 g of yeast-water solution (80 g yeast in 920 g water), 2 g of yeast is  $\frac{1}{40}$ <sup>th</sup> of the 80 g dried active yeast. Thus,  $\frac{1}{40}$ <sup>th</sup> of 1000 g of the yeast-water solution which is 25 g (23 g water and 2 g yeast) is required to give the required amount of yeast needed for each dough formulation. For bran enriched dough formulations, the extra water was added directly into each formulation for mixing.

In the case of AX enriched dough formulations, since water was needed to dissolve both AX and make yeast solutions (as discussed in Table 6.3 above), the amount of water used to prepare yeast solutions was reduced and the amount of dried yeast was doubled. 160 g dried yeast was dissolved in 840 g of ultrapure water. Thus,  $\frac{1}{80}$ <sup>th</sup> of 1000 g yeast solution gives us 12.5 g solution for the control dough sample (10.5 g water and 2 g yeast). This leaves 20 g water in the case of the control dough to prepare the AX solutions.

The ingredients were placed in the mixer and water at 27°C was added. In the expansion experiments, the yeast solution was added first and then the excess water was used to rinse the remaining yeast from the beaker into the mixer; this ensured that all of the yeast was added to minimise the risk of residual yeast remaining in the beaker. This was only possible for bran enriched dough formulations but not AX enriched dough formulations. Table 6.5 shows the amount of yeast solution and the amount of additional water required for each dough formulation.

Table 6.5: Calculation for the mass of yeast solution and water added to all dough formulations

	Total amount of water required (g)	Amount of yeast solution required (g)	Amount of water in yeast solution (g)	Amount of additional water required (g)
<b>Control dough</b>	30.500	25.000	23.000	7.500
<b>5% bran dough</b>	31.750	25.375	23.375	8.375
<b>10% bran dough</b>	33.000	25.750	23.750	9.250
<b>15% bran dough</b>	34.250	26.125	24.125	10.250
<b>Control dough AX</b>	30.500	12.500	10.500	20.000
<b>0.5% AX dough</b>	30.625	12.670	10.670	19.955
<b>1% AX dough</b>	30.750	12.810	10.810	19.940
<b>1.5% AX dough</b>	30.875	12.970	10.970	19.905
<b>2% AX dough</b>	31.000	13.125	10.125	20.875

#### 6.4.4 Dynamic Dough Density measuring equipment

The Dynamic Dough Density technique follows the changing density of a yeasted dough sample; as the yeast produces carbon dioxide gas, the dough expands and the density changes. The functional property of dough that is of interest is its ability to expand and retain gas; the maximum expansion, as indicated by the minimum density achieved by the dough, is therefore a measure of this quality of the dough (Campbell *et al.*, 2008a,b,c). The DDD technique is sensitive and is therefore a useful technique for investigating the effects of ingredients or processing conditions on dough quality.

For the current experiments, four density measurement systems were used. A single density measurement system comprises an analytical balance (Precisa 125A, Precisa balances Ltd, UK) with a jacketed beaker, a double-cup sample holder and a J-type thermocouple wire, as illustrated in Figure 4.1 and Table 6.4. The double-cup is equipped with an anti-float cap and is used to weigh the

sample both in air and immersed in the liquid (xylene) contained in the beaker. Xylene was purchased from Fisher Scientific (Loughborough, UK) with a density of  $0.86059 \text{ g/cm}^3$  at  $38^\circ\text{C}$ . It should be noted that the DDD system is located in a fumehood because of the hazardous nature of xylene (it is carcinogenic, flammable and can cause infertility in females). Xylene is used instead of water because it has a lower density and a non-wetting/non-dissolving property. (Campbell *et al.*, 2001). The anti-float cap (Figure 4.1) was used to prevent the dough from rising once the density became less than that of the xylene. The thermocouple junction is placed below the double cup and towards the radial centre of the beaker. The water bath is maintained at  $40^\circ\text{C}$  and water circulated through the jackets of the beakers, to give a xylene temperature of  $\sim 38^\circ\text{C}$ . The changing weight of the dough piece and the xylene temperature are recorded every 10 seconds by a computer programme written in LabVIEW 7.0 (National Instruments, UK).

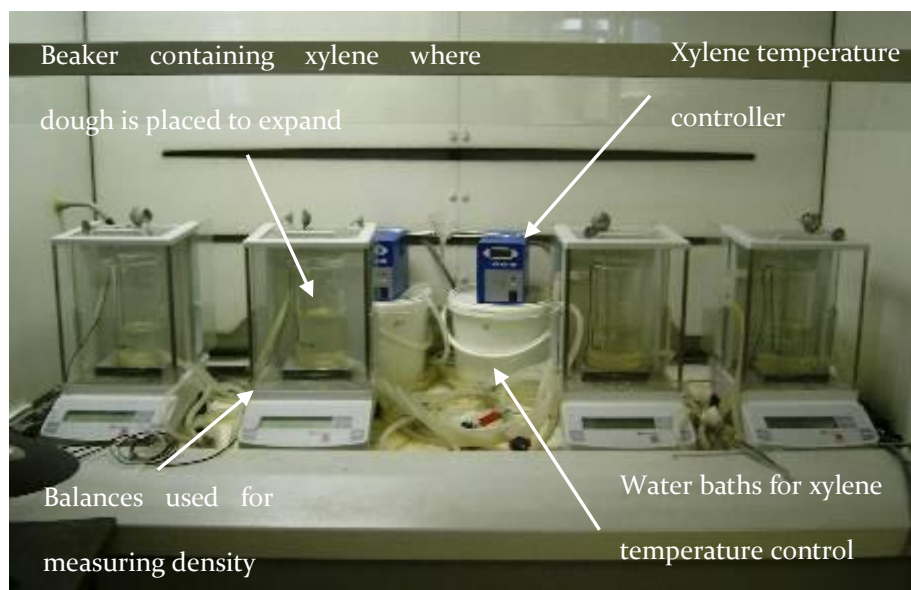


Figure 6.4: The Dynamic Dough Density (DDD) measuring system within the fume cupboard

After mixing, dough samples of about 5 g were cut using the spherical shaped cutter before weighing on top of the double cup. Once the weight was recorded, the sample was carefully placed in the inner cup (balance was tethered and care was taken to ensure the thermocouple had no contact with the double cup), immersed in xylene and the experiment was started. The computer recorded readings every 10 s for about an hour, until the density had reached its minimum (which corresponds with maximum expansion) and begun to rise. Samples were analysed in duplicates, so each dough formulation had a total number of eight replicates for further analysis. Trials were run in a random order

#### 6.4.5 Dough rheology

There is a unique property found only in doughs produced from the mixing of wheat flour and water and that is the viscoelastic rheological properties. This allows for the retention of gases, which is a major attribute for dough

development. The process of dough production is therefore the optimisation of process and the control of this process is very crucial (Cauvain, 2003; Cauvain, 2015;). This is best understood by measuring the resistance to deformation of the dough because resistance increases with hydration during mixing (Cauvain, 2003).

A series of tests were carried out in order to understand the rheology of the dough formulations used in this research, thus, providing an insight into the effect of fibre (bran and AX) on dough rheology using creep-recovery testing.

Rheology tests were carried out using a Kinexus rheometer. The rheometer was used in determining the deformation of dough samples in regard to creep and recovery test capabilities within the linear viscoelastic range (LVR). The LVR is the region where the normal viscoelastic properties of a sample divert by less than 10% from its normal linear properties. It is used to determine the appropriate range to carry out rheological studies without compromising the results. The rheometer was used to run the amplitude sweep test and creep-recovery tests.

#### **6.4.5.1 Amplitude sweep strain controlled**

This test was carried out to determine the Linear Viscoelastic range (LVR) of the dough formulations used for further rheological studies. To determine the LVR of each formulation, the amplitude strain sweep was subjected to small oscillatory shear. The conditions set for the amplitude sweep were shear strain 0.01- 100%, a gap distance of 1 mm and a frequency of 1 Hz with about 2 g of freshly prepared dough sample. At low strains, the structure of the dough is

preserved but as the strains increase, a complete disruption in the structure is observed. For each dough formulation, the LVR was determined (10 Pa) by obtaining a corresponding shear stress range for each shear strain within the linear viscoelastic range. The shear stress values for all formulations were compared, and the lowest common shear stress value was used for the creep-recovery test.

#### **6.4.5.2 Creep-recovery test**

Creep-recovery tests were carried out on a controlled rheometer to determine the resulting elastic deformation and viscous flow within the LVR. The creep-recovery test was used because it is an oscillatory test that measures the extent to which a viscoelastic sample can expand and recover without being destroyed. These experiments were performed on a Kinexus rotational rheometer (Malvern Instruments, Malvern, United Kingdom) equipped with a serrated plate geometry (PU40X SW1287 SS) and a corresponding serrated Peltier cartridge (PLS40X S2007 SS). A piece of sub-dough (about 2 g) was retrieved from the inner part of a dough, loaded between the serrated plates of the rheometer and compressed to obtain a gap distance of 1 mm. The excess sample after compressing was trimmed and silicon oil placed around the sample to prevent the edges from drying out during the experiment. The temperature of the dough was kept constant at 25°C. A sample relaxation time of 10 minutes was set in order for the dough to reach normal force after sample handling, before the commencement of creep-recovery experiment. Three variables have been chosen for the creep-recovery test, specifically the length of the creep phase, the shear stress applied during creep and the length of the recovery phase. The

Kinexus rheometer was used to determine the extensibility and resistance to extension of the dough samples instead of the Kieffer dough and gluten extensibility rig because the rheometer is known to be more precise and the Kieffer rig is not available at the University.

A shear stress was imposed on a dough sample and the sample's deformation. This shear stress value was obtained from the corresponding LVR shear strain value from the amplitude sweep (ranged from 0.001% to 100%) and a frequency sweep of 1 Hz (6.283 rad/s). Creep tests were carried out at a shear stress of 10 Pa with a creep time of 30 minutes (Mezger, 2014). The results are expressed as compliance (1/Pa), which corresponds to the strain divided by the imposed shear stress. In the recovery phase, the stress is removed, and the dough sample is allowed to recover (instantaneous and retarded) as much of the original form as possible from the deformation. The recovery phase was performed for 80 minutes to ensure the dough sample recovery reaches pseudo-equilibrium.

#### **6.4.5.3 Burgers model**

Parameters readily available from creep-recovery curves are the maximum creep compliance  $J_{c,max}$  and the maximum recovery compliance  $J_{r,max}$ , which were measured at the end of the creep and recovery phase respectively. Creep deformation is the combination of three types of deformation: instantaneous elastic, retarded elastic and viscous deformation. When compliance increases linearly with time, the region of steady is reached. The recovery phase can be divided into instantaneous elastic recovery and retarded elastic recovery. The different types of deformation were quantified by applying the Burgers model on the creep data (Van Bockstaele *et al.*, 2011). The model is a mathematical

expression of the combination of mechanical analogues which represent the viscoelastic behaviour. The Burgers model was originally designed for the modelling of linear viscoelastic properties but has now also been a tool for examining creep-recovery curves obtained within the LVR (Lazaridou *et al.*, 2007; Skendi *et al.*, 2011). Burgers model can either be a 4-parameter model or a 6-parameter model (Mezger, 2014). The 4-parameter model was used for analysis of all creep data obtained from the experiments.

$$J_c = J_0 + J_1 \left(1 - e^{\left(-\frac{t}{\lambda}\right)}\right) + \frac{t}{\eta_0} \quad (6.4)$$

where  $J_c$  is the creep compliance,  $J_0$  is the instantaneous compliance,  $J_1$  is the retarded elastic compliance,  $t$  is time,  $\lambda$  is the retardation time, and  $\eta$  is the steady state viscosity (Mezger, 2014).

A 3-parameter model was used for the analysis of data obtained from the recovery phase, describing the elastic response after removal of the shear stress.

$$J_r = J_0 + J_1 \left(e^{\left(-\frac{x}{\lambda}\right)}\right) \quad (6.5)$$

where  $J_r$  is the recovery compliance (Mezger, 2014).

#### 6.4.5.4 Statistical analysis

Creep-recovery test data were analysed using Graphpad Prism 6.0 (Graphpad software, USA). This software was used in creating a model which best fits the results obtained from each dough creep-recovery test carried out with the use of non-linear regression data analysis. Descriptive statistics as well as one-way ANOVA with post-doc Tukey tests were carried out to determine if there were any significant differences between each dough sample under specific experimental conditions. ANOVA was carried out to determine whether there

was a statistical difference between the different dough formulations and the Tukey test was carried out to determine what doughs in particular were different.

#### **6.4.5.5 Scanning Electron Microscope studies**

A variety of techniques have been used to investigate the changes in the microstructure of bread doughs during different stages of breadmaking process. Dough mixing is the most important stage in the breadmaking process and has been studied for different reasons over the years using a diverse set of methods and techniques (Alava *et al.*, 2001). While some studies focused on the chemical changes occurring in wheat glutenin during dough processing, other studies focused on the microstructure of bread dough (Alava *et al.*, 2001). Dough was prepared using a series of ingredients containing different wheat bran samples and yeasts. The aim was to characterise these prepared doughs by a series of techniques including Thermal Analysis and Scanning Electron Microscopy. The procedure used for Scanning Electron Microscopy (SEM) was discussed in the following paragraph.

1 g of dough was taken from the middle of the ball of dough and the prepared dough was placed onto an aluminium stub suitable for introduction to the SEM chamber. As the dough is organic based then there is a need to coat the sample with gold to produce nuclei large enough to cause the incident electrons to be reflected to the back scattered electron detector. Gold coating was carried out using a Quorum 7620 Sputter Coater. The coater is armed with a Gold/Palladium disc which when voltage applied creates a gold plasma. Coating was carried out under near vacuum conditions with a low bleed of argon gas for

45 seconds to provide a uniform coating of approximately 3 nm. The coated dough sample is then introduced into the JEOL 6060 SEM and placed under high vacuum. When sufficient vacuum has been achieved, a voltage of 10kV (or 20kV – check) was applied and the resulting back scattered electron image (BSEI) collected using the back scattered electron detector.

## **6.5 Investigations of the effects of wheat bran and AX on dough structure and microstructure**

Using the materials and equipment discussed above, experimental investigations were carried out on the effects of and interactions between fine and coarse wheat bran, WBAX and SCBAX on aeration of bread dough during mixing and the expansion capacity during proving. But before that, the particle size distribution of the wheat bran samples is discussed as well as the compositional analysis of all samples.

### **6.5.1 Wheat bran particle size**

Wheat bran obtained from BDC was milled, sieved and a comparison between the particle sizes of the fine and coarse bran was carried out. Moisture and protein content of all samples were carried for use within other experiments. The effect of fine and coarse wheat bran on bread dough were analysed using the DDD system as well as rheological testing.

Figure 6.5 and Table 6.6 and 6.7 below show the particle size distribution of both wheat bran samples. According to the European standards (The International Standards, ISO 565), fine aggregates refer to materials which are

4000  $\mu\text{m}$  or smaller. Hence, the characterisation of wheat bran samples into coarse or fine particle size. Although the starting sieve aperture used was 2000  $\mu\text{m}$ , it was observed that 99.3% of coarse wheat bran passed through the sieve compared to the 100% passing of the fine wheat bran sample.

Table 6.6: Coarse wheat bran particle size distribution

Sieve aperture size (µm)	Weight of bran retained (g)				% total weight on each sieve	% smaller than X	% Passing
	1	2	3	Average			
2000	0.5800	0.8100	0.6600	0.68330	0.6833	0.6833	99.3167
1000	14.8600	15.4500	14.8800	15.0633	15.0633	15.7466	84.2534
500	30.1200	32.5000	38.0800	33.5667	33.5667	49.3133	50.6867
250	44.0800	42.7800	38.4800	41.7800	41.7800	91.0933	8.9067
125	8.7800	7.0800	6.4900	7.4500	7.4500	98.5433	1.4567
75	0.4500	0.3900	0.4200	0.4200	0.4200	98.9633	1.0367
0	0.8700	0.6400	0.6200	0.7100	0.7100	99.6733	0.3267

Table 6.7: Fine wheat bran particle size distribution

Sieve aperture size (µm)	Weight of bran retained (g)				% total weight on each sieve	% smaller than X	% Passing
	1	2	3	Average			
2000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000
1000	0.1600	0.1200	0.2000	0.1600	0.1600	0.1600	99.8400
500	23.7900	30.9800	33.8800	29.5500	29.5500	29.7100	70.2900
250	29.1000	35.9000	31.3900	32.1300	32.1300	61.8400	38.1600
125	37.5600	27.6200	31.3500	32.1767	32.1767	94.0167	5.9833
75	7.6400	4.1800	1.2500	4.3567	4.3567	98.3734	1.6266
0	0.5200	0.3700	0.0500	0.3133	0.3133	98.6867	1.3133

X is the of bran left on the previous sieve screen.

$$\%total\ weight\ retained = \frac{weight\ retained\ on\ each\ sieve}{total\ sample\ weight} \times 100 \quad (6.6)$$

$$Cumulative\% = \%weight\ retained\ on\ preceeding\ sieve + \%weight\ retained\ on\ immediate\ succeding\ sieve \quad (6.7)$$

$$\%Passing = 100 - cumulative\% \ of\ each\ sieve \quad (6.8)$$

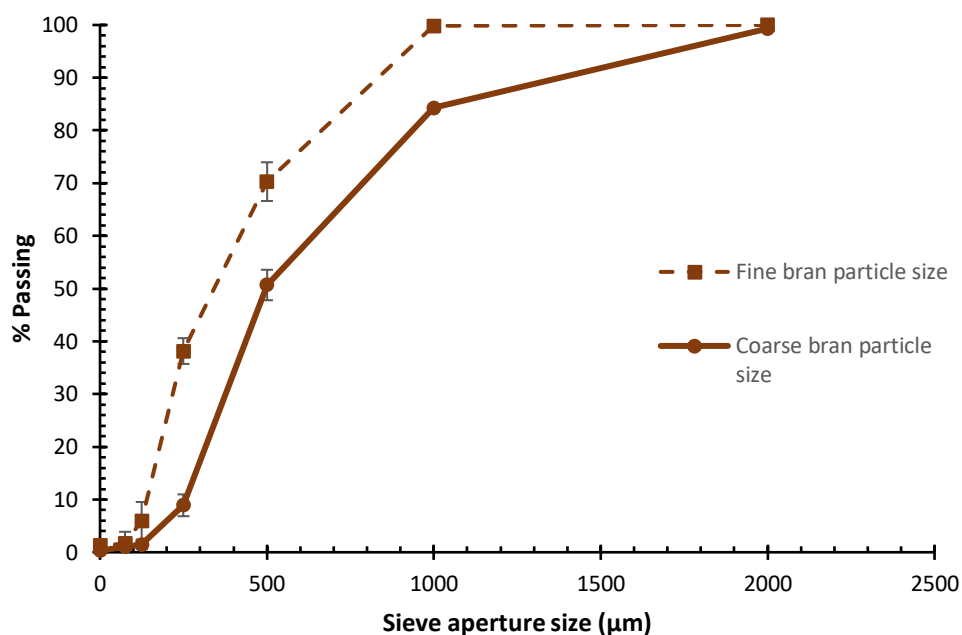


Figure 6.5: The particle size distribution of fine and coarse wheat bran samples

### 6.5.2 Compositional specification analysis

The moisture and protein content of flour and wheat bran used were analysed and used for further analyses.

### 6.5.3 Moisture content

With the use of the oven method, sample weights were taken in triplicate and an average used for final calculations. The weight of the empty crucible, weight of the crucible and approximately 2 g of AX sample before and after heating were recorded. The moisture contents of flour, coarse and fine wheat bran were calculated.

$$\% \text{Moisture} = \frac{w_0 - w_1}{w_0} \times 100 \quad (6.9)$$

where  $w_0$  and  $w_1$  are the weights of crucible with sample before and after drying, respectively.

Flour:

$$\begin{aligned}\%Moisture &= \frac{37.27-37.04}{2.0007} \times 100 \\ &= \frac{0.23}{2.0007} \times 100 \\ &= 11.50\%\end{aligned}$$

Coarse wheat bran:

$$\begin{aligned}\%Moisture &= \frac{33.57-33.37}{2.0004} \times 100 \\ &= \frac{0.2}{2.0004} \times 100 \\ &= 10\%\end{aligned}$$

Fine wheat bran:

$$\begin{aligned}\%Moisture &= \frac{37.01-36.89}{2.0004} \times 100 \\ &= \frac{0.12}{2.0004} \times 100 \\ &= 6\%\end{aligned}$$

Fine wheat bran was observed to have a lesser moisture content than the coarse bran. This was because during milling of wheat bran into a finer particle size, the sample went through extra drying from the heat of the mill. Therefore, although both samples were from the same source, further processing (milling to a finer particle size) caused the 'finer' sample to also be the drier sample. Flour used was observed to have a higher moisture content (11.5%) than both wheat bran samples.

#### 6.5.4 Protein content

The titration was carried on all samples (average titre) including the blank sample and results used to calculate the % nitrogen content of flour, coarse and fine wheat bran. The % nitrogen contents obtained were finally used to calculate the % protein content of the samples.

$$\%N = \frac{\text{sample titre (ml)} - \text{blank sample (ml)} \times \text{HCl normality} \times 14 \times 100}{\text{weight of sample (mg)}} \quad (6.10)$$

$$\text{Protein content} = \%N \times F \quad (6.11)$$

where F is the conversion factor (5.7 for wheat bran)

Flour:

$$\begin{aligned} \%N_f &= \frac{(17.505 - 0.725) \times 0.1 \times 14 \times 100}{1250} \\ &= \frac{16.78 \times 0.1 \times 14 \times 100}{1250} \\ &= 1.88 \end{aligned}$$

$$\text{Protein content} = 1.88 \times 5.7$$

$$= 10.72\%$$

Fine wheat bran:

$$\begin{aligned} \%N_{fb} &= \frac{(20.265 - 0.725) \times 0.1 \times 14 \times 100}{1250} \\ &= \frac{19.54 \times 0.1 \times 14 \times 100}{1250} \\ &= 2.19 \end{aligned}$$

$$\text{Protein content} = 2.19 \times 5.7$$

$$= 12.48\%$$

Coarse wheat bran:

$$\%N_{cb} = \frac{(19.86 - 0.725) \times 0.1 \times 14 \times 100}{1250}$$

$$= \frac{19.135 \times 0.1 \times 14 \times 100}{1250}$$

$$= 2.14$$

$$\text{Protein content} = 2.14 \times 5.7$$

$$= 12.2\%$$

For WBAX:

$$\%N_{wbax} = \frac{(30.99 - 2.76) \times 0.1 \times 14 \times 100}{1000}$$

$$= \frac{28.23 \times 0.1 \times 14}{1000}$$

$$= 3.95$$

$$\text{Protein content} = 3.95 \times 5.7$$

$$= 22.52\%$$

For SCBAX:

$$\%N_{scbax} = \frac{(10.87 - 2.76) \times 0.1 \times 14 \times 100}{1000}$$

$$= \frac{8.11 \times 0.1 \times 14}{1000}$$

$$= 1.14$$

$$\text{Protein content} = 1.14 \times 5.7$$

$$= 6.5\%$$

Wheat bran arabinoxylan was observed to have the highest protein content of all samples tested.

#### **6.5.5 Viscosity behaviour of AX extracts**

Viscometric analyses were carried out on both AX samples at different concentrations. For SCBAX, solutions of five concentrations (1% - 5%) were made and viscometric analyses carried out on all. In the case of WBAX, although solutions of five different concentrations were also prepared, only solutions of concentrations one and two (1-2%) were possible for usage as the remaining three were visibly too viscous to get appropriate samples for viscometric analysis. Of the five concentration samples of SCBAX, only the first three were used for discussion purposes. This is because an additional unmeasured amount of water was added to concentrations four and five (Figure 6.11-6.12) and thus, cannot be interpreted using same conditions as the others. Additional water was added because samples formed a thick viscous liquid. The reason the graphs were put in was to show that a continuous decline (shear thinning) occurs as the concentrations are increased.

Figures 6.6-6.12 show graphs of viscosity curves at different concentrations with respect to shear rate and shear stress. All graphs were obtained from a replicated experimental data set.

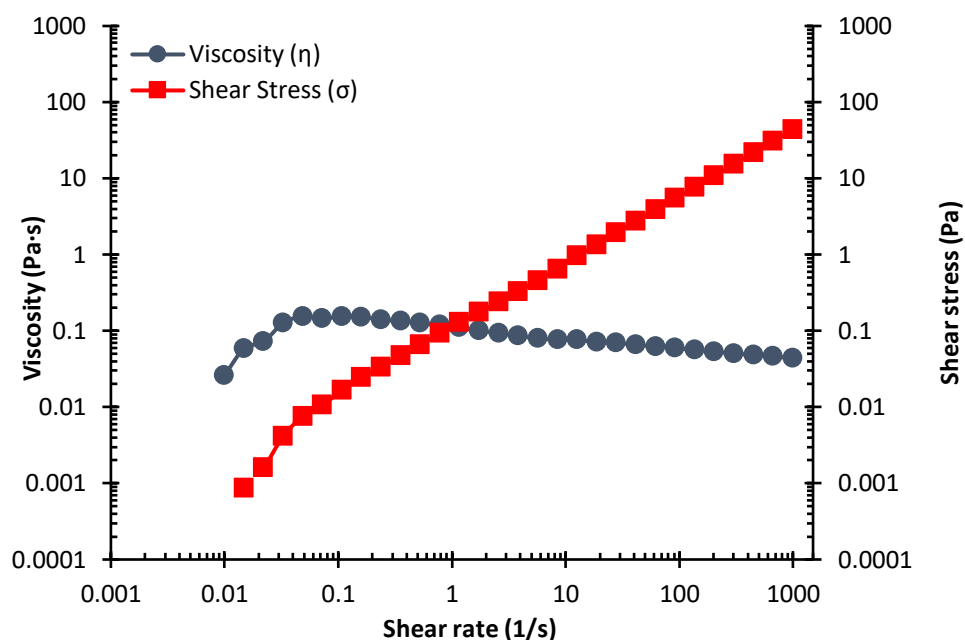


Figure 6.6: Viscosity and shear stress as a function of shear rate for WBAX at 1% concentration

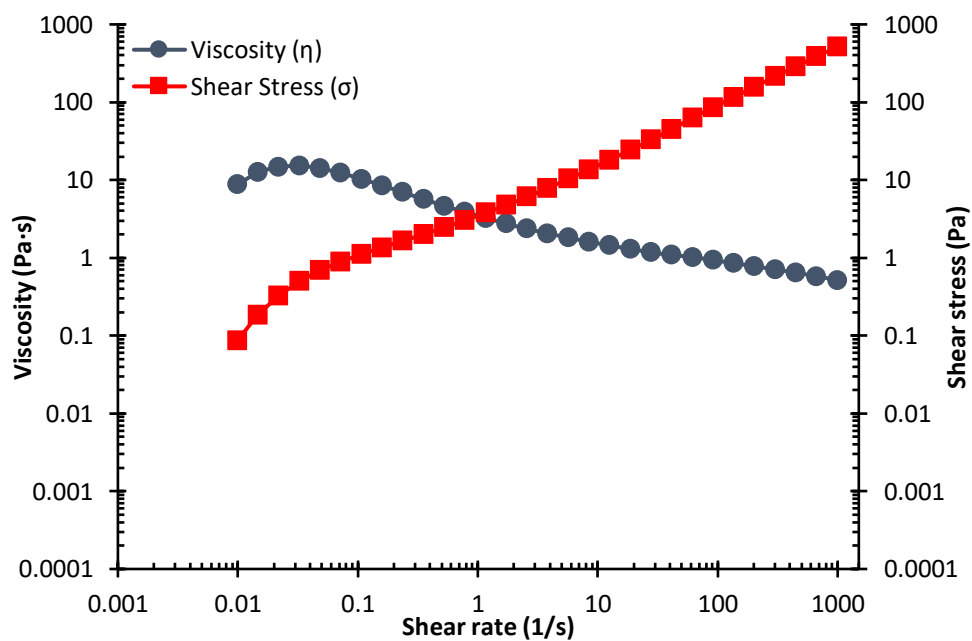


Figure 6.7: Viscosity and shear stress as a function of shear rate for WBAX at 2% concentration

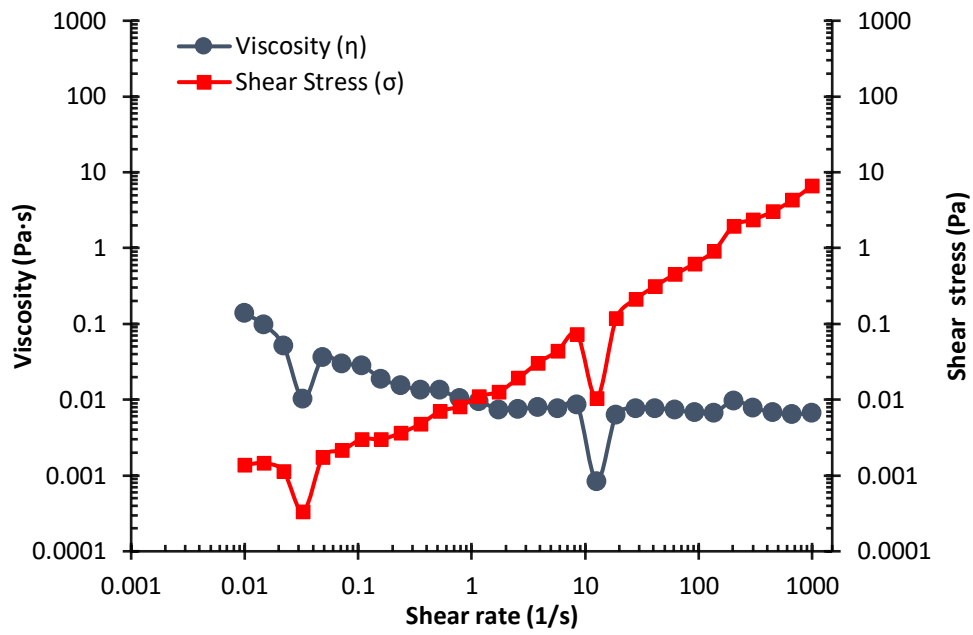


Figure 6.8: Viscosity and shear stress as a function of shear rate for SCBAX at 1% concentration

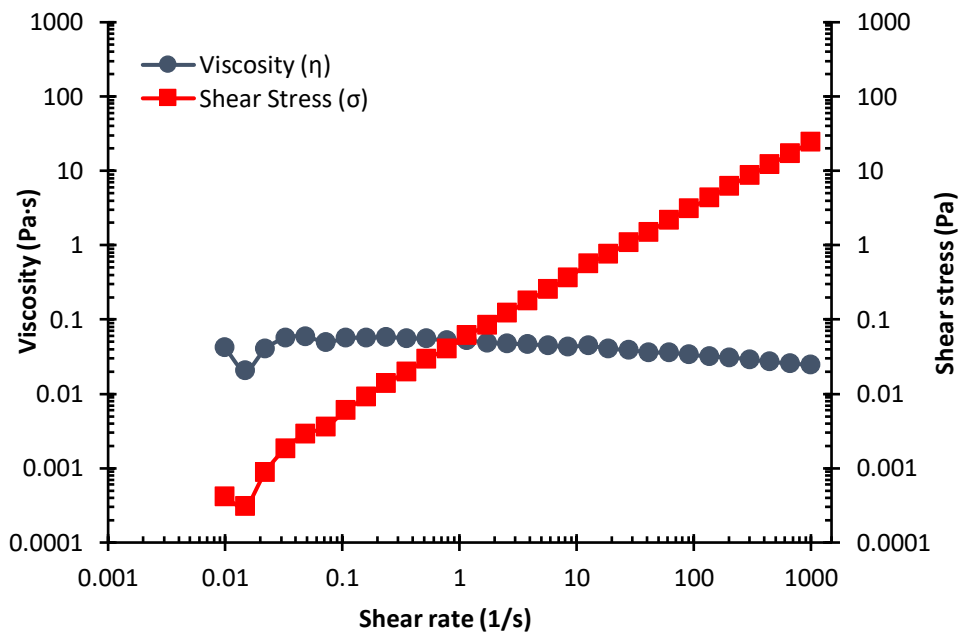


Figure 6.9: Viscosity and shear stress as a function of shear rate for SCBAX at 2% concentration

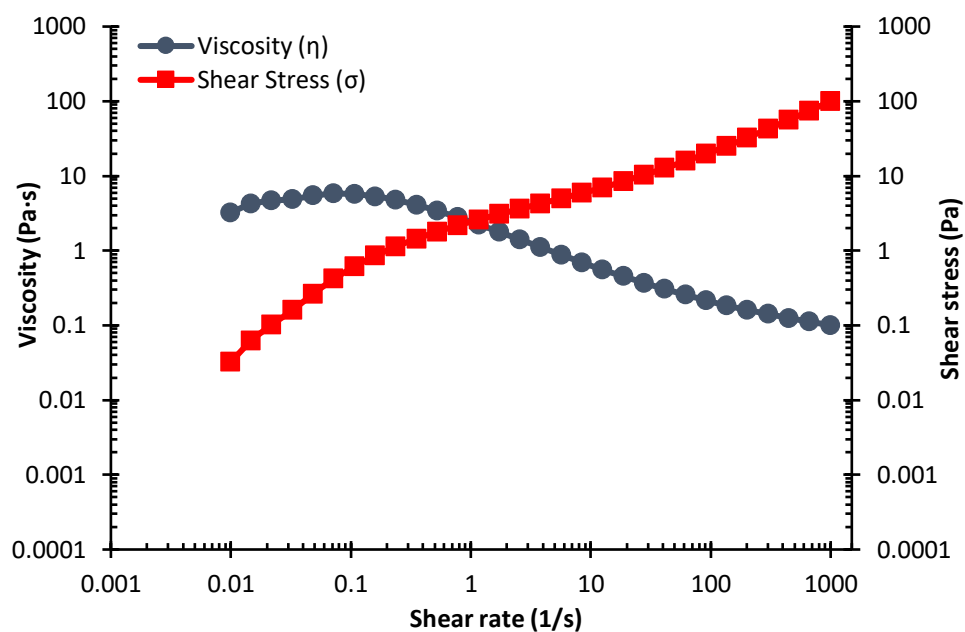


Figure 6.10: Viscosity and shear stress as a function of shear rate for SCBAX at 3% concentration

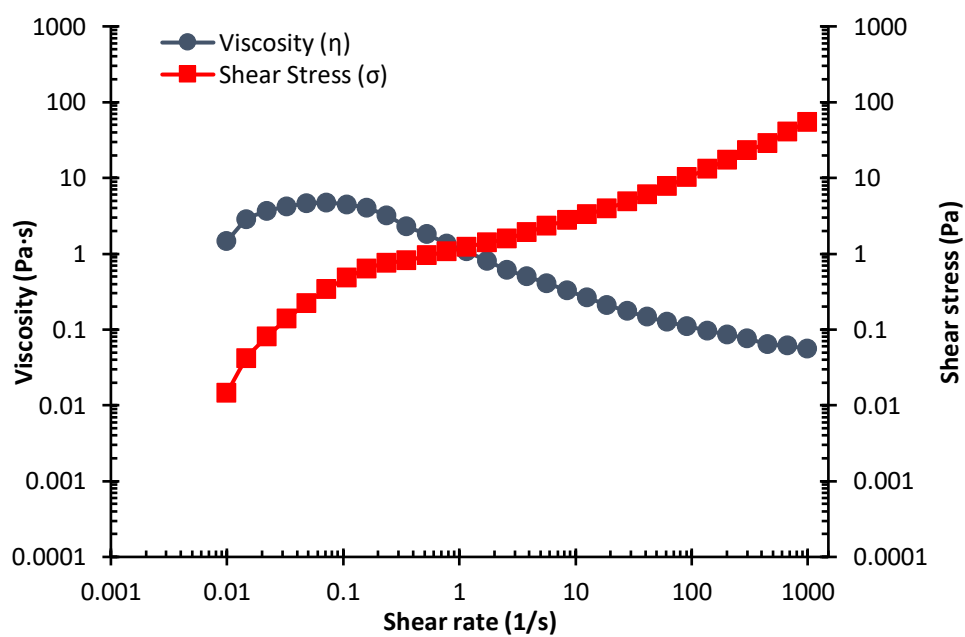


Figure 6.11: Viscosity and shear stress as a function of shear rate for SCBAX at 4% concentration

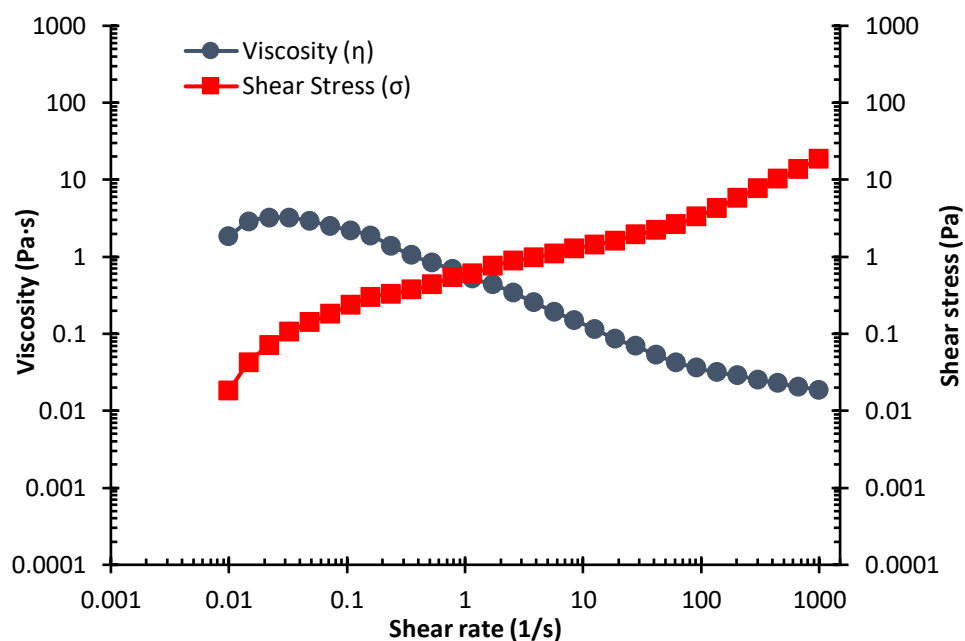


Figure 6.12: Viscosity and shear stress as a function of shear rate for SCBAX at 5% concentration

Figures 6.6- 6.12 show the viscosity and shear stress of WBAX and SCBAX at different concentrations. Clearly, from Figures 6.6-6.12, the SCBAX produced solutions that were shear thinning, i.e. the viscosity decreased at higher shear rates. At higher concentrations the viscosity increased for WBAX. This agrees with works from Girhammar & Nair (1992b, 1992a) and Saulnier *et al.* (2007). This indicates that increasing the concentration of a sample reduces the disturbance observed during analysis and eases understanding the behaviour of the sample. An irregular behaviour was observed for the 1% SCBAX (Figure 6.8) because the concentration was too low and thus, noise disturbance occurred within the system causing the curve to be zigzag rather than for shear thinning to occur like the other samples.

For both WBAX and SCBAX, as the shear rate increases, a continuous reduction in viscosity occurs, indicating shear thinning behaviour. Morris *et al.*, (1981)

similarly reported shear thinning behaviour in random coil polysaccharides although Rumpagaporn *et al.*, (2012) and Kale *et al.*, (2015) reported Newtonian behaviour for arabinoxylans from different sources. No previous work has been done using AX extracts from sugarcane bagasse, but the assumption is all AX extracts are polymers or polysaccharides of similar molecular weights and thus, should have similar behaviours. WBAX was more viscous than SCBAX, indicating variations in their molecular weights and/or structures. The molecular weight of polysaccharides is one of the factors that affect the viscosity of AX extracts (Kale *et al.*, 2015). The higher protein content of WBAX could be another reason why this extract is more viscous than SCBAX.

As shear rate increases, the shear stress also increases with reverse links with viscosity of AX extracts. Higher viscosity levels are obtained for WBAX than SCBAX and thus, shear thinning is observed at higher values also. Only two concentration samples of WBAX were possible for viscometric analysis unlike SCBAX where three concentration samples were used, as the WBAX was more viscous than SCBAX, limiting the concentrations that could be tested. The viscosity curves exhibited a peak at low shear rates. WBAX has a peak viscosity level of 15.2 Pas while SCBAX has a peak viscosity level of 5.8 Pas. A higher peak viscosity was observed in samples with additional water for the SCBAX samples while WBAX were higher viscous, hence the higher peak viscosity obtained. The peak viscosity is the highest/optimum viscosity of a sample. Figure 6.13 shows the peak viscosity of AX extracts at different concentrations.

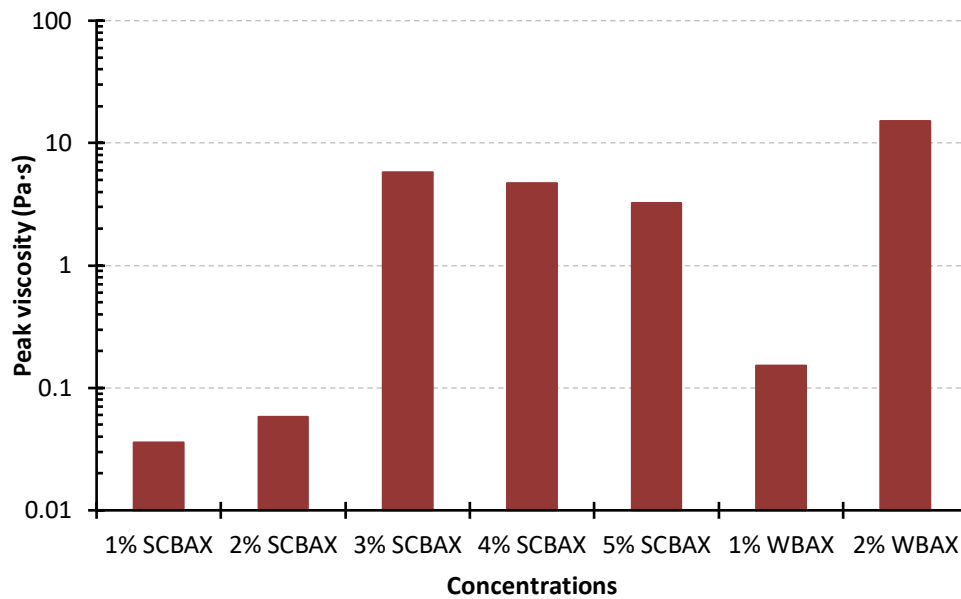


Figure 6.13: Peak viscosity of AX extracts against concentration

#### 6.5.6 Effects of level and particle size of bran on dough expansion

This section discusses the effect of wheat bran (fine and coarse) on dough formulations which were prepared using the Minorpin mixer and used to investigate the growth of the dough piece and retention of gas, as indicated by changes in dough density. The purpose of these trials was to understand the effects of high fibre ingredients on dough expansion after mixing (during proving). Two types of flour samples (Sainsbury's and Allinson) were also analysed alongside the different wheat bran particle sizes.

Figure 6.14 illustrates the DDD profiles for bran-enriched doughs and a control dough formulation using Sainsbury's flour prepared using the Minorpin mixer, and Figure 6.15 plots the minimum density (averaged from eight replicates). Clearly, an increase in the %wheat bran used in a dough formulation results in a decrease in the expansion capacity of the dough (a higher minimum density).

Although both wheat bran particle sizes produce bread doughs with reduced expansion capacities, a more drastic effect was observed with fine wheat bran than with coarse wheat bran. Figure 6.16 shows the time to average minimum dough density for each dough formulation using the Minorpin mixer. A decline in the time to reach minimum density was observed as %wheat bran added to dough formulations was increased; in other words, the ability to retain gas was lost sooner with bran in the formulation, and more so for fine bran.

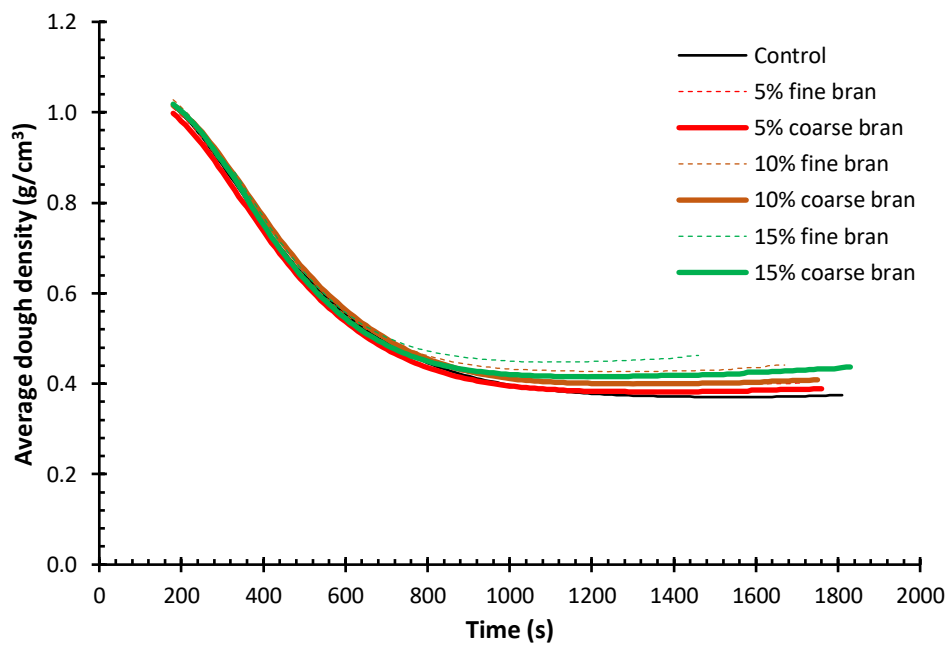


Figure 6.14: Effect of wheat bran on dough formulations using DDD system Sainsbury's flour

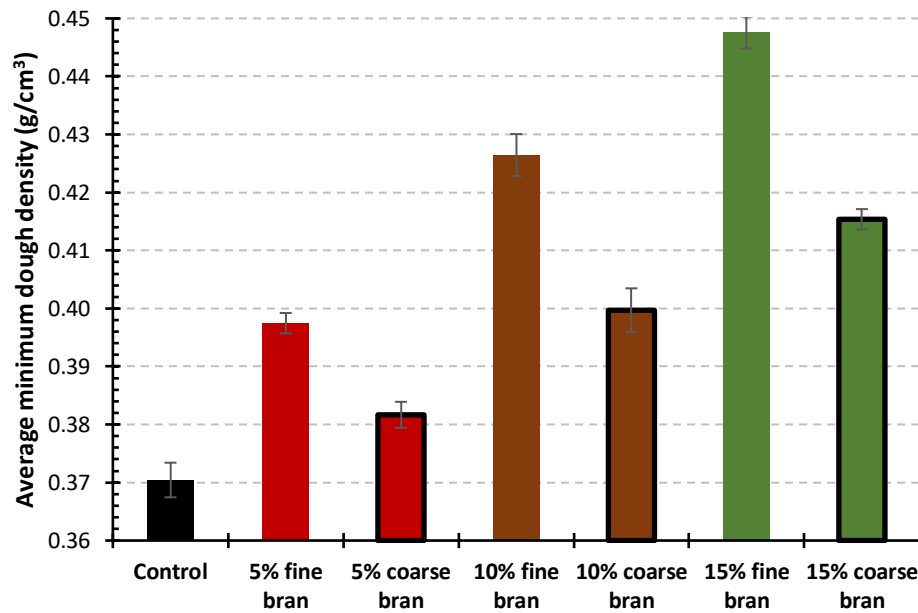


Figure 6.15: Average minimum dough density for wheat bran enriched formulations using Sainsbury's flour

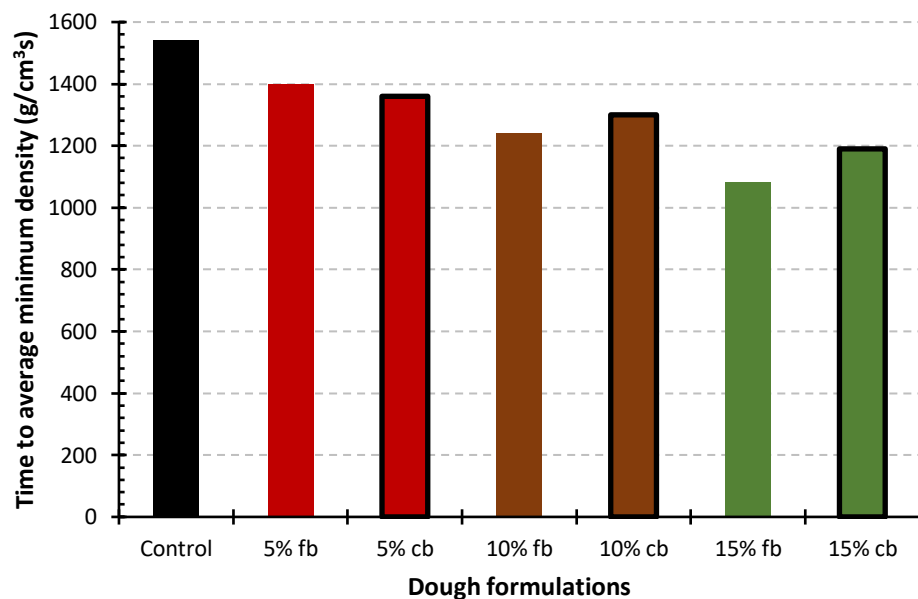


Figure 6.16: Average time to minimum dough density for wheat bran enriched dough formulations using Sainsbury's flour (fb: fine bran and cb: coarse bran)

The control doughs (in black in Figure 6.14) showed a density profile typical of those reported previously (Campbell *et al.*, 2008), in which the density shows a short lag before decreasing down to a minimum density. The lag occurs because

it takes a short time for the yeast to start producing carbon dioxide gas, which initially dissolves in the liquid phase of the dough before diffusing into the bubbles. As more CO<sub>2</sub> diffuses into bubbles, these grow, and the density of the dough decreases. Although the production of CO<sub>2</sub> by yeast fermentation/activation continues indefinitely, the dough reaches a limit to its capacity to expand and retain this gas. The minimum density indicates the maximum expansion capacity, which in this case occurred at a density of 0.3704 gcm<sup>-3</sup> after about 1800 s (30 minutes).

Figure 6.17 shows the effect of wheat bran on dough formulations using DDD system, Allinson flour and a Minorpin mixer. Clearly, it was observed that an increase in the %wheat bran added to the dough formulations results in an increased density profile for corresponding dough formulation samples. Figure 6.18 shows the average minimum density of each dough formulation enriched with either fine wheat bran or coarse wheat bran. Just as observed with Sainsbury's flour, an increase in the %wheat bran resulted in a drastic increase in the average minimum dough density of all dough formulations. Control dough (0.3844 g/cm<sup>3</sup>) and 5% coarse bran (0.3871 g/cm<sup>3</sup>) had similar dough minimum density (maximum expansion). This means that the amount of 5% coarse particles does not have much of an effect as the size could mean less of an amount is put and thus, no effect is observed. Also, fine wheat bran had more effect than coarse wheat bran on the expansion capacity of the overall dough formulation expansion capacity. This means that, fine wheat bran particles sizes had a more detrimental effect of bread doughs than coarse with bran. From the set of results obtained from Sainsbury's flour and Allinson flour, dough

formulations from Allinson flour showed a more detrimental effect than those obtained from Sainsbury's flour. This means that wheat bran enriched dough formulations from Sainsbury's flour expanded better than Allinson flour irrespective of the size of wheat bran used. Figure 6.19 shows the time to minimum dough density of all dough formulations using Allinson flour. The higher the %wheat bran added to each dough formulation; the lesser time required to attain the minimum density (Campbell *et al.*, 2008b,c).

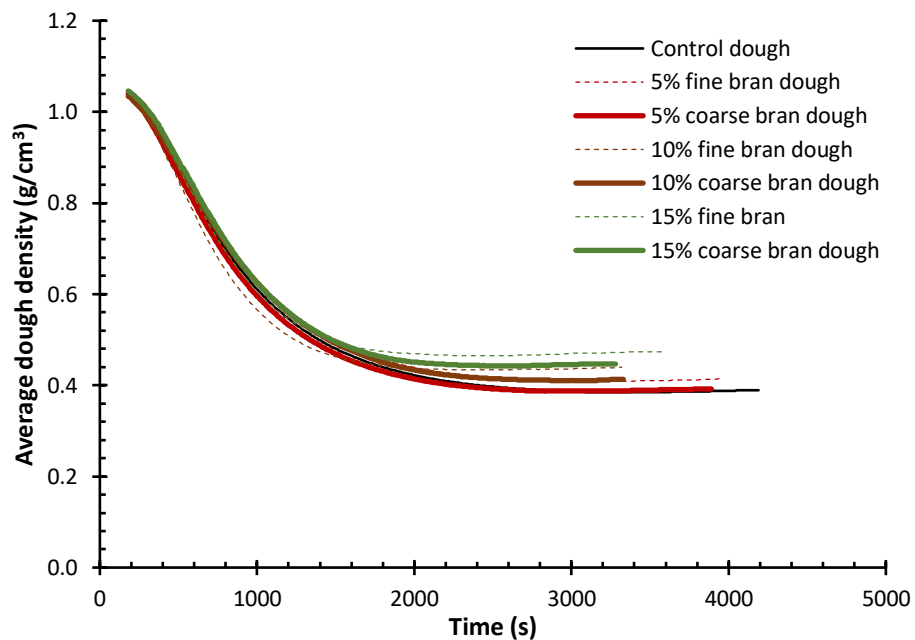


Figure 6.17: Dynamic dough density profile for wheat bran enriched doughs formulations using Allinson flour

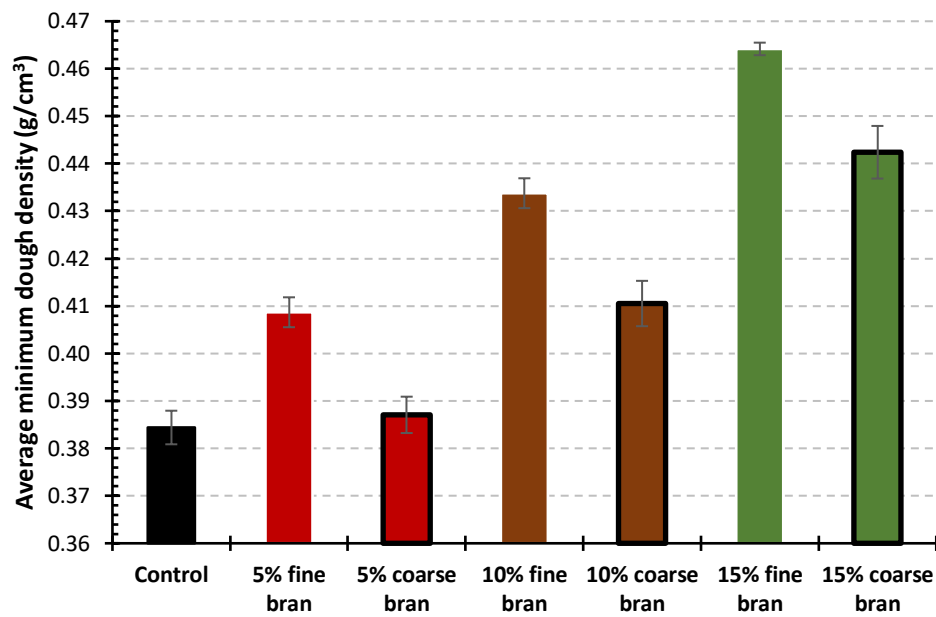


Figure 6.18: Average minimum dough density for wheat bran enriched formulations using Allinson flour

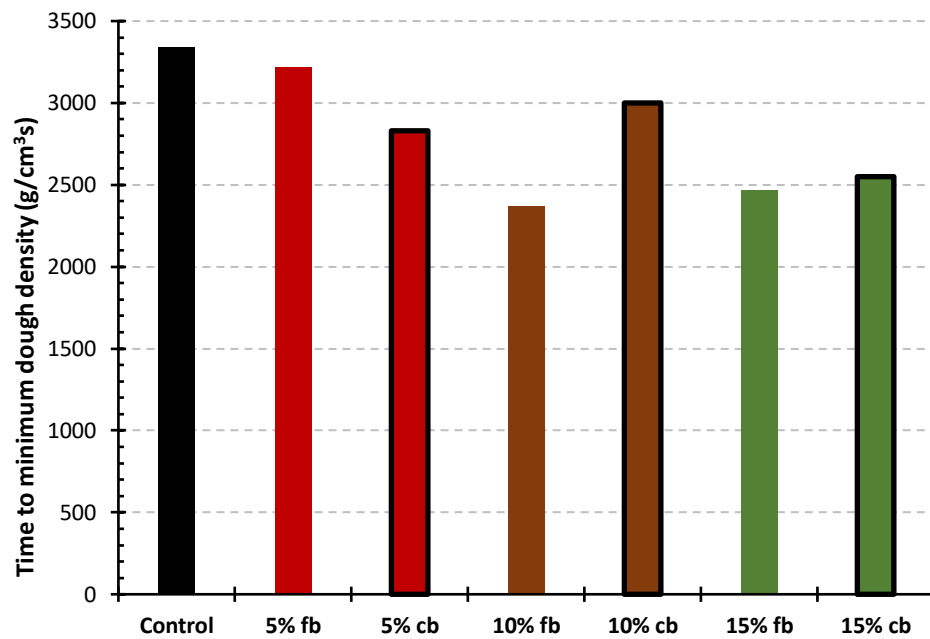


Figure 6.19: Average time to minimum density for all wheat bran enriched Allinson flour

Figure 6.20 shows the average minimum dough density for all wheat bran dough formulations using both Sainsbury's and Allinson flour respectively. The figure compares the minimum density of both flour types fortified with different

amounts and particle sizes of wheat bran. Clearly, the dough samples made from Sainsbury's flour produced better expanded bread doughs than samples obtained from Allinson flour.

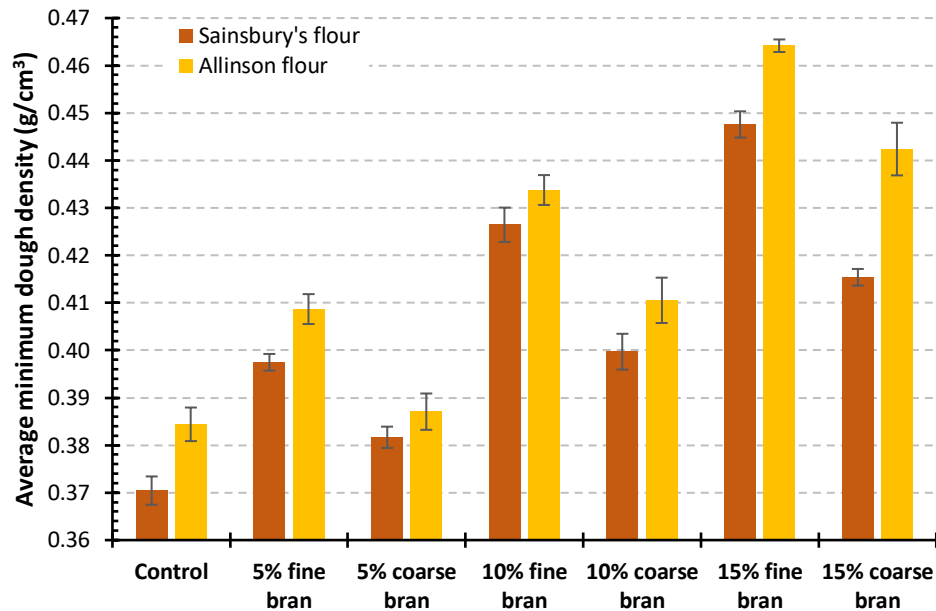


Figure 6.20: Minimum density comparison Allinson and Sainsbury's flour wheat bran

Addition of bran clearly reduced the ability of the dough to expand for both fine and coarse samples. It must be noted here that the water level was altered to allow for the water absorbing ability of bran. Thus, the decrease in expansion capacity is largely a result of the bran soaking up some of the water, making this unavailable for gluten formation within the main dough network. For the fine bran samples, it was observed that increasing the amount of fine bran in the dough formulation resulted in the expansion capacity decreasing. The minimum density of fine wheat bran for Sainsbury's flour increased from 0.3975 gcm<sup>-3</sup> to 0.4476 gcm<sup>-3</sup> while fine wheat bran for Allinson flour increased in density from 0.4087 gcm<sup>-3</sup> to 0.4642 gcm<sup>-3</sup>. This is accordance with previous

studies (Campbell *et al.*, 2008c; Packkia-Doss *et al.*, 2019). The same behaviour was observed for the coarse bran samples. Increasing the quantity of coarse bran in the formulation decreased the expansion capacity of the dough for both Sainsbury's and Allinson flour. Sainsbury's flour increased from 0.3817 gcm<sup>-3</sup> to 0.4154 gcm<sup>-3</sup> while Allinson flour increased from 0.3871 gcm<sup>-3</sup> to 0.4424 gcm<sup>-3</sup>. This increase was observed from the 5% to 15% wheat bran enrichment levels. It was also observed that 15% fine wheat bran samples from Allinson flour had the highest initial density value (0.4612 gcm<sup>-3</sup>). This means that the amount of bran in the dough formulations initiated an increase in the initial density leading to the lower expansion rates observed among the samples.

The minimum density of the control dough formulation for Sainsbury's flour was 0.3704 gcm<sup>-3</sup> which among all dough formulations had the lowest minimum density thus, the highest expansion capacity. This means that fortification of flour with bran (either fine or coarse) reduced the expansion capacity of bread dough. Irrespective of the kind or level of wheat bran used, uniform negative effects were observed. Thus, the higher the amount of wheat bran added to a dough formulation, the more damaging the dough structure becomes and the lower the expansion capacity.

The findings in this section were in agreement with previous studies, which tend to show fine bran as more damaging than coarse bran at an equivalent level (Campbell *et al.*, 2008c; Hemdane *et al.*, 2016); in general, the larger number of bran particles in fine bran influences more bubbles and hence has a greater

damaging effect on gas retention than the coarse bran where particle sizes are larger but less packed.

#### **6.5.7 Effects of type and level of arabinoxylan extract on dough expansion**

This section discusses the effects of type and level of arabinoxylans on bread dough expansion using the DDD system and the Minorpin mixer. Arabinoxylans were used in two forms, dry powder and dissolved into liquid. The reason for this was that after mixing the dough with AX in dry powder form, the AX particles were not only quite obvious, it was observed that AXs were not properly hydrated. Thus, instead of increasing the mixing time of the dough, AX was dissolved overnight in ultrapure water and the solution accounted for some part of the total water required for dough preparation.

Figures 6.21-6.30 show the effects of different AX samples on dough expansion and the time to maximum dough expansion.

Figure 6.21 shows the DDD profile of all dough formulations enriched with two types of AX (WBAX and SCBAX) and four levels of fortification. Clearly, the control dough had a distinct lower density profile compared to the both types of AX (WBAX and SCBAX). The AX samples took a longer time to reach minimum density as was observed from the DDD profile in Figure 6.23.

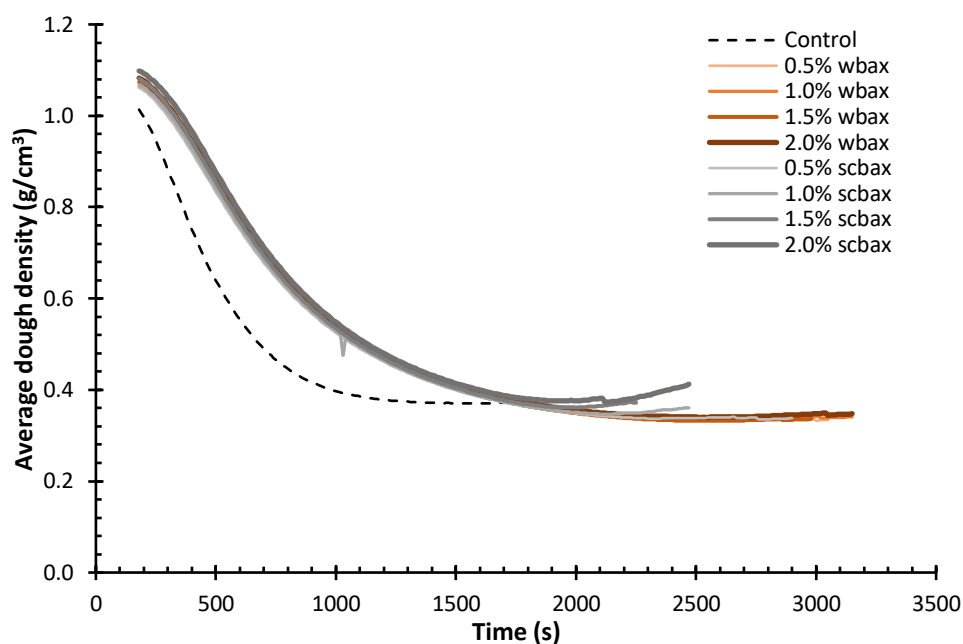


Figure 6.21: Dynamic dough density profile for dissolved AX enriched doughs formulations using Sainsbury's flour

Figure 6.22 shows the average minimum dough density for wheat bran AX and sugarcane bagasse AX dough samples. Interestingly, dough formulations enriched with either AX samples gave a much lower minimum dough density than the control dough. The only exception was 2% SCBAX ( $0.3728 \text{ gcm}^{-3}$ ) which had a minimum density similar to that of the control dough sample ( $0.3704 \text{ gcm}^{-3}$ ). 0.5% WBAX had the lowest minimum density ( $0.3321 \text{ gcm}^{-3}$ ) of all dough formulations. While little increase was observed as the % WBAX was increased, an increase was observed with the increase in %SCBAX in corresponding dough formulations. SCBAX had a more detrimental effect of dough expansion than with WBAX but better than the control dough. This means that the addition of AX into dough formulation increases the expansion capacity of the dough. It should be noted that very little amounts of AX were added to each sample (not

more than 2%) and this could be the reason for such amazing findings. Above 2% dough samples obtained with AX addition were observed to have an unpleasant texture and colour.

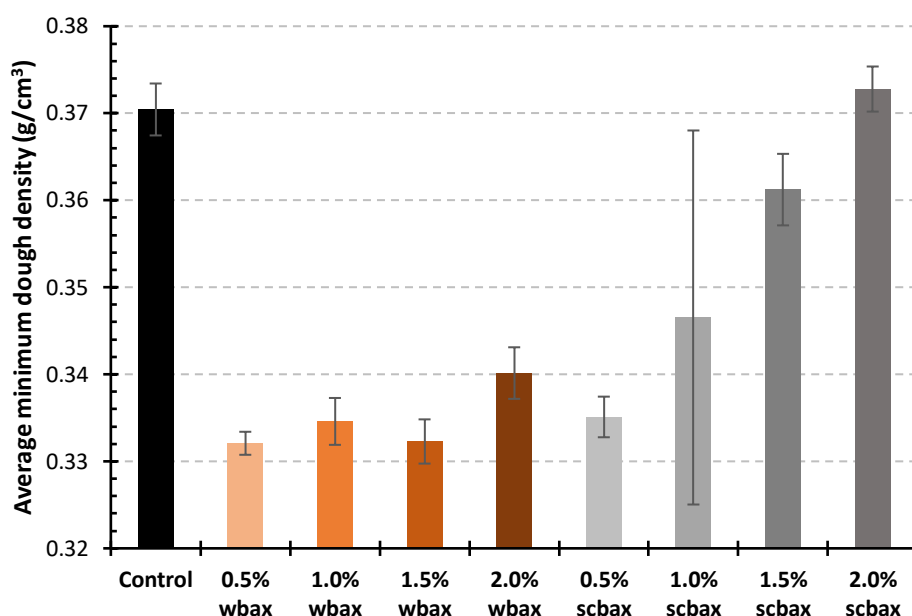


Figure 6.22: Average minimum dough density for dissolved AX enriched formulations using Sainsbury's flour

Figure 6.23 shows the time it took for each AX dough sample to reach its corresponding minimum density. Clearly, control dough sample was the fastest sample (1540 s) to reach its minimum density while 0.5% SCBAX took the longest time (2760 s) to reach its minimum density. All WBAX dough formulations took around the same time to reach individual minimum dough density while the time to reach the minimum density for SCBAX decreased with an increase in the %SCBAX in dough formulations.

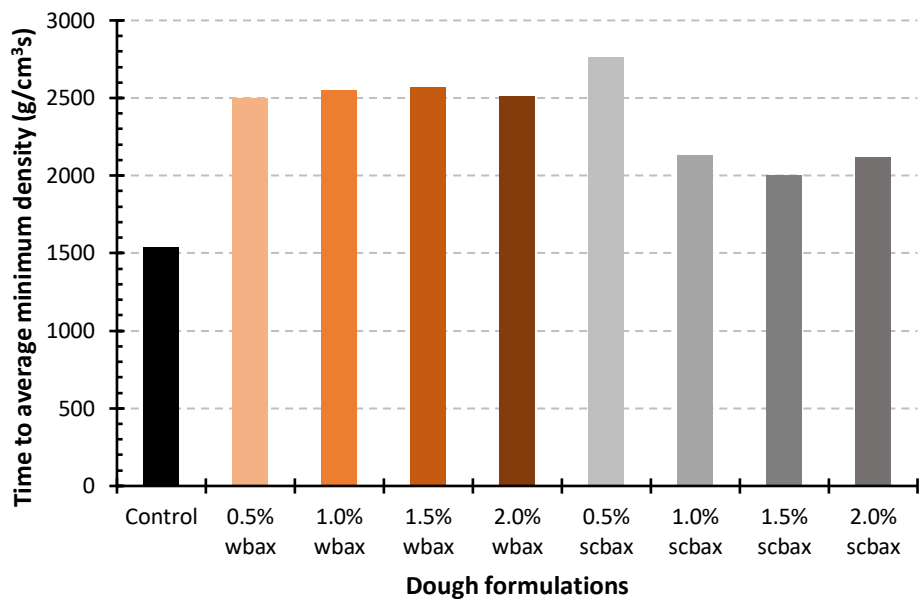


Figure 6.23: Time to average minimum dough density of dissolved AX bread dough formulations using Sainsbury's flour

Figure 6.24 shows the density profile curve for all arabinoxylans (WBAX and SCBAX) enriched dough formulations. AX used for these set of experiments were added in the form of dried powder just as the wheat bran samples. Clearly from the curves, WBAX were seen to have lesser dough density profiles compared to control dough and SCBAX dough samples. Although WBAX expanded better than other dough formulations, an increase in the amount of WBAX used in dough formulation preparation resulted in lesser expansion of the dough. Given that the AX added to dough formulations did not look properly hydrated after mixing, the decision was made to solubilize AX in ultrapure water over night instead of mixing for longer; as discussed earlier in section 6.4.3 (Table 6.3).

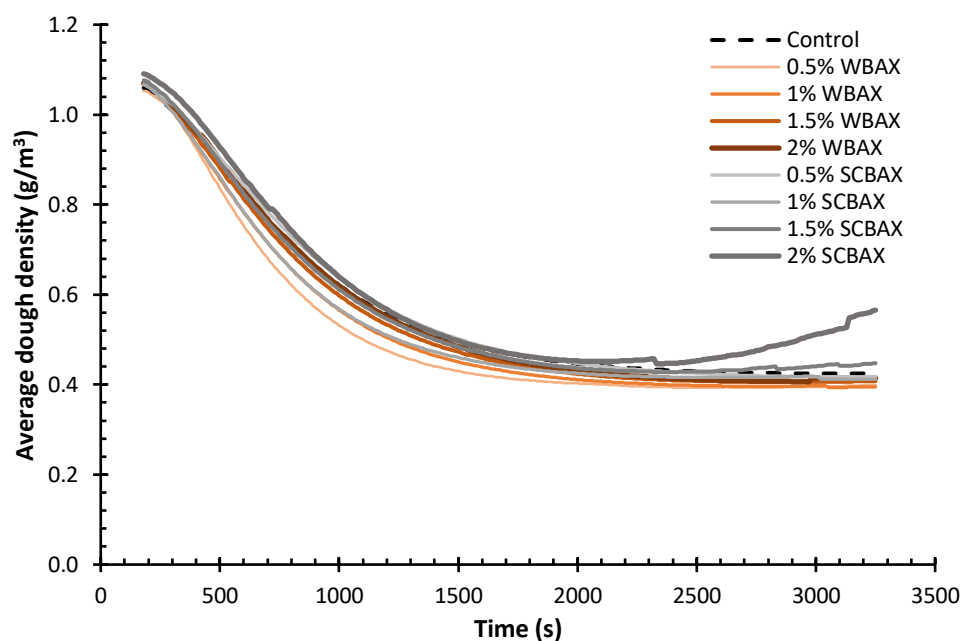


Figure 6.24: Dynamic dough density profile for undissolved AX enriched doughs formulations using Allinson flour

Figure 6.25 shows the minimum density of all AX enriched dough formulation and a control dough sample. Clearly, the AX enrich dough formulations have lesser minimum dough density when compared to the control dough sample. This means that better expansion was observed from bread doughs fortified with arabinoxylans. Also, better expansion was obtained from wheat bran arabinoxylans dough formulations than from sugarcane bagasse dough formulations.

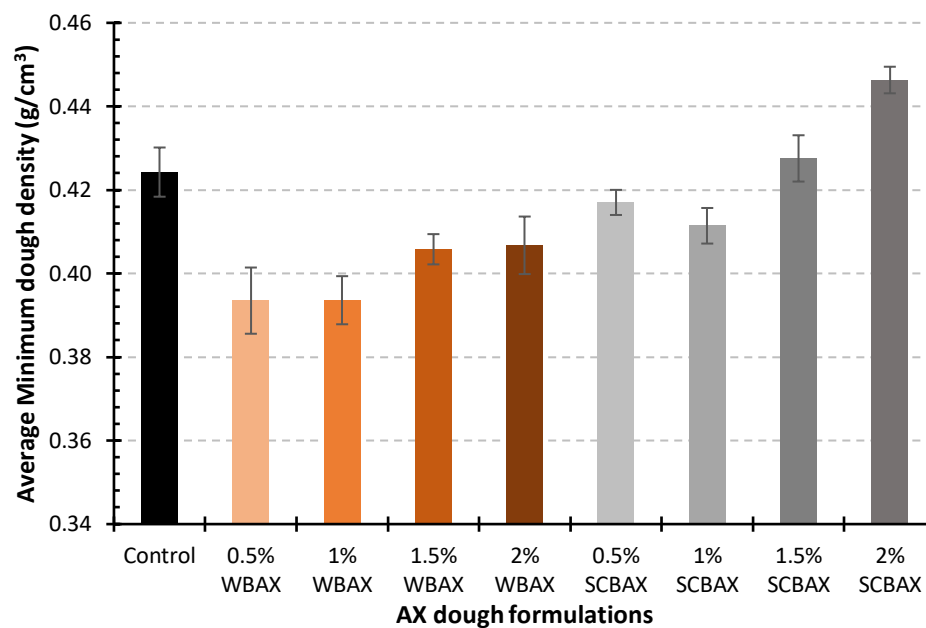


Figure 6.25: Average minimum dough density for undissolved AX enriched formulations using Allinson flour

Figure 6.26 shows the time to reach minimum dough density for all undissolved AX dough formulation. A good majority of dough samples took lesser time to reach minimum density when compared to the control dough samples. Only 1% SCBAX (3099 s) took a longer time to reach minimum density than the control dough sample (3090 s) while other samples reached corresponding minimum densities within shorter times.

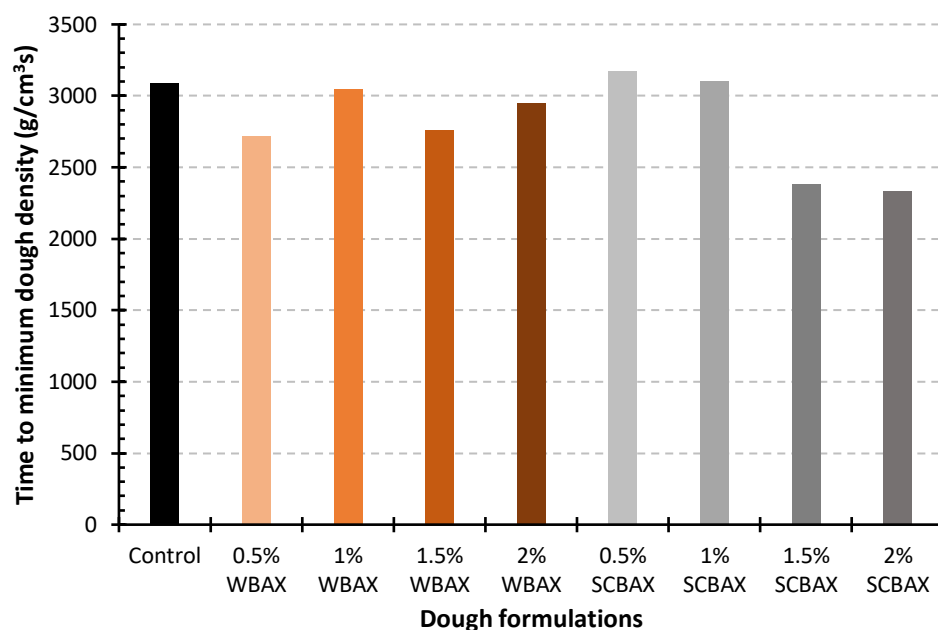


Figure 6.26: Time to average minimum dough density of undissolved AX bread dough formulations using Allinson flour

Figure 6.27 shows the dynamic density profile of all AX dough samples using Allinson flour. Arabinoxylans were dissolved overnight before being used to prepare bread doughs for this experiment. Clearly, a change in behaviour between the undissolved and dissolved AX dough formulations was observed. In the present experiment, the control dough samples showed a density profile lower than the AX enriched dough sample density profiles.

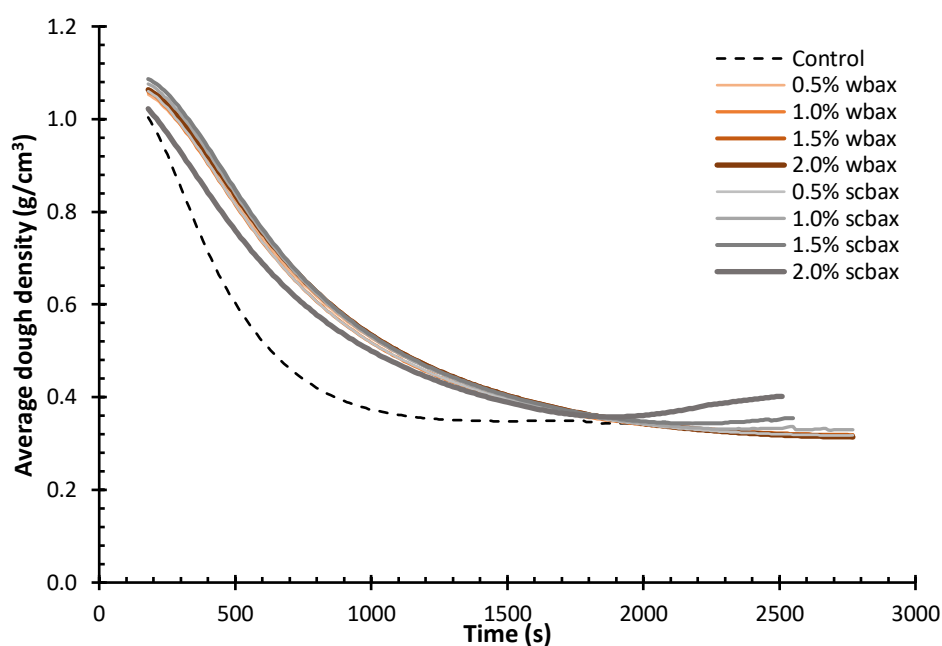


Figure 6.27: Dynamic dough density profile for dissolved AX enriched doughs formulations using Allinson flour

Figure 6.28 shows the average minimum dough density of all AX enriched dough formulations as well as a control dough. Clearly, wheat bran AX dough formulations gave better expanded dough according to the DDD system. An increase in the % WBAX (0.5% - 2%) added to dough formulations did not necessarily increase or decrease the expansion capacity of corresponding dough samples. In the case of sugarcane bagasse AX dough formulation, for every increase in the %SCBAX (0.5% - 2%) added to dough formulations, a corresponding increase in minimum density was observed. That means increasing the %SCBAX in dough formulation had a detrimental effect on dough expansion. 2% WBAX was observed to have the least average minimum dough density ( $0.3117 \text{ gcm}^{-3}$ ) while 2% SCBAX had the highest minimum dough density ( $0.3519 \text{ gcm}^{-3}$ ).

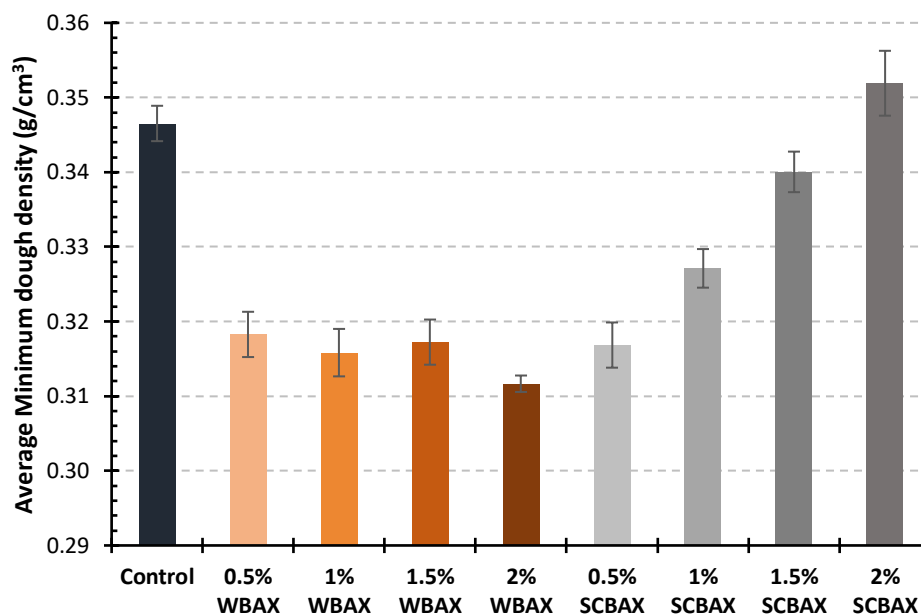


Figure 6.28: The average minimum dough density for dissolved AX enriched formulations using Allinson flour

Figure 6.29 shows the time it took for each AX dough formulation to attain minimum density (maximum expansion). Clearly, there was quite a difference in the times that each AX dough formulation reached its corresponding minimum density. Control dough was the fastest in reaching its minimum density (1850 s) although the expansion capacity was very minimal while 0.5% WBAX took the longest time to attain its minimum density (3360 s) compared to the other samples. No conclusive pattern was observed with WBAX dough samples while with SCBAX dough samples it was observed that increasing the % of SCBAX in dough formulations resulted in the minimum density being attained with relatively shorter time. This means that the addition of more SCBAX inhibited the expansion rate of the corresponding dough.

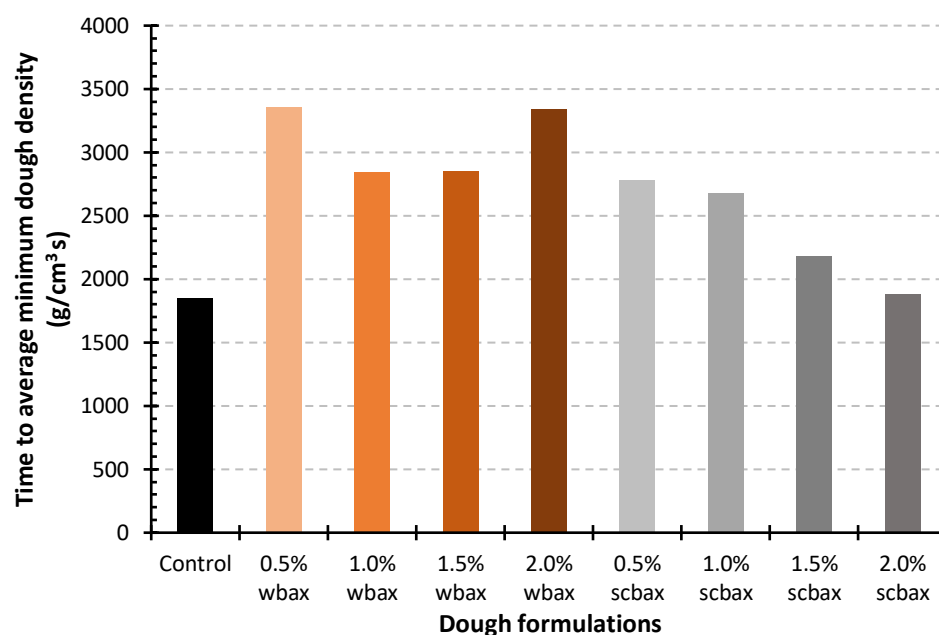


Figure 6.29: Time to average minimum dough density of dissolved AX bread dough formulations using Allinson flour and Minorpin mixer

The pattern observed in this last experiment was also the same as observed with Sainsbury's flour and Allinson flour with undissolved AX samples.

Figure 6.30 shows the average minimum density of all sets of experiment carried out to investigate the effect of AX on wheat bread dough expansion. Interestingly, dough samples prepared with Allinson flour and dissolved AX samples were observed to have the best expansion capacity while samples prepared with undissolved AX gave most of the worst results. All samples fortified with both AX showed similar patterns irrespective of flour type and state of AX. Results obtained from Sainsbury's flour did not provide a conclusive pattern although the AX samples used were dissolved. Undissolved AX dough samples were observed to have the most detrimental effects on dough expansion except for 1% WBAX, 2% WBAX and 1% SCBAX where Sainsbury's

flour was observed to produce the least expanded bread dough of all three samples.

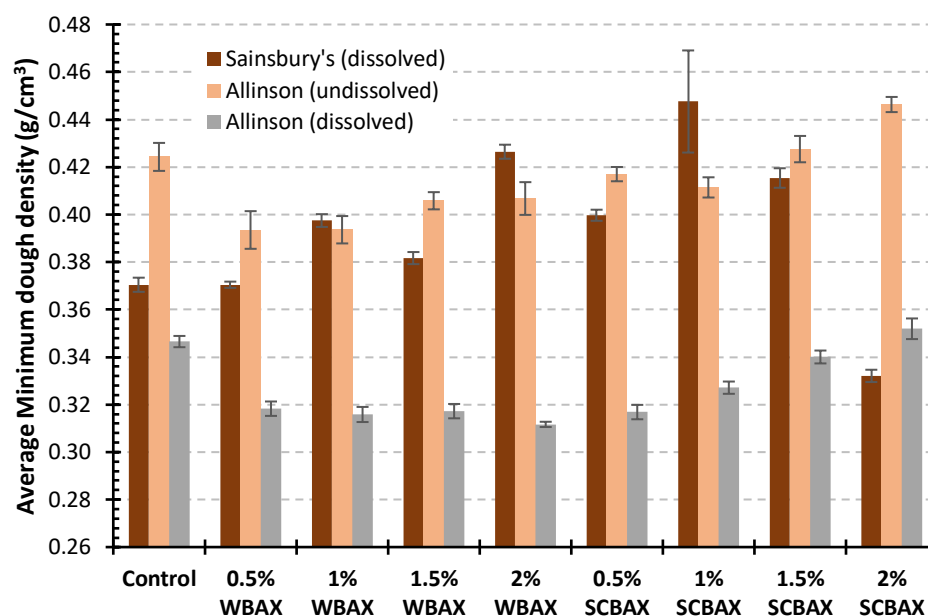


Figure 6.30: Comparison between all different flour types, amount of AX and state of AX in dough formulations

Overall, the DDD trials showed that AX slowed the growth of the dough piece, such that doughs were able to expand more than the control because they were expanding for longer, but higher levels of AX, whether from wheat or from bagasse, gave less expansion. The work clearly shows that DDD profiles are sensitive to the addition of AX, and that AX affects the ability of doughs to expand. It is likely that at least part of this decrease in expansion capacity arises from effects of AX on the dough rheology. Further evidence was therefore sought via oscillatory rheometry experiments.

### 6.5.8 Effects of bran on dough rheology

Figure 6.31 shows the strength of each dough formulation as obtained from the creep-recovery tests.

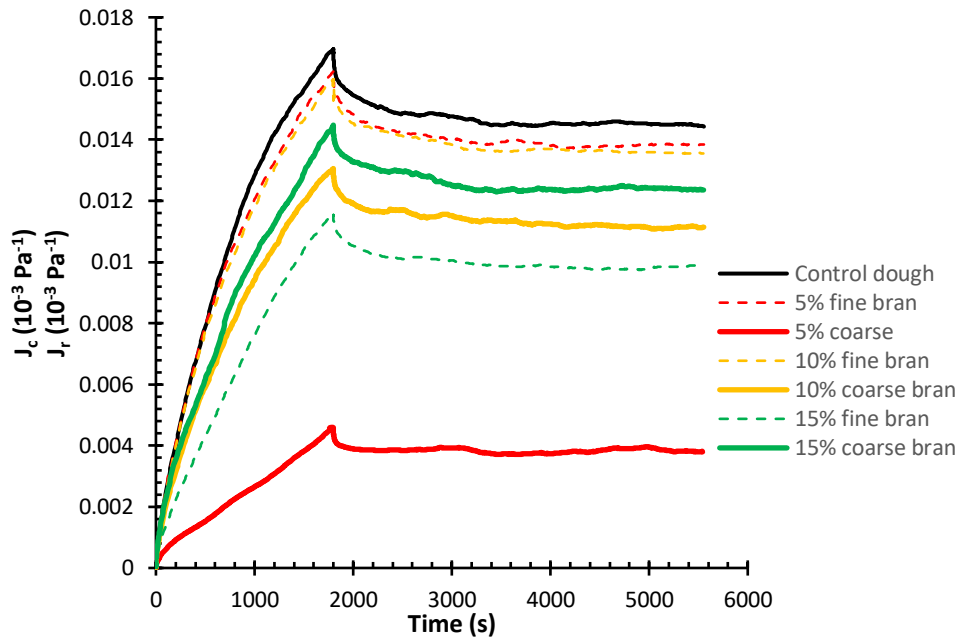


Figure 6.31: Effect of wheat bran on each dough formulation strength using creep-recovery test

Creep-recovery curves were recorded for each dough formulation in order to understand the effect of wheat bran on fortified dough strength. All experiments were carried out with the LVR (10Pa) and same conditions. The amount of water used for each formulation is the same as discussed previously. It was observed that with the addition of wheat bran, there was a decline in the creep compliance. While the control dough sample was observed to give the highest and steadiest creep compliance, the fine wheat bran dough formulations (thin lines) were observed to have slightly less creep compliance as compared with coarse wheat bran dough formulations (thick lines). Increasing the amount of fine wheat bran in dough formulations did not give as

much difference in creep compliance (except 15% fine bran) and it was also observed that with every increase in the amount of wheat bran, creep compliance reduced. The reverse was observed in the case of coarse wheat bran dough formulations. 5% coarse bran dough sample gave the least creep compliance and 15% coarse bran wheat sample gave the most compliance. This could be related to the results for 5% coarse wheat bran dough formulations from the SRC and DDD tests. In the SRC tests, 5% coarse bran was the only sample to give results that behaved as expected while in the case of DDD test, the results showed that this sample did not behave like the other samples, having the highest initial dough density. An explanation for this behaviour cannot be provided yet but further studies will be carried out to provide adequate interpretation.

The control dough sample was observed to have the highest recovery compliance among all the formulation (Figure 6.31). More recovery compliance was observed with the fine bran dough formulations (thin lines) than the coarse wheat bran dough formulations (thick lines) with 5% coarse wheat bran sample recovering the least. This means 5% coarse bran dough was affected the most by the creep-recovery test (most deformed), inhibiting the sample and not as much recovery as with other dough samples was observed.

Table 6.8 and 6.9 illustrate the effect of wheat bran on different dough formulations using the 4-parameter Burgers model. This gives an insight on the effect of bran on dough in regard to the instantaneous elastic compliance, retarded elastic compliance and retardation time at both the creep phase and

recovery phase. The superscript a, b, c, d or e and a, b or c for the creep phase and recovery phase respectively, signify the differences between the various dough formulations.

*Table 6.8: Effect of wheat bran on each dough formulation in the creep phase of the creep-recovery test using Burgers model*

<b>Creep phase</b>	<b><math>J_0 (10^{-4} \text{ Pa}^{-1})</math></b>	<b><math>J_1 (10^{-4} \text{ Pa}^{-1})</math></b>	<b><math>\lambda \text{ (s)}</math></b>	<b><math>\eta (10^3 \text{ Pas})</math></b>
Control dough	$3.37 \pm 0.29^a$	$173.30 \pm 47.24^a$	$930.80 \pm 176.11^a$	$643.47 \pm 119.57^a$
5% fine bran dough	$2.42 \pm 1.30^a$	$91.76 \pm 22.86^{a,b}$	$523.00 \pm 185.61^b$	$320.36 \pm 18.06^b$
5% coarse bran dough	$0.76 \pm 0.91^b$	$5.76 \pm 2.88^b$	$43.02 \pm 1.36^c$	$247.82 \pm 47.67^b$
10% fine bran dough	$3.04 \pm 0.29^a$	$104.60 \pm 52.33^{a,b}$	$405.60 \pm 59.65^{b,e}$	$228.37 \pm 45.51^b$
10% coarse bran dough	$0.78 \pm 0.14^b$	$26.86 \pm 41.74^b$	$296.70 \pm 192.50^b$	$231.14 \pm 53.45^b$
15% fine bran dough	$0.59 \pm 0.08^c$	$26.61 \pm 43.80^b$	$2.59 \pm 2.06^{c,d}$	$235.85 \pm 109.26^b$
15% coarse bran dough	$2.45 \pm 1.01^{a,b}$	$70.83 \pm 88.02^{a,b}$	$143.40 \pm 16.15^{c,d}$	$175.45 \pm 17.92^b$

Burgers model was fitted to the creep-recovery curves obtained from the different dough formulations. In the creep phase, with a change in dough formulations, significant differences were observed on all samples except the steady state viscosity ( $\eta$ ) where there was a significant difference between the control dough sample and all other wheat bran formulations, but not among the bran dough formulations. This means the steady state viscosity remains the same irrespective of the wheat bran type or amount, there is only a difference between the steady state viscosity of the control sample and wheat bran. Fortification of dough clearly influences the level of creep-recovery as observed by the curve in Figure 6.31 and also as observed from the model (Table 6.8 and

6.9). The control dough sample was observed to have the highest values for  $J_0$ ,  $J_1$ ,  $\lambda$  and  $\eta$ , while the results observed for the fine bran dough samples fluctuated for all parameters except  $\lambda$  where a reduction was observed with an increase in wheat bran in the formulations. For coarse bran dough formulations,  $J_0$  and  $J_1$  showed increase with increase in wheat bran amount, a decrease in  $\lambda$  values while  $\eta$  values were observed to fluctuate.

Table 6.9: Effect of wheat bran on each dough formulation in the recovery phase of the creep-recovery test using Burgers model

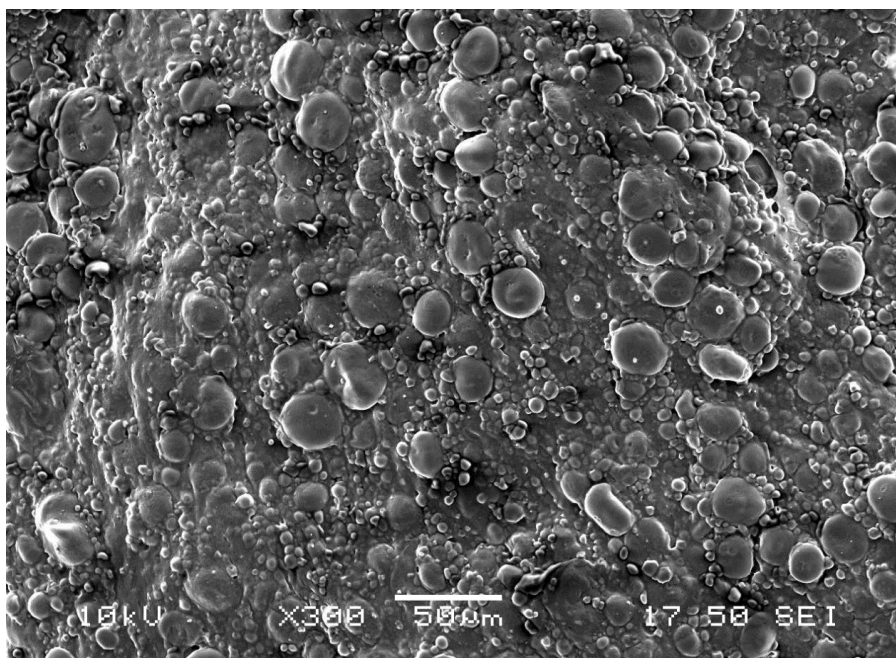
Recovery phase	$J_0 (10^{-3} \text{ Pa}^{-1})$	$J_1 (10^{-3} \text{ Pa}^{-1})$	$\lambda (s)$
Control dough	$14.55 \pm 1.56^a$	$2.09 \pm 0.26^a$	$307.80 \pm 26.90^a$
5% fine bran dough	$13.81 \pm 2.13^a$	$2.15 \pm 0.98^a$	$475.60 \pm 78015^b$
5% coarse bran dough	$6.15 \pm 2.81^b$	$1.89 \pm 0.53^a$	$94.28 \pm 39.13^c$
10% fine bran dough	$13.63 \pm 0.59^a$	$2.05 \pm 0.14^a$	$309.10 \pm 25.90^a$
10% coarse bran dough	$14.14 \pm 0.18^a$	$1.77 \pm 0.23^a$	$207.00 \pm 77.35^{a,c}$
15% fine bran dough	$11.85 \pm 0.62^{a,b}$	$1.54 \pm 0.18^a$	$230.20 \pm 32.55^{a,c}$
15% coarse bran dough	$12.37 \pm 3.30^a$	$1.82 \pm 0.18^a$	$578.50 \pm 49.40^b$

In the recovery phase, there was no significant difference observed between samples at the retarded elastic phase ( $J_1$ ) while the individual values of all fine wheat bran formulations for all three parameters reduced and coarse wheat bran formulation values fluctuated for  $J_0$  and  $J_1$  but increased values were observed for  $\lambda$ , thus significant differences were observed. This means retarded elastic recovery takes place at around the same time irrespective of the dough formulation.

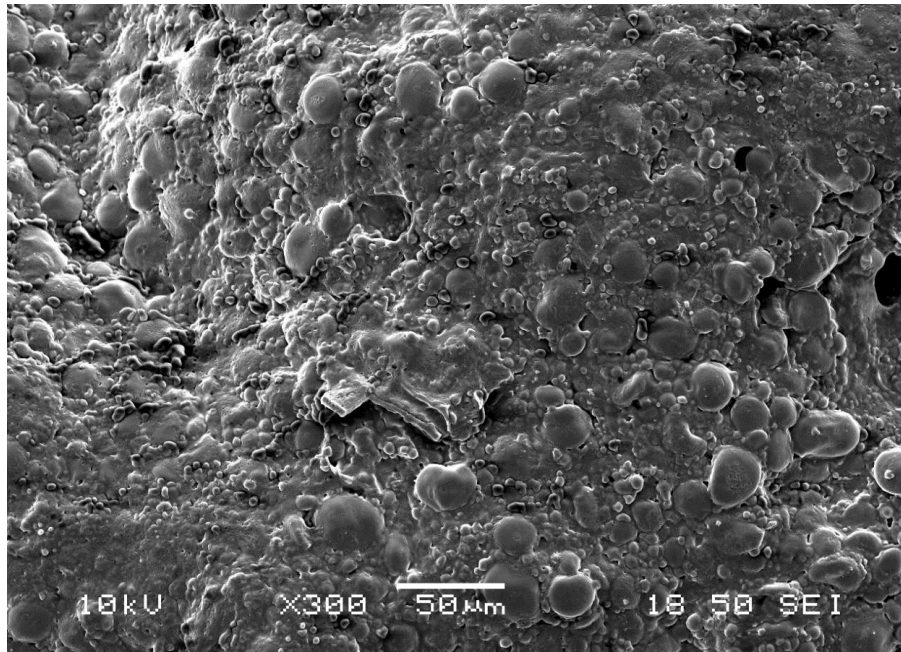
#### 6.5.9 Effect of wheat bran on dough microstructure using a scanning electron microscope (SEM)

The effect of wheat bran on bread dough formulations was also investigated by studying the effects of wheat bran at different levels and particle sizes on the microstructure of each corresponding sample. This investigation was only carried out on wheat bran dough samples and not arabinoxylan dough samples due to the limited amount of AX available for experimentation.

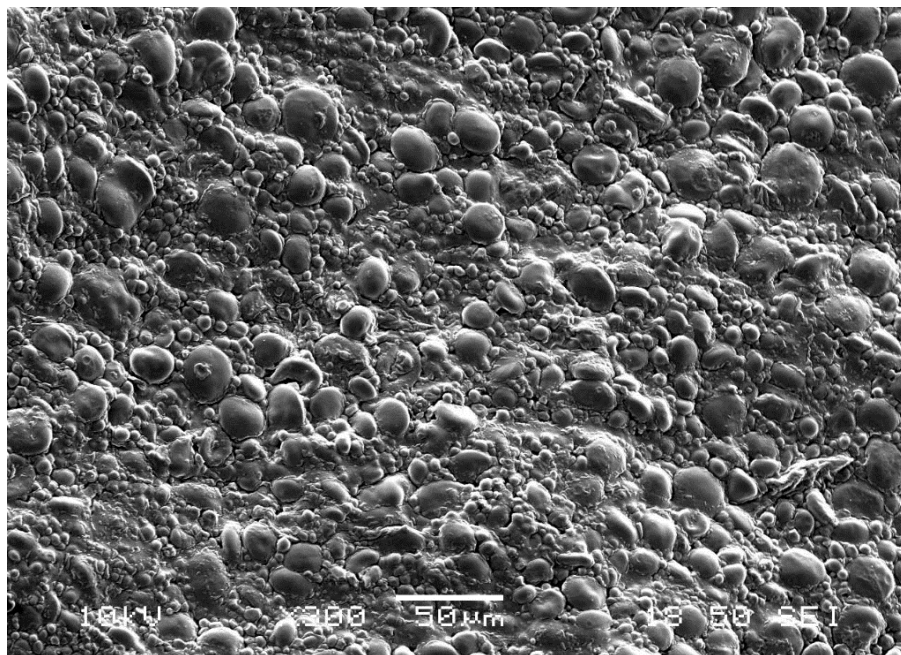
Figures 6.32-6.38 show the effect of wheat bran (fine and coarse) on dough microstructure using a scanning electron microscope (SEM) at a magnification of  $\times 300$ . While bran particles are evident in some of the image, the starch-gluten network looks very similar in all the formulations; addition of bran does not result in efforts that can be easily seen by SEM.



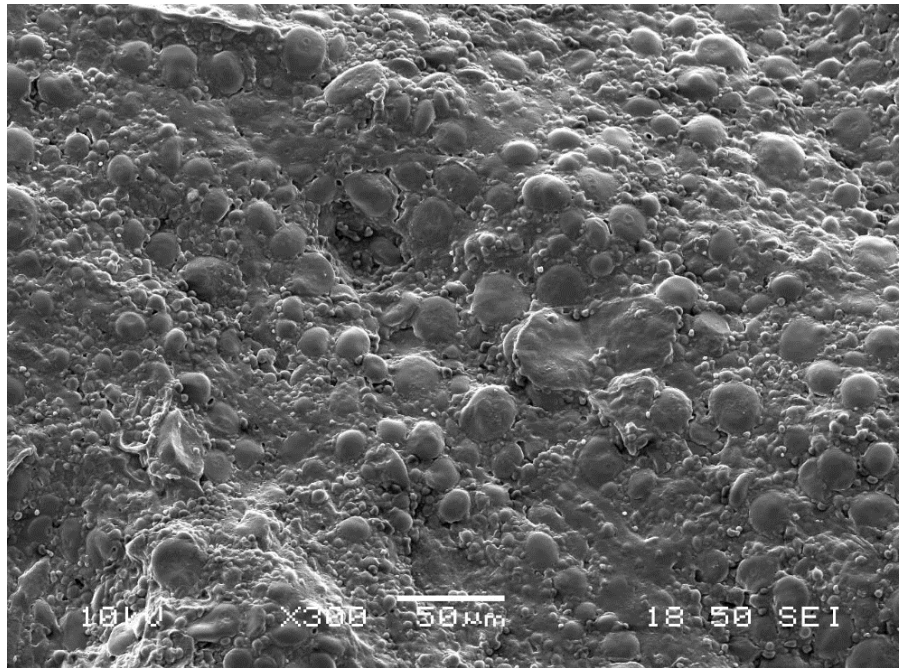
*Figure 6.32: SEM micrograph of control dough sample at a magnification of  $\times 300$*



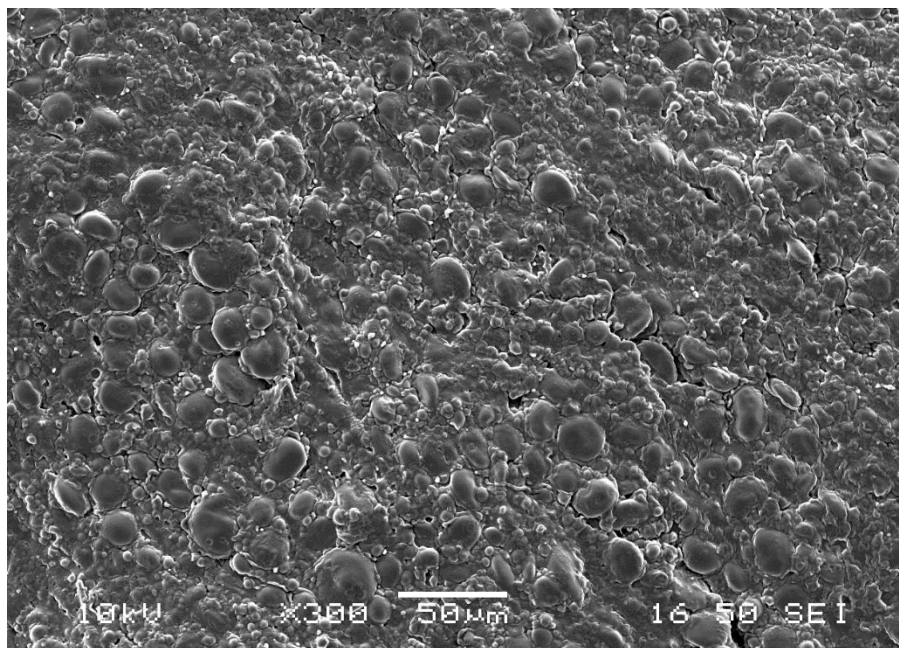
*Figure 6.33: SEM micrograph of 5% fine bran bread dough*



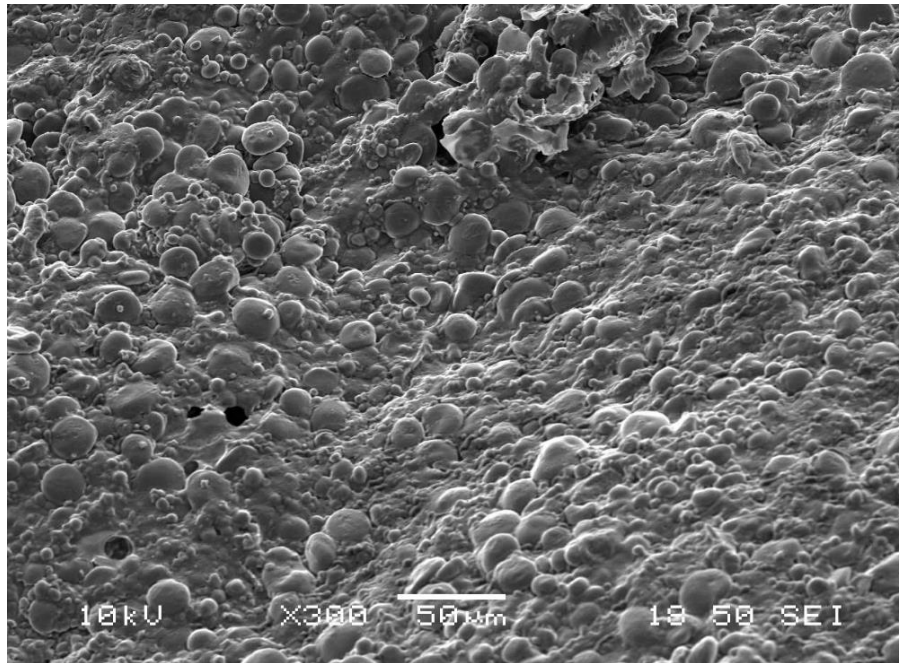
*Figure 6.34: SEM micrograph of a 5% coarse bran bread dough*



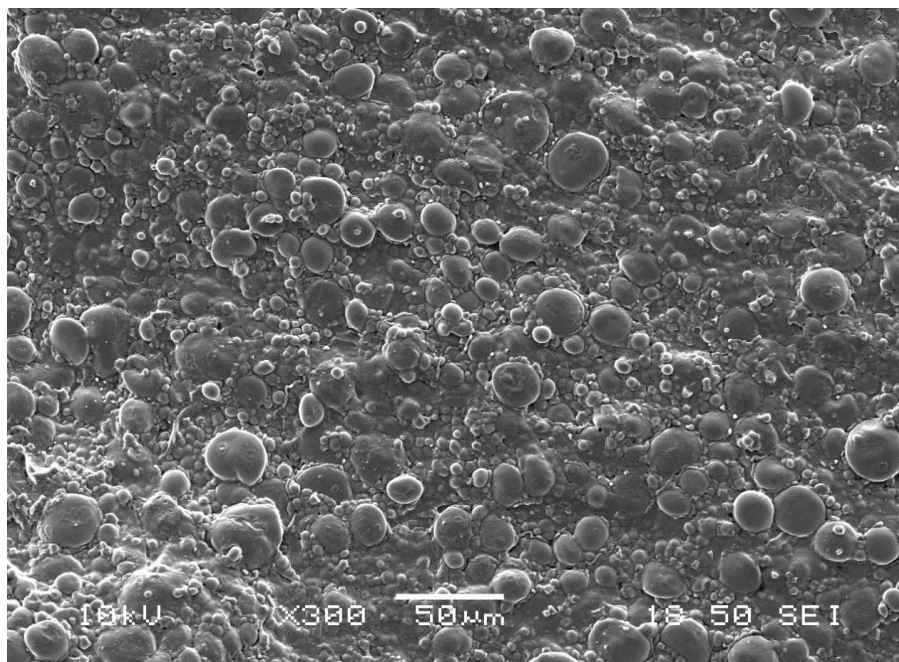
*Figure 6.35: SEM Micrograph of 10% fine bran bread dough*



*Figure 6.36: SEM Micrograph of 10% coarse bran bread dough*



*Figure 6.37: SEM micrograph of 15% fine bran bread dough*



*Figure 6.38: SEM micrograph of 15% coarse bran bread dough*

## 6.6 Summary

This chapter has presented a series of studies aiming to better understand the relationship between dough aeration and rheology when fibre is added in the

form of coarse or fine bran or as arabinoxylans. Initial studies using the Minorpin mixer were carried out to prepare samples used in each dough formulations to help understand better the results obtained from specific investigations. Wheat bran was milled from the original coarse particle size to produce a fine bran (size reduction) with the same composition.

Effects of wheat bran (fine and coarse), wheat bran AX and sugarcane bagasse AX on dough expansion capacity were measured using the Dynamic Dough Density system. Addition of wheat bran and AX samples inhibited CO<sub>2</sub> gas retention, resulting in a minimum density higher than the control sample, indicating lower expansion capacity. Rheological tests (amplitude strain-controlled sweep and creep-recovery tests) were carried out to determine dough LVR and the strength of the different dough samples respectively. Although a difference was observed between the control dough and bran-enriched doughs, there was no such difference observed between the different bran-enriched dough formulations in the creep phase. Thus, irrespective of the %bran added, a negative effect was observed.

Investigations were carried out to measure the effect of bran on dough aeration during mixing and effects of bran, SCBAX and WBAX on expansion capacity on yeasted bread dough during proving. For the measurement of the effect of bran on dough aeration during mixing, the Minorpin mixer was used to prepare the dough formations used as well as to prepare the dough formulations to measure the effect of bran SCBAX and WBAX on expansion capacity on yeasted dough during proving. The Dynamic Dough Density (DDD) system was used to

measure the expansion capacity of the yeasted dough samples during proving and identify the interactions between bran and arabinoxylans.

Fine bran had a higher minimum density than coarse bran irrespective of the flour type (Sainsbury's or Allinson) used. Both dissolved and undissolved AX dough samples showed the same expansion behaviour; WBAX dough samples expanded better than SCBAX. Dough samples made from Sainsbury's flour expanded better than Allinson flour samples.

The level of viscosity of AX samples was also obtained. Wheat bran arabinoxylan solutions were more viscous than sugarcane bagasse arabinoxylans and exhibited shear thinning properties. The higher the level of AX solution used for viscosity tests, the lower the shear thinning with increase. Viscosity decreased as the shear rates increased. WBAX produced more viscous solutions than SCBAX. The bread dough microstructure was reviewed for all dough formulations using Scanning electron microscope.

The next chapter outlines the use of a high-speed mixer (Tweedy 1) for dough development by investigating the effect of high fibre ingredients (wheat bran and arabinoxylans) of different particle sizes and levels on dough expansion and baking properties.

## **Chapter 7. Investigations using the Tweedy 1 mixer**

### **7.1 Introduction**

Dough development during mixing is often characterized in terms of the rheological changes occurring in the dough structure. A dough is said to be fully developed when its structure displays certain rheological qualities such as having high strength or extensibility. These rheology changes also affect air inclusion into dough during mixing; in short, dough rheology affects dough aeration (Campbell & Martin, 2012). Less widely acknowledged is that aeration may affect rheology (Chin & Campbell, 2005b) (Figure 2.3). Aeration provides baked products with their unique shapes, volume, texture and sensory attributes, and the aeration process is made possible by the rheological properties which result from the distinct gluten proteins of wheat flour. Both dough rheology and dough aeration have been widely studied (discussed in Chapter 2), but generally as separate topics. Consequently, the inter-relationships between dough rheology and dough aeration have not been fully proven. The changes in dough rheology observed during dough development have an effect on the gas bubbles incorporated during mixing, while the evolution of these bubbles into gas cells in the final baked loaf is the key relationship of dough aeration and rheology (Chin & Campbell, 2005b).

This chapter presents a series of studies that investigate dough aeration and rheology together. Section 7.2 introduces the differences observed with different mixing methods, specifically the high-speed mixing and low speed mixing in relation to fibre hydration. Differences in the mixer type and speed of

mixer used affects dough development. A further reminder of the uniqueness of the dynamic dough density (DDD) system is discussed in section 7.3 and how this unique piece of equipment was used for experiments in this chapter. Section 7.4 discusses the material and methods used for investigations in this chapter. Further to works discussed in chapter 6, section 7.5 investigates the effects of wheat bran and arabinoxylans (AX) in relation to particles size and type of sample on dough using the Tweedy 1 mixer. This section also investigates effect of bran and AX on dough expansion using the Tweedy 1 mixer and DDD system, the effect of wheat bran and AX on gas-free dough density and gas content at different pressures, the static as well as rheological studies on baked loaves using Texture Profile Analysis (TPA). The volume, resilience, texture during eating and taste of the baked loaf are all dependent on the final crumb structure (Scanlon & Zghal, 2001); some of these attributes are investigated in this chapter.

## **7.2 Differences between high speed mixing (mechanical dough development) and low speed mixing in relation to fibre hydration**

The mixing of ingredients is the most important stage in the breadmaking process, particularly for mechanically developed doughs such as in the CBP; Campbell & Martin (2012) described mixing as “the critical control point in no-time breadmaking processes (and) the most complicated of operations in the process”. For bakery products that require the development of smooth, elastic dough, mixing correctly is crucial (Cauvain, 2015). This is particularly true for doughs used in the production of bread products where the dough enables gas

retention during processes following mixing. Dough development is driven by changes in the wheat protein network (Campbell & Martin, 2012; Cauvain, 2003). Gluten is developed during the hydration of wheat flour proteins during mixing and further developed throughout the breadmaking process. Approximately 8-16% dry mass of wheat flour is flour protein and 80% of that directly produces gluten from hydration (Cauvain, 2003).

There are different types of dough mixers, these include those that generate low work inputs on the dough (such as hand mixers or small-scale mixers) and those that generate a greater work input on dough (such as Tweedy-type mixers). The major differences between these two types of mixers are the dough development time, speed of mixing, effect of mixing blade, shape of mixing bowl and the level of dough development (Alava *et al.*, 2001; Cauvain, 2003). Doughs produced from low work input mixers take a longer time to produce a homogenous and properly developed dough compared to mixers of greater work input (Cauvain, 2003). With high speed mixing, unlike low speed mixing a fermentation phase is not required as development of the gluten network occurs within the mixing bowl (Alava *et al.*, 2003). Dough development and thus fibre hydration take place all at once for high speed mixers, in contrast to mixing using a low speed mixer where a fermentation stage is required for proper dough development. In the case of the high-speed mixer, the mixer blade acts as a need which encourages dough development faster than in the case of a low speed mixer.

In most western countries, industrial breadmaking is carried out using mechanical dough development processes (MDD). This is achieved by the

exertion of high work input over a very short period of time (Wilson *et al.*, 2001). The main high speed mechanical dough mixing process used in the UK is the Chorleywood Bread Process (CBP) (Alava *et al.*, 2001). Dough aeration studies were first investigated by Baker and Mize before the introduction of the Chorleywood Bread Process (Chamberlain *et al.*, 1962a,b; Chin *et al.*, 2004; Martin *et al.*, 2004). This CBP was introduced in Chapter 2 and is discussed more extensively in this section.

The work input exerted on a flour during mixing is known as the energy required to reach the peak of the torque as dough is formed. Hence when mixing dough, the resistance observed by the mixer increases to a peak then decreases. In order to be more efficient, dough work input is determined on a laboratory scale rather than on an industrial scale (Wilson *et al.*, 2001; Wilson *et al.*, 1997). The CBP is a type of mechanical dough development process where the work input is exerted intensively to develop dough using high speed mixers (Burth, 1971; Chin *et al.*, 2004; French & Kemp, 1985). A unique feature of CBP is its ability to mix under partial vacuum and also under positive pressure. The ability of the CBP to develop dough at positive pressures was determined by Chin *et al.* (2004) after numerous studies on the effect of mixing under partial vacuum on dough development using the CBP (Campbell *et al.*, 2001, 1993; Cauvain, 1994; Cauvain, 2003; Chamberlain, 1975; Chamberlain *et al.*, 1962a; Chamberlain, Collins, & Elton, 1967; Chin & Campbell, 2005b; Chin *et al.*, 2004; Chiotellis & Campbell, 2003b; Gan, Ellis, & Schofield, 1995; Zounis & Quail, 1997).

The Tweedy type mixer is the most common type of mixer used for mechanical dough development process of high speed industrial mixers and was designed based on the Chorleywood Bread Process (adopted by the UK, New Zealand, Australia, South Africa and Israel) (Wilson *et al.*, 2001, 1997). The Tweedy-type mixer is unique for having a distinct mixing action, an approximately constant motor torque while producing a consistently textured dough (Chin *et al.*, 2004). Tweedy 10 mixer was designed to mix doughs based on 4.54 kg (10 pounds) of wheat flour giving a highly consistent dough at a very high mixing speed (Chin *et al.*, 2004). The industrial dough mixer (Tweedy mixer) was found to result in less sensitive mixing scale than the laboratory scale mixing and thus concluded to be better for developing a variety of flours (irrespective of wheat breed, cultivar and type) (Chin *et al.*, 2004; Martin *et al.*, 2004). This is a very beneficial attribute of the Tweedy mixer to the food industry. The sensitivity of the laboratory scale mixer is greater for research purposes and thus, a better to use in food research facilities (Chin *et al.*, 2004). Since scientific research entails the finding and understanding of intrinsic details of any given focus, having a mixer type that is sensitive enough to aid in the analysis of the effects of varying factors to flour, dough and eventually bread. This will bridge the gap between the wants/needs of the industrial scale mixer and laboratory scale mixer, enabling appropriate design of protocols for bread dough production (Wilson *et al.*, 1997).

Dough mixers can be classified based on the type of mixer blade. A high speed mixer produces a proper homogenous and well developed dough in less than 5 minutes while a low speed mixer requires up to 10 minutes of mixing to produce

a dough of similar quality. Interestingly, the University of Huddersfield is the only academic institution to have a very small Tweedy type mixer (specifically a Tweedy 1 mixer, scaled down to size suitable for mixing doughs based in 1 pound (454 g) of flour, although in the current work 400 g of flour was used); this mixer type is not the most common type. This Tweedy 1 mixer was used for all experiments discussed in this chapter which is a scaled down version of the Tweedy 10 mixer used industrially. The names Tweedy 1 or 10 are solely based on the dough capacity in pounds (i.e. a Tweedy 1 can produce a pound of dough while a Tweedy 10 mixer produces 10 pounds of dough with one mixing).

The Henry Simon Minorpin mixer (Figure 4.3) an example of a low-speed mixer (Zounis & Quail, 1997), basically behaves in a contrasting way to how the high-speed MDD process occurs. This mixer has a base, mixing bowl, top-plate and housing. The revolving head has two pairs of pins rotating in a planetary motion while the mixer bowl has three stationary pins which function to prevent excessive and uncontrolled movement of the dough by the mixing head. The bowl is located within the housing by a quick release device.

Table 7.1 shows the different parameters that distinguish a low speed mixer from a high speed mixer. The characteristics of three different mixer types for each mixer speed has been stated. Major differences between both are the mixing times and volumes.

*Table 7.1: Details of low and high speed mixers used in bread dough experiments (source: Chin, 2003)*

Mixer name	Low speed			High speed		
	Henry Simon Majorpin	Henry Simon Minorpin	Brabender Farinograph	Tweedy 1	Tweedy 10	Tweedy 35
<b>Mixer bowl</b>						
Diameter (mm)	250	115		140	306	429
Height (mm)	175	70	140	126	296	408
Width (mm)			130			
Length (mm)			160			
<b>Mixing volumes (g flour)</b>	400	60	300	380-400	4000	11000
<b>Mixing time (min)</b>	5-20	5-20	3-18	2-5	2-5	2-5
<b>Blade speed (rpm)</b>						
Loaded	52	144		733	360	
Unloaded	102	214	60	747	383	~ 383

Figure 7.1 shows the mixing bowl of the Tweedy 1 mixer with the z-blade which is one of the mixers used in studies in the current chapter. Figure 7.2 shows the lid of the mixer with all the pin that help ensure pressure and vacuum mixing is possible in this type of mixer.

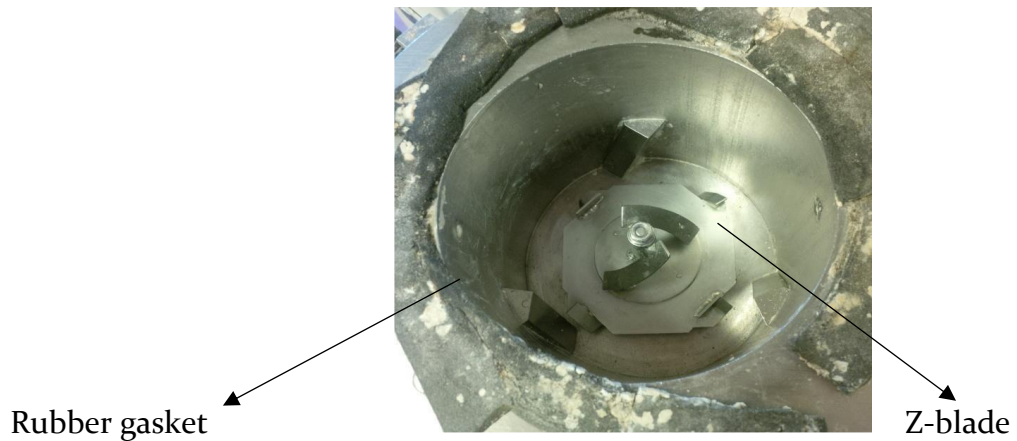


Figure 7.1: Tweedy 1 mixer bowl

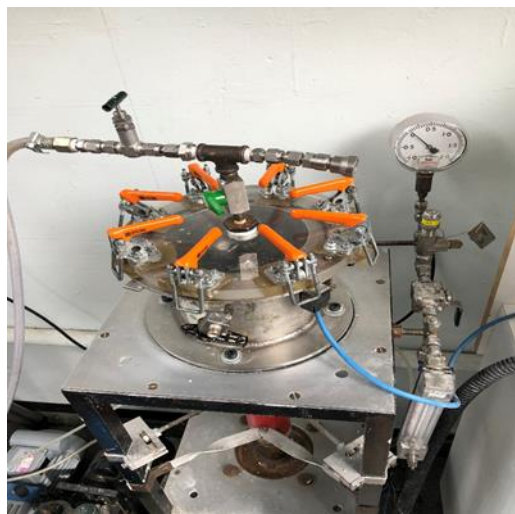


Figure 7.2: Tweedy 1 mixer stand

### 7.3 Effects of particles on dough aeration and rheology

Although AX has been found to play a key role in bread and dough quality (Döring *et al.*, 2016; Döring *et al.*, 2015; Izydorczyk & Biliaderis, 1992), detrimental effects have also been recorded. The most detrimental effects in bread dough quality have been observed at very high levels of AX concentrations and disrupts the gluten network formation as dough development occurs during mixing and proving (Döring *et al.*, 2015). This could also affect the entire breadmaking process as the dough properties are

inherently damaged as the AX competes for water just like wheat bran for purposes of hydration (Biliaderi & Izydorczyk, 2006; Biliaderis *et al.*, 1995). This effect is solely observed in wheat dough where dough extensibility and gluten yield are extensively influenced by the presences of AX (Döring *et al.*, 2015; Michniewicz, & Bushuk, 1991; Wang *et al.*, 2003). For this reason, determining the amount of additional water needed for each AX-dough formulation is very important as the excess water accounts for the AX hydration and hence appropriate dough development.

The Dynamic Dough Density (DDD) system (Figure 6.4) discussed in section 6.3 was the major tool used to study the effects of wheat bran and two types of arabinoxylans on bread dough expansion using the Tweedy 1 mixer. With the Tweedy 1 mixer being a high-speed mixer, studying how this development is affected by the addition of AX and wheat bran could help in the overall understanding of the final baked loaf.

#### **7.4 Materials and methods used for Tweedy 1 mixer studies**

This section details the materials, equipment and methods used to investigate the effects of wheat bran and arabinoxylans (WBAX and SCBAX) during proving. This proving stage is mimicked by the DDD system while expansion is being measured simultaneously. Studies looked at effects of particle size, type and concentration of both wheat bran (fine and coarse) and AX (WBAX and SCBAX) dough formulations. Most of the materials, equipment and methods

used in this Chapter were the same as used in Chapter 6 except the Tweedy 1 mixer and the Texture analyser used for rheological studies of baked loaves.

The milling and particle size determination (Section 6.4), weighing equipment (Section 6.4.1) and all compositional specifications (Section 6.4.2) were the same as the sample were used for experiments. The following sections describe the procedures used to measure aeration during mixing, gas expansion during proving and to prepare final baked loaves.

#### **7.4.1 Dough preparation**

Dough samples were prepared similarly to samples used in Chapter 6. Two types of flours (Sainsbury's and Allinson flour) as well as sugar (1.5%), salt (1.6%), fat (5%), yeast (4%) and water were used, as listed in Table 7.2. List of ingredients and each source is the same as Table 6.1 and just like section 6.4.3, wheat bran and AX samples were substituted for corresponding amounts of flour. The Tweedy 1 mixer was used for all experiments in this Chapter (described in Section 7.2). All ingredients were based on 400 g flour weight. Dry samples were put in first followed by yeast solution and AX solution and all rinsed with the extra water left if any. Samples were mixed for three minutes at atmospheric pressure in the airtight Tweedy 1 mixer bowl. After mixing, dough samples were placed on a clean surface between two steel rods and a clear plastic rolling pin used to roll the dough to a uniform thickness of 12 mm. With the use of a cylindrical steel cutter, two dough samples between 4-6 g were cut and placed in a flat-bottom flask then swirled for 30 seconds before being transferred to the DDD system.

Given that more water is required as dough samples are being fortified with different concentrations and types of fibre, accounting for the extra water required was a very important part of understanding the effects of these fibre samples on bread dough. Table 7.2 below shows the amount of flour and fibre needed as well as the water adjustment levels.

*Table 7.2: List of ingredients and the amount of water required for each dough formulation*

<b>Dough formulation</b>	<b>Quantity of flour used (g)</b>	<b>Quantity of fibre used (g)</b>	<b>% water required</b>	<b>Water required (g)</b>
Control	400.00	0.00	61.00	244.00
5% wheat bran	380.00	20.00	63.50	254.00
10% wheat bran	360.00	40.00	66.00	264.00
15% wheat bran	340.00	60.00	68.50	274.00
0.5% AX	398.00	2.00	61.25	245.00
1% AX	396.00	4.00	61.50	246.00
1.5% AX	394.00	6.00	61.75	247.00
2% AX	392.00	8.00	62.00	248.00

Works from Döring *et al.* (2015); Michniewicz *et al.* (1991) and Wang *et al.* (2003) have stated the different possible effects of AX on dough and one factor that was agreed on by all authors was the issue of lack of dough hydration and gluten network development. For this reason, increasing the amount of water used while preparing dough formulations was proposed and the table above (Table 7.2) accounts for that this extra % of water.

While increasing the amount of water has been accounted for, it was observed that mixing AX samples directly as part of the dough formulation did not give the AX enough time to hydrate and mix in properly. Also, AX particles were observed as unattractive individual dots all over the dough. For this reason,

dissolving the arabinoxylans samples overnight was decided on. This gave the opportunity of AX samples to be properly hydrated, increasing the prospects of an adequately mixed dough. The amount of water used was also accounted for from the total amount of water required for each dough formulation. The dissolved AX sample solutions were made based on the total amount of water (61%) of the control dough (244 g) and on the fact that some of the total amount of water was also used for yeast solution preparation. Water calculations for arabinoxylan experiments using the Tweedy 1 mixer were made up of:

### **Control**

- Flour weight = 400 g (100%)
- Water = 244 g (61%)
- Salt = 6.4 g (1.6%)
- Yeast = 8 g (2%) or 16 g (4%)
- Sugar = 6 g (1.5%)
- Fat = 20 g (5%)

Note: 2% yeast was used for baking trials and 4% for DDD tests because double the yeast concentration is needed to speed up the test.

For experiments concerning wheat bran dough formulations and containing 8 g of yeast in solution while making available an adequate amount of water for hydrating samples before dough preparation, the 8 g of yeast comes from 1000 g of yeast solution (which is 80 g suspended in 920 g water) while the other 92 g is water. This 100 g will contain 8 g yeast and 92 g water. This leaves 152 g water to be added to the dough formulation to give a total of 244 g.

In the case of AX dough samples, in order to increase the amount of water available to dissolve AX while also obtaining the right amount of yeast required

for each formulation, the yeast solution concentration was doubled (160 g of yeast suspended in 840 g of distilled water). 8 g of yeast was therefore provided by 50 g yeast solution, with the other 42 g being water. The total water requirement at 61% water absorption is 244 g; hence this leaves 202 g of water available for solubilizing AX samples (WBAX and SCBAX) (Table 7.5). However, adding fibre requires an increase in the base water absorption.

In the case of wheat bran fortification, following Campbell *et al.* (2008b,c) the amount of water was increased by half the % of wheat bran to be used (that is, if 5% wheat bran was to be added, an extra 2.5% water would also be added to account for wheat bran hydration and sufficient gluten development). The same formulation was tried for AX samples and was found not to be sufficient. Increasing the amount of water by the same amount of AX was also proposed but that was also found not be sufficient to give adequate gluten development. Following guidance by Biliaderis *et al.* (1995), it was decided to increase the amount of water by an amount of 2.5 times the level of AX added. All AX solutions were prepared the night before and left overnight to hydrate and completely dissolve. This was done because initial trials where AX samples were added directly were observed to remain as particulates and not have any effect on dough. For this reason, solubilising the AX samples before adding into dough formulations was trialled and observed to have an effect on dough.

In summary, three different water adjustments were investigated when adding AX: increasing water absorption by half the AX percentage (in line with the

practice for bran), by equal to the AX percentage, and by 2.5 times the AX percentage (following Biliaderis *et al.*, 1995).

Table 7.3 illustrates the calculations when the amount of water was increased by an amount equal to the level of AX addition. For example, if adding 2% AX, increase water absorption by 2%, which equates to an extra 8 g water for a dough based on 400 g flour. The total water absorption increases to 63% or 252 g, of which 42 comes from the yeast solution, leaving the other 210 g to dissolve the AX.

Table 7.3: Water calculations for dissolved AX experiments in which the water absorption was increased by a percentage equal to the percentage of added AX.

	Flour (g)	Water absorption (%)	Dissolve (g)	in water (g)
<b>Control</b>	400	61.0	0	160
<b>0.5% WBAX</b>	398	61.5	2	162
<b>1.0% WBAX</b>	396	62.0	4	164
<b>1.5% WBAX</b>	394	62.5	6	166
<b>2.0% WBAX</b>	392	63.0	8	168
<b>0.5% SCBAX</b>	398	61.5	2	162
<b>1.0% SCBAX</b>	396	62.0	4	164
<b>1.5% SCBAX</b>	394	62.5	6	166
<b>2.0% SCBAX</b>	392	63.0	8	168

#### 7.4.1.1 Preparation of Yeast solution

Since a mechanical high-speed mixer (Tweedy 1 mixer) was to be used, making the yeast into a solution was the best way to save hydration time and activate yeast prior to mixing. Two yeast samples were prepared; one for wheat bran and the other for AX samples. 80 g of yeast was added to 920 g of water at 30°C and mixed with a magnetic stirrer for approximately 30 minutes or until yeast is

completely dissolved for wheat bran; and 160 g of yeast was added to 840 g of water for AX samples. AX yeast solution concentration was doubled to allow for more water to be available for dissolving AX. A fresh batch of yeast was prepared at the start of day for each experiment.

Table 7.4 summarises the increase the yeast solution required based on the % bran and AX added in each dough formulation.  $x$  denotes the amount of yeast needed for each formulation, which was calculated using the total amount of ingredients in each sample and comparing against the control dough sample, in order to keep the ratio of yeast to other ingredients constant.

Table 7.4: Yeast solution calculation for each dough formulation

Ingredients	Control dough	5% wheat bran	10% wheat bran	15% wheat bran	0.5% AX	1% AX	1.5% AX	2% AX
Flour (g)	400.0	380.0	360.0	340.0	398.0	396.0	394.0	392.0
Fibre (g)	0.0	20.0	40.0	60.0	2.0	4.0	6.0	8.0
Water (g)	244.0	254.0	264.0	274.0	246.0	248.0	250.0	252.0
Yeast (g)	8.0	$x$	$x$	$x$	$x$	$x$	$x$	$x$
Salt (g)	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Sugar (g)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Fat (g)	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Total (g)	684.4	$686.4 + x$	$696.4 + x$	$706.4 + x$	$678.4 + x$	$680.4 + x$	$682.4 + x$	$684.4 + x$

244 g of water was required for a 400 g flour-based dough formulation (excluding other ingredients). After preparing a 1000 g of yeast-water solution,

1/10<sup>th</sup> of the solution (100 g) contained 8 g yeast and 92 g water for wheat bran dough formulations and 1/20<sup>th</sup> (50 g) contained 8 g yeast and 42 g water for AX dough formulations respectively, the extra water was used to rinse off excess yeast solutions into the mixer. Table 7.5 summarises the amount of yeast solution and extra water needed for each formulation.

Table 7.5: Calculation for the yeast solution and water added to all dough formulations

	<b>Control dough</b>	<b>5% bran dough</b>	<b>10% bran dough</b>	<b>15% bran dough</b>	<b>Control dough AX</b>	<b>0.5% AX dough</b>	<b>1% AX dough</b>	<b>1.5% AX dough</b>	<b>2% AX dough</b>
<b>Total amount of water required (g)</b>	244.00	254.00	264.00	274.00	244.00	246.00	248.00	250.00	252.00
<b>Amount of yeast solution required (g)</b>	100.00	101.50	103.00	104.50	50.00	50.13	50.31	50.44	50.63
<b>Amount of water in yeast solution (g)</b>	92.00	93.50	95.00	96.63	42.00	42.13	42.31	42.44	42.63
<b>Amount of additional water required (g)</b>	152.00	160.50	169.00	177.37	202.00	203.87	205.69	207.56	209.37

#### 7.4.2 Static and Dynamic Dough density

Density measurements of unyeasted doughs mixed at different pressures were made in order to quantify the gas content in dough (Campbell *et al.*, 2001; Martin *et al.*, 2004). The higher the gas content in a dough, the lower the density. Dough samples of about 6 g were weighed in air and then immersed in xylene (Fisher Scientific, Loughborough, UK) using a double cup system placed on a Precisa Electronic Balance 125A (Figure 6.4). The temperature of xylene was maintained using a jacketed beaker through which water is re-circulated from

a temperature-controlled bath (Figure 6.4). The entire system was set-up and used in a fumehood. Six dough samples for each formulation were tested and their density calculated as:

$$\rho = \frac{m_{air}}{m_{air} - m_{xylene}} \rho_{xylene} \quad (7.1)$$

where  $\rho$  is the dough density ( $\text{g cm}^{-3}$ ),  $m_{air}$  is the mass of dough in air (g),  $m_{xylene}$  is the mass of dough in xylene (g), and  $\rho_{xylene}$  is the density of xylene ( $0.86059 \text{ g cm}^{-3}$  at  $30^\circ\text{C}$ ).

Four different pressure levels were used when mixing dough samples to measure the static dough density (aeration during mixing) for each dough formulation (six sample replicates).

The ingredients were placed in the mixer and water at around  $26^\circ\text{C}$  was added. For expansion experiment, the Tweedy 1 mixer, the rubber ring gasket and Perspex lid were attached to seal off the content of the mixer and also prevent air escape from vacuum mixing. The green start button for the mixer is pressed simultaneously with the stopwatch. Figure 7.3 shows the entire mixer connected to the operating system.



*Figure 7.3: Tweedy 1 mixer attached to the monitor and signalling panel*

The ingredients were mixed under partial pressure and under pressure monitoring. To mix under partial vacuum, the vacuum pump was turned on and the pressure levels monitored and regulated to required pressures using the pressure gauge. Line schematics of the pressure flow around the Tweedy mixer has been drawn below (Figure 7.4). Valves 3 and 4 were fully opened to create vacuum in the mixer. Following this, valve 5 was closed until the desired pressure was achieved. It was then maintained and controlled by the manual adjustment of valve 4 throughout the mixing period. Once mixing was completed, the mixer and the computer were stopped, the vacuum pump was switched off, valves 3 and 4 closed and valve 5 was slowly opened to return the mixer to atmospheric pressure.

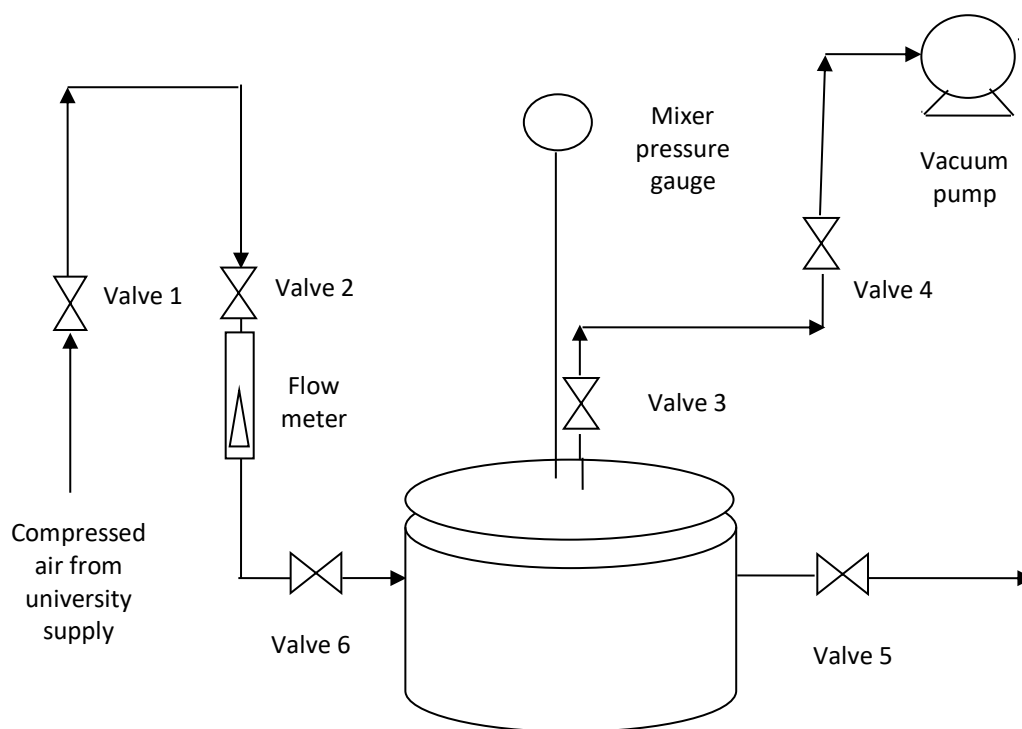


Figure 7.4: Line diagram of Tweedy 1 mixer

To achieve high pressure (based on the pressure capacity of the mixer, 2 bar abs without causing damage) mixing, compressed air was allowed to flow into the mixer. As for mixing under vacuum, it was vital that the rubber ring gasket (shown clearly in Figure 7.1) was fitted correctly under the mixer lid so that the mixer remained airtight and the pressure maintained. Firstly, for safety reasons, valve 5 was opened so air could escape from the system and prevent inadvertent excessive pressure build-up. The compressed air supply was switched on at the main inlet (valve 1) and valve 2 adjusted until the gas flow meter recorded a flow of 6 – 8 L min<sup>-1</sup>. To achieve the exact pressure required, and make precise pressure adjustments, valves 5 and 6 were adjusted. After completion, the compressed air supply was switched off using valves 1 and 2, and valve 5 was fully opened to allow the pressure in the mixer to return to atmospheric pressure.

The gas-free dough density was measured by mixing each dough formulation at different headspace pressures and extrapolating back to zero pressure (Campbell *et al.*, 1993; Shah *et al.*, 1998).

#### **7.4.3 Baked Loaf Trials**

The Tweedy 1 mixer was used to prepare doughs that were characterised in terms of aeration of the dough during mixing and their gas expansion capacity during proving. Baked loaves were prepared in the food laboratory at the University of Huddersfield.

Baking trials were performed to help further understand the effects of wheat bran (coarse and fine) and arabinoxylans (WBAX and SCBAX) on dough

expansion and in this case of the final baked loaf. Doughs based on 400 g of flour were mixed in the Tweedy 1 mixer at atmospheric pressure with ingredients shown in Table 7.4. These baked samples were then analysed using the Texture Profile Analyzer (TPA).

Doughs were prepared using the same recipes as for the DDD experiments, but with half the yeast level. After mixing in the Tweedy mixer for three minutes, doughs were manually moulded then placed in the individual baking trays. Dough samples were then placed in the oven to prove for 40 minutes at 40°C after which samples were baked at 175°C for 27 minutes. The volume and the texture of final baked loaves were measured by Rapeseed displacement and by texture analysis, respectively, as described below. The Stable MicroSystems (Godalming, UK) Texture Analyzer (TA-XT2) was used to determine the individual bread compression characteristics (hardness). These were measured after each loaf volume was determined using the Rapeseed displacement method (AACC 10-05.01) (AACC, 2010). For all samples, an average was obtained for result interpretation.

#### **7.4.3.1 Measurement of specific volume of bread**

Using the AACC method 10-05.01 (AACC) (AACC American Association Of Cereal Chemists, 1985; AACC. American Association Of Cereal Chemists, 2000; Ranasalva & Visvanathan, 2014), the specific volume of a bread loaf is measured by calculating the volume (cc) of a loaf using rapeseed displacement method and dividing it by the weight (g) of the loaf (AACC American Association Of Cereal Chemists, 1985; AACC. American Association Of Cereal Chemists, 2000; Ranasalva & Visvanathan, 2014).

The weight of each loaf was measured a day after baking to allow for foam structure to be properly set. After this, the loaves were immersed into a cylindrical flask containing a known volume of rapeseed (AACC American Association Of Cereal Chemists, 1985; AACC. American Association Of Cereal Chemists, 2000; Ranasalva & Visvanathan, 2014). The difference between the volume of rapeseed and the volume of rapeseed containing the loaf. The volume of the baked loaf is dependent on the crumb structure of the loaf (Scanlon & Zghal, 2001).

Loaf Specific Volume (LSV), was calculated as:

$$\text{LSV} = \text{Loaf volume (cc)} / \text{Loaf weight (g)}$$

Loaves were marked at 1 cm points, sliced and the crust cut off all four sides of each slice. The middle slices were used from each loaf and at least two or three slices were measured from each baked loaf.

#### **7.4.3.2 Determination of firmness/hardness of composite bread**

One of the characteristics of a loaf is the hardness of the loaf and this was measured using the TA.TX texture analyser. Using a meter rule, loaves were sectioned into 1 mm slices and a thickness of 25 mm with the crust cut off from all the sides before carrying out the tests. Each slice of bread was placed 10 mm between the sampling base and measuring probe, and the maximum force recorded as the probe made contact with the bread slice (AACC, 2010; Visvanathan & Ranasalva, 2014).

Loaf slices were about a thickness of 25 mm which was compressed with a P36 probe that feeds information to the software for analysis. Loaf slices placed at

the centre of the probe were compressed to a strain of about 40% and the strain measured in newtons (N) (Ranasalva & Visvanathan, 2014). Placing the samples in the centre was done to avoid inconsistent measurements and inaccurate results. Thickness is measured automatically as the force exerted on the strain which is in N using the Macro Testing function of the texture analyser.

The crumb hardness value was obtained after the first compression (Hardness: peak force that occurs during the first compression) of the two-bite texture profile analysis (TPA). The other parameters of TPA relevant to this study included: cohesiveness (indicates how well the product withstands a second deformation relative to its resistance under the first deformation; measured as the ratio between the area of work during the second compression and area of work during the first compression; no units); springiness (indicates how well a product physically springs back after it has been deformed during the first compression and has been allowed to wait for 5 s of relaxation time between two compressions; the springiness is measured at the down-stroke of the second compression; unit: mm); gumminess (calculated as product of hardness and cohesiveness; unit: N) and chewiness (calculated as product of gumminess and springiness; unit: Nm).

Table 7.6: TA-XT2 Settings used (adapted from: Visvanathan & Ranasalva (2014))

<b>Mode</b>	Measure Force in Compression
<b>Option</b>	Return to Start
<b>Pre-test speed (mm/s)</b>	1.0
<b>Test speed (mm/s)</b>	1.7
<b>Post-test speed (mm/s)</b>	10.0
<b>Strain</b>	40 per cent
<b>Trigger type</b>	Auto 5 g
<b>Data acquisition rate (pps)</b>	250
<b>Probe</b>	AACC 36 mm cylinder probe with radius (P/36R) using 5 kg load cell

Figure 7.5 illustrates an example of the hardness profile of a baked loaf while Figure 7.6 shows the dough and bread in different stages of baking.

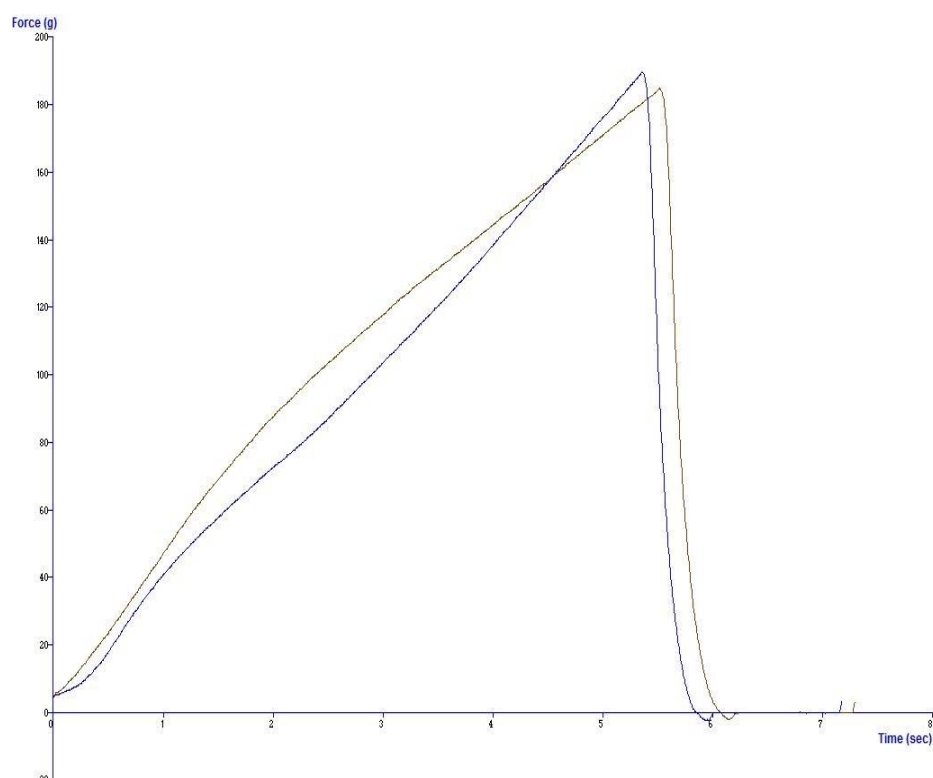


Figure 7.5: Example of the hardness texture analyzer profile of two bread slices (25mm thick) from same sample (Albasir, M. (2018))

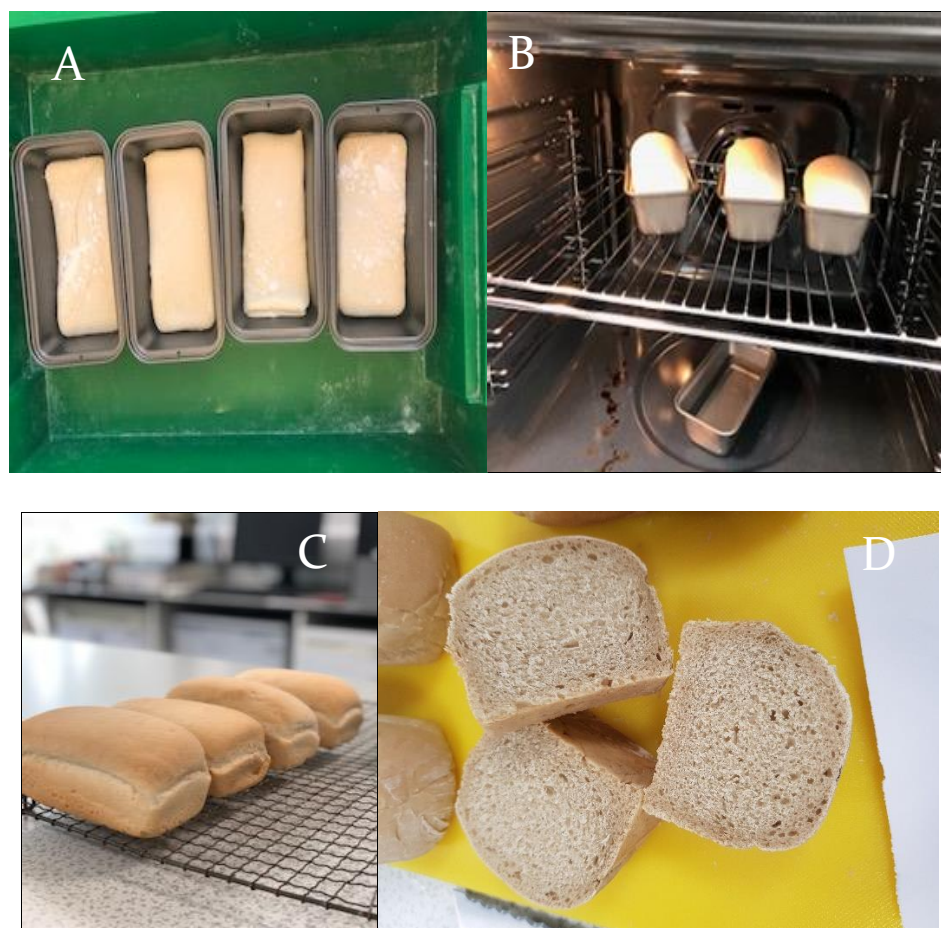


Figure 7.6: Dough and loaf samples between mixing and baking. After mixing (A) after proving (Albasir M., 2018) (B) after baking (Albasir M., 2018) (C) and the sliced loaf (D)

## 7.5 Effects of wheat bran and AX on dough using the Tweedy 1 mixer

Materials and equipment discussed in the previous section were used to carry out experimental investigations on the effect of wheat bran and AX (WBAX and SCBAX) on aeration of bread dough during mixing and the expansion capacity during proving. Dough samples were also baked, and rheological analysis carried out using the TPA. While in chapter 6 rheological studies were carried out using the creep and creep-recovery analysis to understand and predict the effect of fibre on dough sample, this chapter investigates the effect these fibre ingredients have on baked loaves.

This section discusses the effect of wheat bran (fine and coarse) on dough formulations prepared using the Tweedy 1 mixer and used to investigate the fibre dough expansion, gas voidage and baked loaves quality using Allinson flour. These trials provided an understanding to how the mixer type can also cause varying development and expansion capacity of mixed doughs. All samples were carried out in four replicates.

### 7.5.1 Effect of bran on dough aeration during mixing

Figure 7.7 shows the densities of doughs mixed with fine and coarse bran at different pressures in the Tweedy 1 mixer. Clearly, the density of dough decreased as the pressure increases for all wheat bran dough formulations. Regression lines were fitted to each data set, for which the intercept indicates the gas-free dough density and the slope indicates the extent of aeration of the dough (Campbell *et al.*, 1993; Campbell *et al.*, 2008c; Chin & Campbell, 2005; Chin *et al.*, 2004). The gas content at atmospheric pressure,  $\phi$ , is calculated as

$$\phi = 1 - \frac{\rho}{\rho_{gf}} = \frac{sP}{\rho_{gf}}$$

Where  $\rho$  is the density of the dough at pressure  $P$ ,  $\rho_{gf}$  is the gas-free dough density, and  $s$  is the slope of the graph. For pressures measured in bar absolute, atmospheric pressure is 1 bar, and the gas content at atmospheric pressure is therefore simply the slope divided by the gas-free dough density.

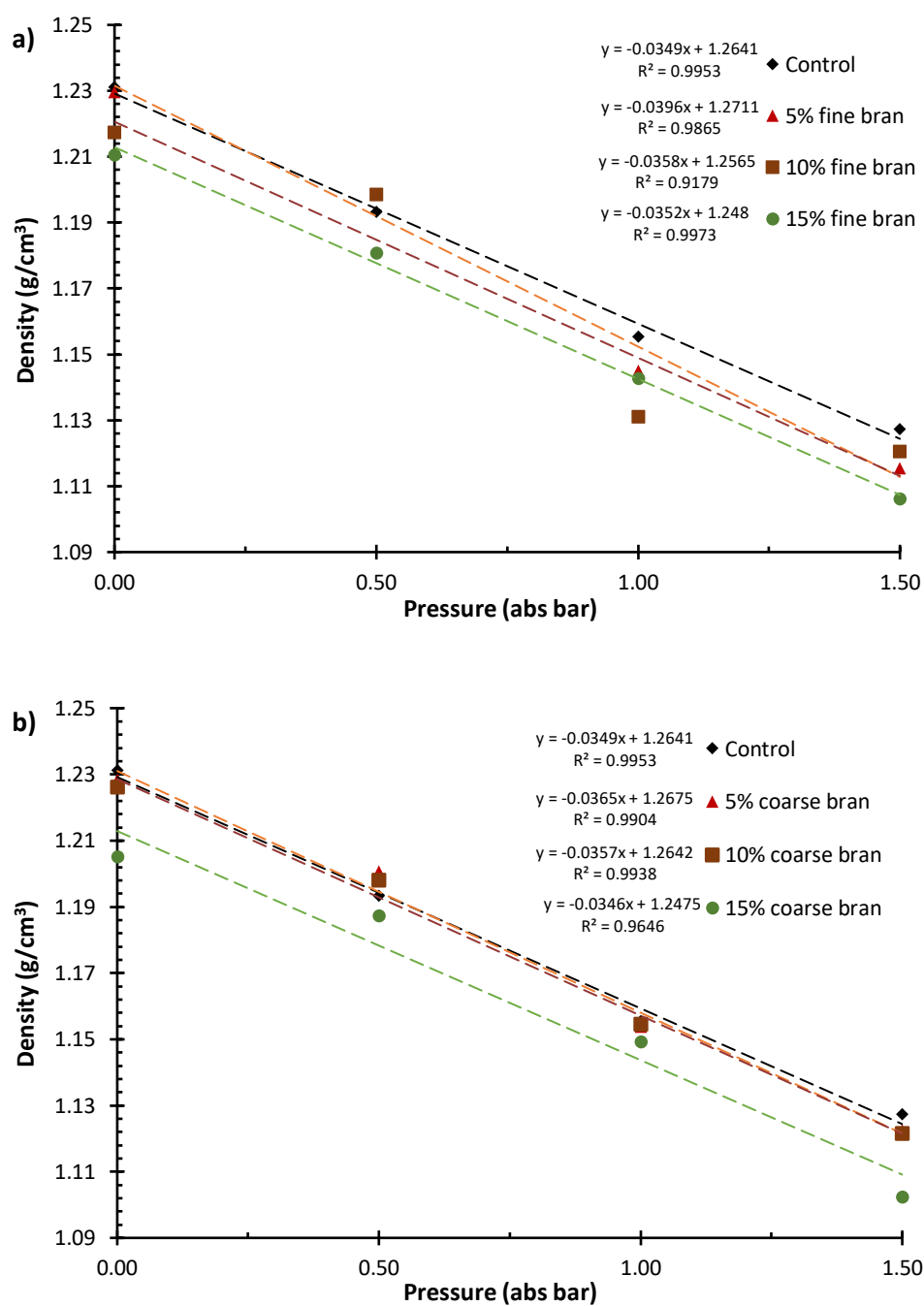
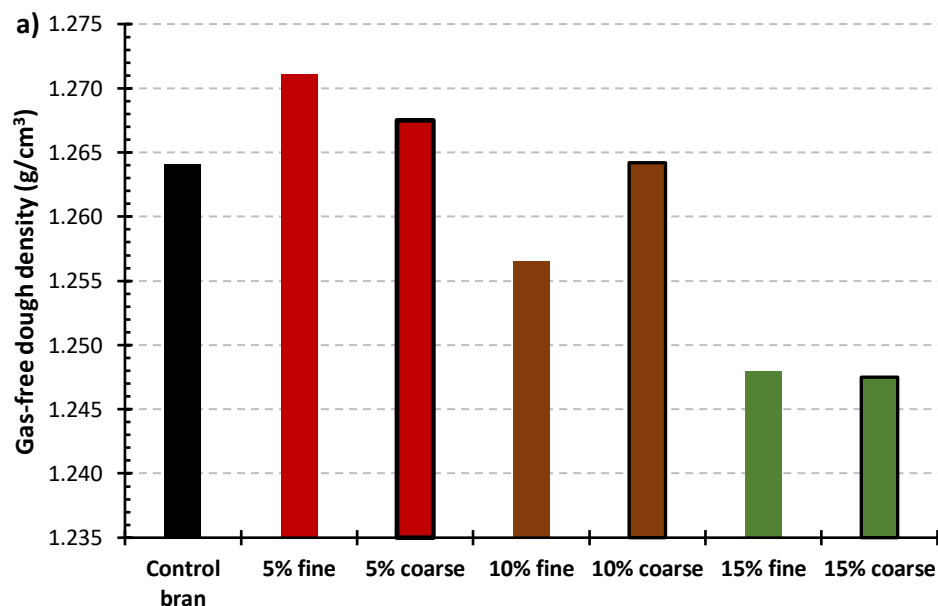


Figure 7.7: Density of dough mixed under different absolute pressures using two wheat bran types a) fine and b) coarse

Figure 7.8 shows the gas-free dough densities and the gas content at atmospheric pressure for doughs mixed with fine and coarse bran. Addition of bran reduced the gas-free dough density, largely because of the extra water, in

agreement with (Campbell *et al.*, 2008c) and (Packkias-Doss *et al.*, 2019). However, the current results are more variable than the results of previous similar studies (Campbell *et al.*, 2008c; Chin & Campbell, 2005; Chin *et al.*, 2004), largely because the set-up of the pressure-vacuum system on the Tweedy 1 in Huddersfield is not yet as controlled as it was when this earlier work was done in Manchester. However, it is clear that the addition of bran tends to increase aeration of the dough during mixing. Campbell *et al.* (2008c) showed that this was because bran increased the rates of both entrainment and disentrainment of gas during mixing, but altered the balance towards the former, hence, giving a larger steady state gas content. As noted previously, aeration of the dough affects oxygen availability for gluten development. Although the presence of bran interferes with gluten development, the additional aeration during mixing probably serves to offset this a little.



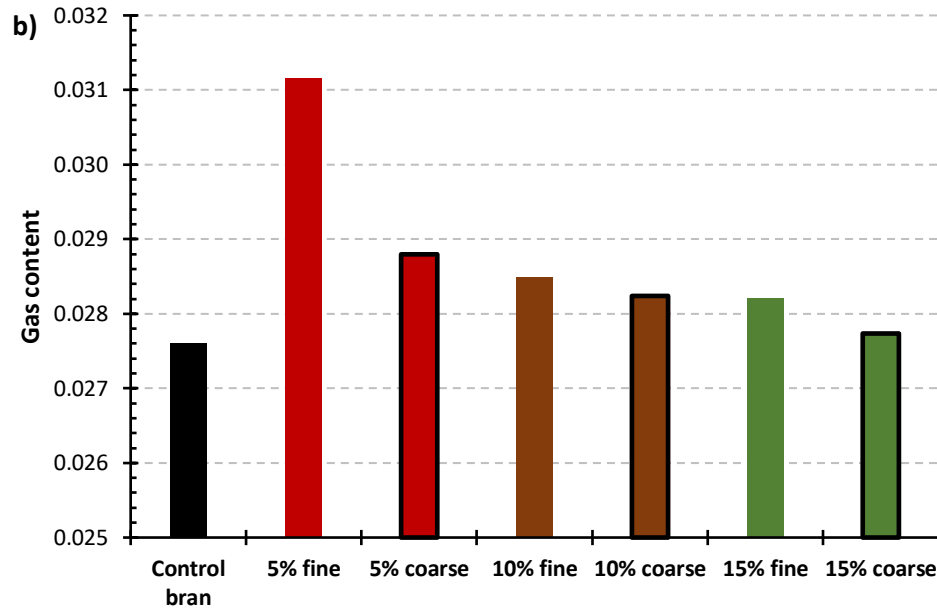


Figure 7.8: Effect of bran particle size on a) gas-free density and b) gas content in bread doughs

### 7.5.2 Effect of AX on dough aeration during mixing

Figure 7.9 shows the dough density versus mixing pressures for doughs containing arabinoxylans WBAX and SCBAX at four different levels. Figure 7.10 shows the gas-free dough densities and gas contents at atmospheric pressure for these doughs. As with the bran results above, the results are somewhat variable compared with previous studies using this approach. Again, it is clear that dough formulations with AX had lower gas-free densities, because of the extra water. WBAX did not have much effect on the gas content of the doughs, but SCBAX appeared to reduce the aeration of the doughs substantially, compared with the Control. This is an interesting new finding that demonstrates a strong effect of this AX on dough aeration, arising from its effects on dough rheology.

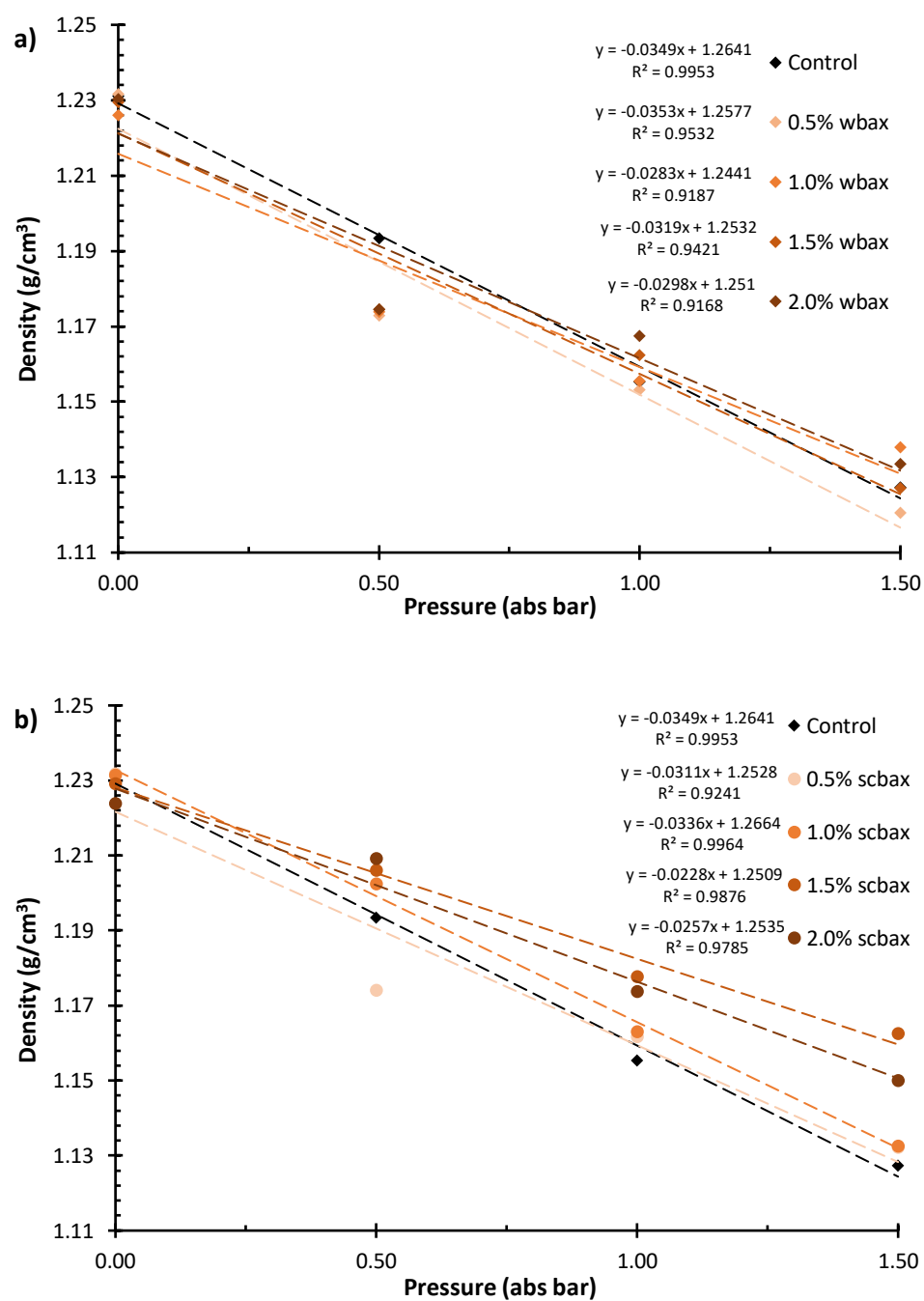


Figure 7.9: Density of dough mixed under different absolute pressures using two types of arabinoxylans (WBAX and SCBAX)

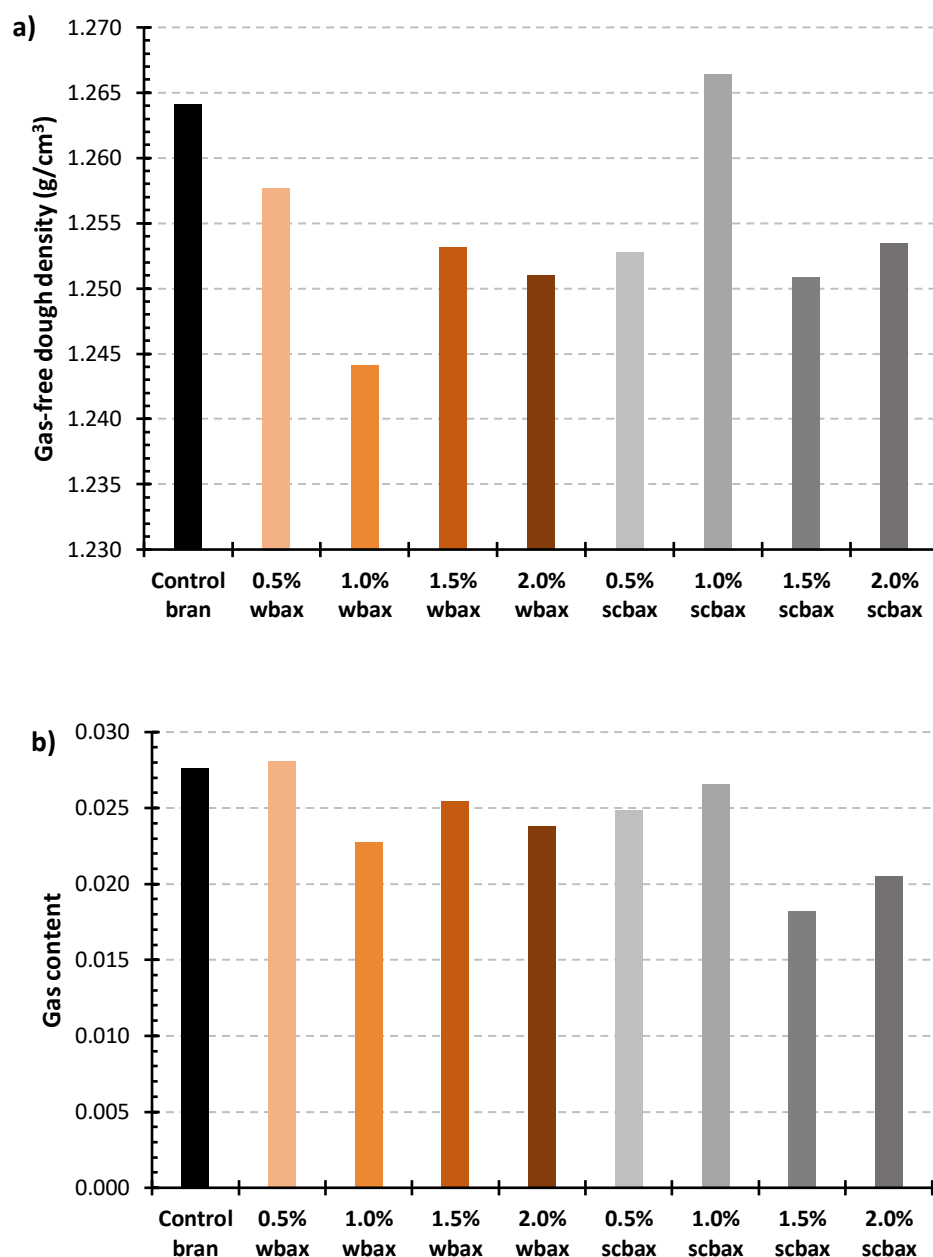


Figure 7.10: Effect of bran particle size on a) gas-free density and b) gas content in bread doughs

### 7.5.3 Effect of bran on dough expansion capacity

Figure 7.11 shows the effect of wheat bran on dough formulations using the dynamic dough density (DDD) system and Tweedy 1 mixer. The use of a high-speed mixer developed the dough more causing an increased dough expansion rate when compared to Figure 6.18. Obviously, an increase in the %wheat bran

added to the dough formulation resulted in the minimum density also being attained in a shorter time (not as developed as the control dough).

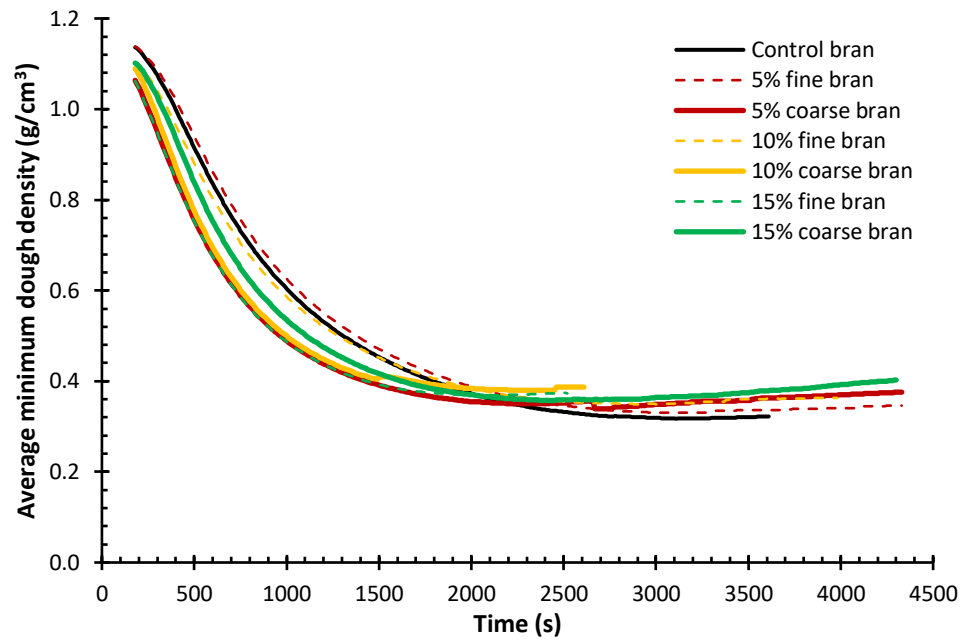


Figure 7.11: Average dynamic dough density profile for wheat bran enriched dough formulations produced using the Tweedy 1 mixer

Figure 7.12 shows the average minimum dough densities for bran enriched dough formulations using the MinorPin mixer (low speed mixing) and Tweedy 1 mixer (high speed mixing). Clearly, dough samples produced with the MinorPin mixer expanded substantially less than dough samples produced using the Tweedy 1 mixer. Although both findings show that an increase in wheat bran concentration increases the minimum density (reduces the expansion capacity), the effect was considerably less for the Tweedy 1 mixer than for the MinorPin mixer. Since literature has already shown that particle size has an effect on dough development and dough expansion (Campbell *et al.*, 2008b,c; Hemdane *et al.*, 2016, 2015, Zhang & Moore, 1999, 1997), it was interesting to

observe the effect of mixer types on dough expansion and to confirm that the greater development achieved by high speed mixing in Tweedy mixer was evident in the expansion capacity of the doughs.

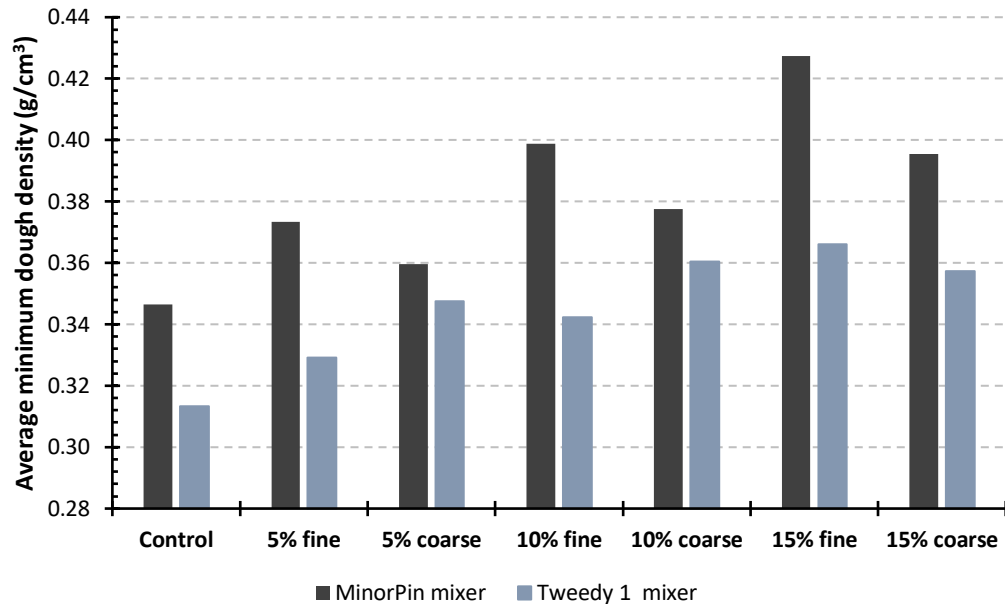


Figure 7.12: Average minimum density of bran enriched dough formulations mixed in two types of mixer

Considering the effect of bran level and particle size, it is clear from Figure 7.11 that increasing the bran level decreases the dough expansion. For doughs mixed in the Minorpin mixer, the effect was greater for fine bran than for coarse bran, in agreement with (Campbell *et al.*, 2008c). However, for doughs mixed in the Tweedy 1 mixer, coarse bran seemed to give a greater decrease in expansion (increase in minimum dough density) at the lower levels of addition (5% and 10%), although at 15% the fine bran was more damaging than the coarse bran, in agreement with previous work. This is an unexplained finding that would need to be confirmed but may indicate a strong interaction between bran particle size and level in a high-speed mixer.

#### 7.5.4 Effect of AX on dough expansion

Figure 7.13 shows the average dynamic dough density of all dough formulations enriched with arabinoxylans and also different control dough formulations, prepared using the Tweedy 1 mixer. At the time when the minimum density is reached, the corresponding maximum density is attained. An increase in the amount of AX added to dough formulation increased the minimum dough density of each formulation (reducing expansion capacity). A control dough at 61% water was made along with doughs with AX at three different levels of water adjustments.

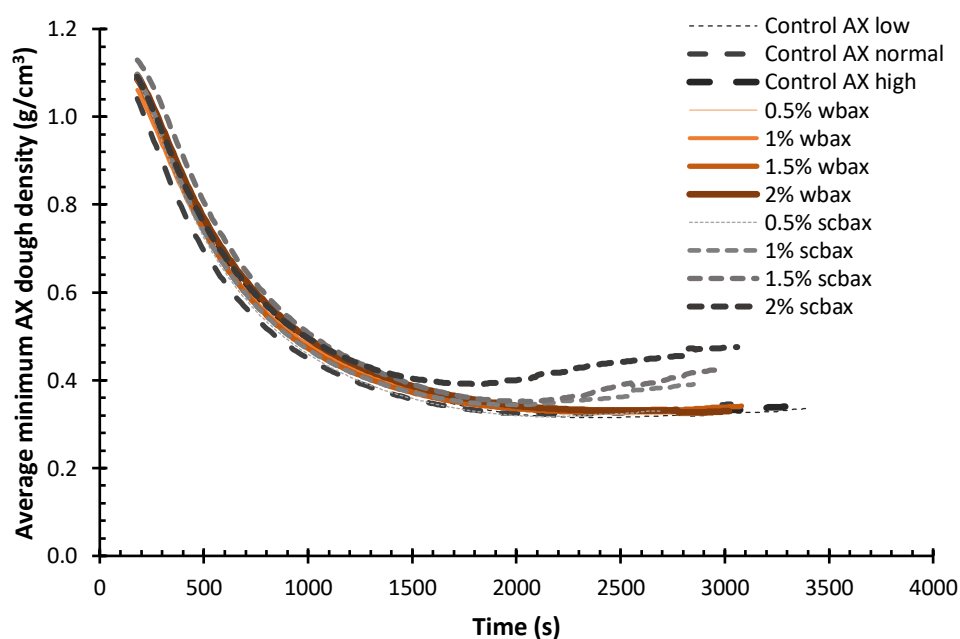


Figure 7.13: Average dynamic dough density for AX dough formulations (WBAX and SCBAX) at different levels of water adjustment: Low = 0.5% per %AX; Normal = 1% per %AX; high = 2.5% per %AX addition

Figure 7.14 shows the average minimum density of dough samples produced in the Tweedy 1 mixer using two types of AX samples (WBAX and SCBAX) and at three different levels of water adjustments: 0.5% increase in water per % addition

of AX; 1% increase in water per %addition of AX; and 2.5% increase in water per %addition of AX. As for the bran results, the control dough from the Minorpin mixer did not expand as well as the control dough from the Tweedy 1 mixer, reflecting the more effective dough development in the high-speed mixer. This was reflected in the SCBAX results, for which the minimum density was consistently lower (greater expansion) for doughs mixed in the Tweedy 1 mixer. However, the WBAX results did not follow this pattern, which is surprising and perhaps erroneous. In general, the WBAX results seemed to be more variable than the SCBAX results. Increasing SCBAX gave a consistent increase in minimum density for both mixers, indicating less expansion when this AX was added to the formulation, while the WBAX results are more mixed, showing no consistent pattern with level or between the two mixers.

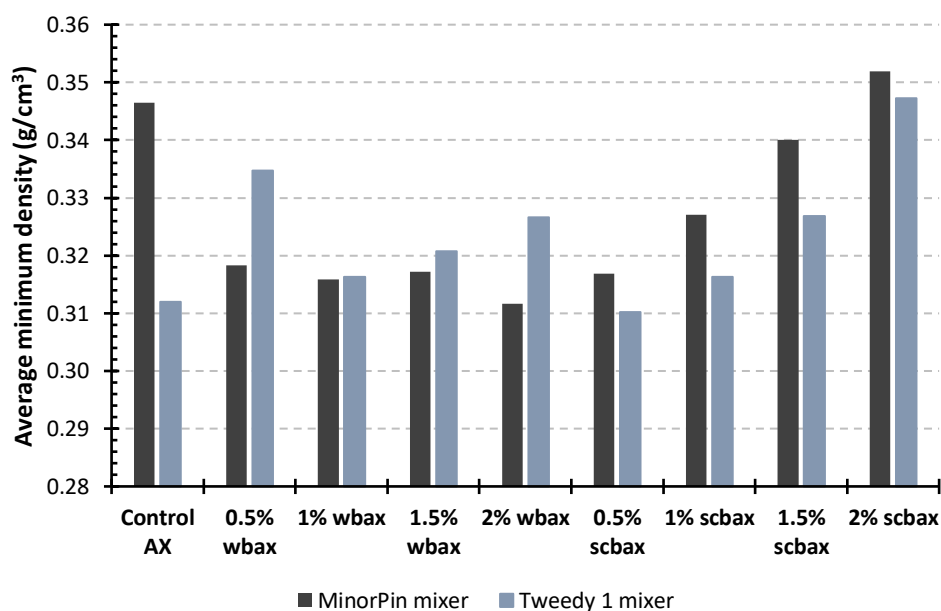


Figure 7.14: Comparison of the average minimum density of AX enriched dough formulations using MinorPin mixer and Tweedy 1

Figure 7.15 shows the comparison of the average minimum dough density of all AX dough formulations with different water levels. Again, there is significant variability in the WBAX results with no clear patterns, while the SCBAX showed the same pattern of increased minimum density (decreased expansion) at higher levels of SCBAX addition. Thus, SCBAX appears to be positively detrimental to dough expansion and unlikely to be a good candidate for a bakery ingredient, while WBAX seems to have minimal influence on dough expansion and may be acceptable as a bakery ingredient that increases fibre content without damaging bread quality. The next section considers these findings further by looking at the effect of these to arabinoxylans on baked loaves.

Increasing the water adjustment from 0.5% to 2.5% per % addition of AX appear not to have had a strong influence on expansion. For the SCBAX, the intermediate adjustment of 1% per % seemed consistently to give the highest expansion, suggesting this is an appropriate level of water adjustment for this AX. For the WBAX, a water adjustment of 0.5% per %AX seemed to give the greatest expansion, suggesting this was an adequate level of water adjustment and that more water made the doughs too slack to retain gas effectively. Thus, these results seem to indicate that the 2.5% water adjustment found by Biliaderis *et al.* (1995) was excessive for the AXs used in the current work.

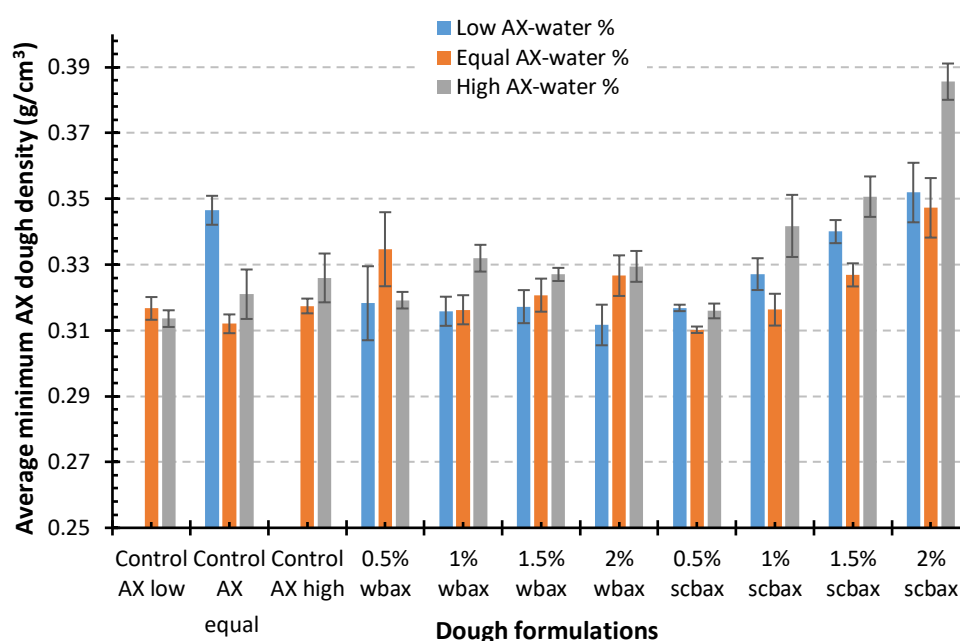


Figure 7.15: Effect of different water levels on dough expansion of different AX formulations

#### 7.5.5 Effect of wheat bran on baked loaves

Figure 7.16 shows the average specific volume of breads produced with fine and coarse wheat bran at 5, 10 and 15%. Surprisingly, the control dough produced the bread with the least volume, which was unexpected as results from earlier sections (Figure 7.12) showed the control dough to have the highest expansion capacity, and other similar work has shown a good correlation between DDD expansion and baked loaf volume (Campbell *et al.*, 2008b). This suggests that possibly the proving time used in current work was not optimal for the control dough, and perhaps it overproved and then collapsed in the oven. Fine bran resulted in larger loaves than coarse bran, which is also unexpected, as fine bran gave lower expansion than coarse bran in the DDD test, and many workers have found that fine bran is generally more damaging to loaf volume than coarse bran (Campbell *et al.*, 2008c; Hemdane *et al.*, 2016; Schmiele *et al.*, 2012; Zhang &

Moore, 1999, 1997), although others have proposed grinding of bran as a way of alleviating its damaging effects; the literature is not consistent on this point. 5% and 10% fine bran produced the largest volume of loaves, hence, showing that the least effect was found in these loaves while 15% fine bran did not behave like its counterparts. This was interestingly not the case for coarse bran samples, although the finer the samples the more detrimental effects observed, as seen by previous authors (Campbell *et al.*, 2008c; Hemdane *et al.*, 2016; Schmiele *et al.*, 2012; Zhang & Moore, 1999, 1997). In the case of coarse bran bread loaves, an increase in the % of wheat bran resulted in a progressive decrease in the specific loaf volume. This agrees with the findings from the DDD system (Figure 7.12) that an increase addition of wheat bran reduces the expansion capacity of the dough; leading to the production of a bread with a small volume. Also, findings showed that because of the possible varied particle sizes that make up the coarse bran, there is the possibility that coarse bran loaves behave like the control baked loaf (Collins & Hook, 1991; De Kock *et al.*, 1999; Hemdane *et al.*, 2016; Hook & Collins, 1987; Jacobs *et al.*, 2015; Lai *et al.*, 1989; Moder *et al.*, 1984; Nelles *et al.*, 1998; Ozboy & Hamit, 1997; Pomeranz *et al.*, 1977; Rao & Rao, 1991; Rasco *et al.*, 1991; Shetlar & Lyman, 1944). The possibility that bran decreases loaf volumes by reducing gas production has been firmly negated, with decreased gas retention clearly established as the reason for lowered loaf volumes (Katina *et al.*, 2010; Packkia-Doss *et al.*, 2019; Pomeranz *et al.*, 1977; Rodgers & Hoseneey, 1982; Sosulski & Wu, 1988). This agrees with present findings in Figure 7.16 where loaves volume decreases as %wheat bran increases. Gluten dilution and

physical disruption by bran particles contribute to this reduced gas retention, along with an assembly of additional contributing factors.

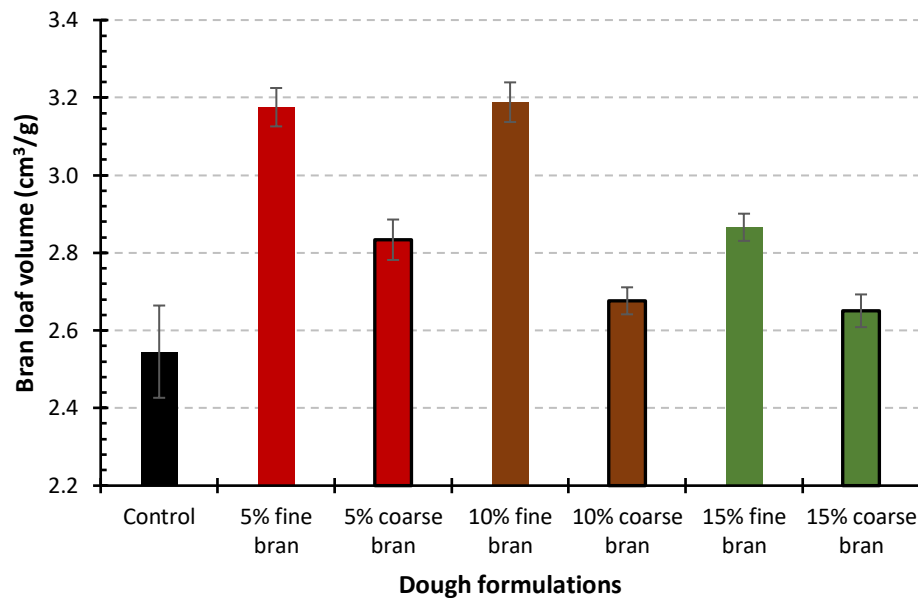


Figure 7.16: Effect of added particle size on specific volume of bread made from wheat bran

Figure 7.17 shows the average baked loaf hardness of wheat bran enriched samples using Allinson flour and two distinct particle sizes (fine and coarse). The addition of wheat bran clearly reduced the hardness of the dough compared to the control loaf sample. Control baked loaf showed to have the hardest loaf. All samples were analysed after being left to rest overnight. Fine bran loaves were seen to reduce in hardness between 5% (6.941 N) to 10% (6.169 N) fortification and increased again at 15% fine bran fortification (6.742 N). This could mean that increasing the amount of fine particle wheat bran above 10% exerts a negative effect on baked loaves. Coarse particle wheat bran on the other hand, generally reduces in hardness as the amount added was increased. This further confirms that fine particle wheat bran has more detrimental effects on

dough/breads than coarse particle wheat bran. Interestingly, control loaf was seen to produce the hardest bread samples. This could simply mean that the control loaf sample had the closest crumb structure (smaller gas cells) than all wheat bran enriched loaves while coarse particle bran had the most opened crumb structure (biggest gas cells). The results suggest an increase in crumb hardness compared the loaf volumes for bran enriched samples was in agreement with finding from (Schmiele *et al.*, 2012) who found an increase in crumb hardness but a decrease in loaf volume. Loaf hardness shortens the shelf-life of the baked bread, causing staling. Results from Figure 7.17 suggest that the control dough would become stale before the fibre-rich loaves; although, this is not the case as fibre-rich breads are known to have a shorter shelf life than control white bread (FOB, 2018).

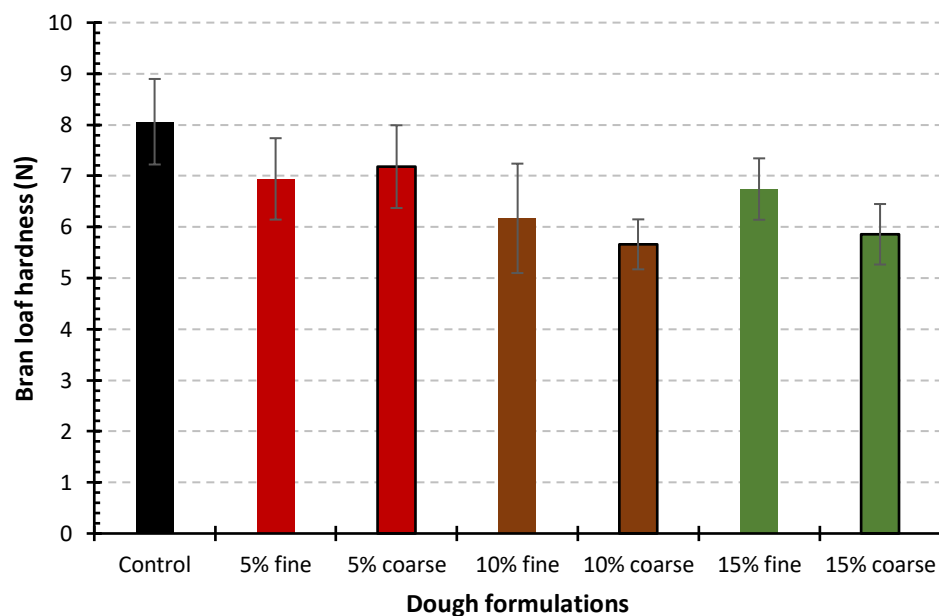


Figure 7.17: Effect of wheat bran on bread hardness using two different particle sizes

#### **7.5.6 Effect of AX on baked loaves**

Figure 7.18 shows the average specific volume of breads produced from WBAX and SCBAX fibres at different levels. All baked loaves apart from 1.5% and 2% SCBAX all showed to have a higher average volume when compared to the control baked loaf. This could suggest an exciting finding, that adding AX can increase loaf volume, but the unexpected result above for bran makes us cautious, while the observation that increasing the level of AX decreased loaf volume suggests that the comparison with the control is not robust. However, the increase in the level of wheat bran AX used in baking bread loaves led to a simultaneous decrease in corresponding loaf volume while the reverse was observed for sugarcane bagasse AX baked loaves. There was no conclusive behavioural pattern observed for sugarcane bagasse AX, but overall the loaf volumes were lower than for WBAX, while the two high levels of AX gave lower specific volumes than the lower levels, suggesting that, like the WBAX, the SCBAX was detrimental to loaf volume, and even more so.

It is clear that SCBAX gave lower loaf volumes than WBAX, confirming the conclusion from the DDD trials that this particular sample of SCBAX does not appear to offer a promising bakery ingredient, while WBAX may be able to be used as a fibre-enhancing bakery ingredient that gives acceptable bread.

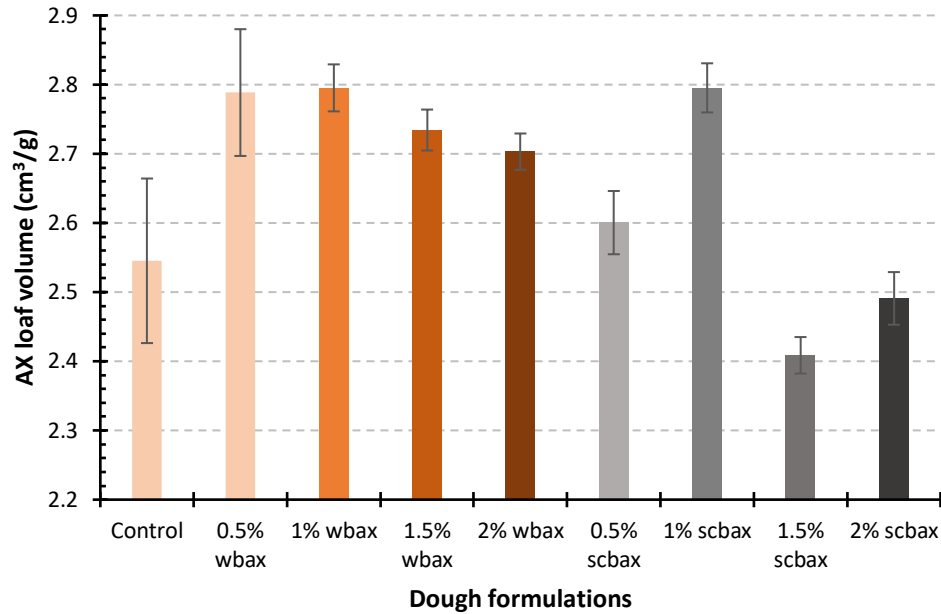


Figure 7.18: Effect of arabinoxylans size on specific volume of bread made using two types of samples at different levels

Figure 7.19 shows the average baked loaf hardness of arabinoxylan-enriched samples using Allinson flour at different levels of formulation. Clearly, the addition of both AX types had an effect on the loaf hardness but not as much as the control dough. Interestingly, the reduced hardness effect was similar to those of the wheat bran loaf sample (Figure 7.17). Control baked loaf showed to produce the hardest loaf. All samples were analysed after being left to rest overnight. Wheat bran AX loaves seemed to increase in hardness as the level of WBAX in formulation was increased; 1% WBAX loaf sample had the hardest loaf (7.381 N) of the WBAX formulation set. 0.5% WBAX was observed to have the least hard bread followed by 1.5% WBAX in comparison to the control loaf sample. WBAX seems to have less of an effect on loaf hardness than SCBAX. In the case of sugarcane bagasse AX loaf samples, an increase in level of SCBAX

added resulted in a harder baked loaf. The fine particle size of both AX samples could be the reason why similar behaviours were observed from both set of loaf sample sets. When compared against the wheat bran (fine and coarse) loaf samples, the tighter crumb structure seen with fine bran loaves could be similar to the AX sample resulting in similar effect pattern.

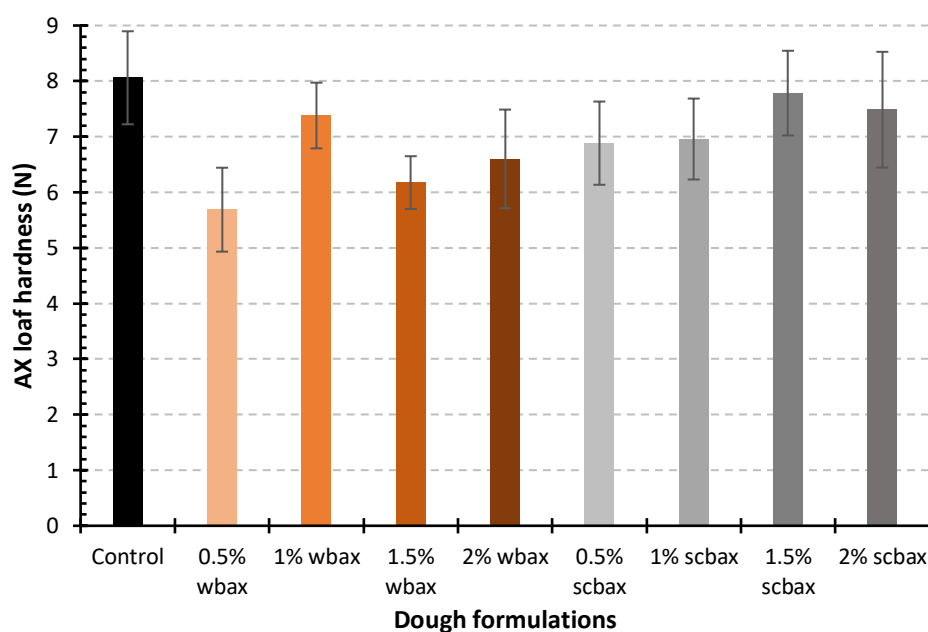


Figure 7.19: Effect of arabinoxylans on bread hardness using two different types of ingredients

Overall, SCBAX does not benefit doughs or baked loaves; SCBAX decreases the ability of doughs to expand, even with increased water addition, and results in baked loaves of lower volume and harder, less appealing crumb structure. WBAX is also somewhat detrimental, but less so than SCBAX, and could

possibly be useful as a bakery ingredient that enhances fibre while retaining acceptable bread quality.

It is important to understand that the two AX samples used in the current work are not optimised for breadmaking. There is evidence from the literature that AX can be beneficial in breadmaking, and we took the opportunity in the current work to see if this was true for these particular AX samples. The conclusion is that they are not, but it is outside the scope of the current work to investigate precisely why this is. It is likely that these samples contain AX molecules that are too large to be useful in breadmaking, and that hydrolysing these (using xylanase enzymes) into smaller AX molecules may make them more suitable as bread ingredients (Courtin & Delcour, 2002). However, the current work has demonstrated novel and systematic approaches to understand how AX samples from a wider range of sources and with different molecular weights and structural characteristics might be investigated to understand how to optimise their use in breadmaking.

## **7.6 Summary**

This chapter presented a series of studies aimed at producing a better understanding into the effect of high fibre ingredients (wheat bran and arabinoxylans) on dough aeration and rheology at different levels and particle sizes using a high speed Tweedy 1 mixer, with some comparisons with a low speed mixer.

Investigations were carried out to measure the effects of wheat bran and arabinoxylans on dough aeration during mixing, expansion capacity of yeasted doughs and baked loaf volumes and structures. Dough aeration was studied at different pressures using the Tweedy 1 mixer to understand the effect of bran and AX on aeration during mixing. The Dynamic Dough Density (DDD) system was used to measure the effects of these fibres on expansion capacity of the yeasted dough samples during proving. Comparison of dough formulations mixed using the bench top Minorpin mixer and the high-speed laboratory Tweedy 1 mixer showed that the use of a high-speed mixer results in better gluten development that allows the doughs to expand more to retain gas during proving. Wheat bran had an expected detrimental effect limiting dough expansion and decreasing loaf volume. Arabinoxylans also damaged the expansion capacity of doughs and decreased loaf volumes, with WBAX than SCBAX. The work confirmed that AX can affect bread doughs and baked loaves and presented novel approaches for studying these effects. Although the effects were negative using the two AX samples available for the current work, the approaches presented will be helpful in identifying AX sources and fractions that might be beneficial in breadmaking.

Chapter 8 concludes this thesis and makes recommendations for further research in the field of bread dough aeration and rheology.

## **Chapter 8. Conclusions and Recommendations for further works**

### **8.1 Introduction**

The research on bread and bread dough presented in this thesis has been designed based on two themes: aeration and rheology. The two themes are seldom considered together in the research literature, although they represent fundamental and important concepts for the physical science of bread dough research. Where they have been studied, in common with most bread literature, the emphasis has been on white flour doughs; wholemeal and high fibre breads are, however, healthier alternatives whose consumption should be facilitated and encouraged. Therefore, the aim of the current thesis was to apply tools and approaches for studying the aeration and rheology of bread dough to high fibre bread formulations. When developing the objectives of this thesis in relation to aeration and rheology studies, the emphasis has been in three areas: absorption capacity of dough samples enriched with fibre ingredients to help determine the water absorption capacity of bread doughs; effect of high fibre ingredients on bread dough expansion; and effects of mixing on development of high-fibre doughs and resulting baked loaves.

## **8.2 Progress of current work**

### **8.2.1 Effect of ethanol and retardation time on dough**

Addition of ethanol decreased the maximum dough expansion but did not affect the time to reach the maximum expansion. By contrast, retarding of doughs increased both maximum expansion and the time to reach the maximum. It was therefore concluded that the effect of retardation on dough growth and bread quality was not due to accumulation of ethanol, but rather to changes in dough rheology during retardation. This study also demonstrated the sensitivity and value of the Dynamic Dough Density test for investigating factors that affect the ability of doughs to expand and retain gas.

### **8.2.2 Water absorption determination: Solvent retention capacity test**

Fibre affects the ability of doughs to retain gas to produce loaves of large volumes and fine structure and affects the amount of water required in the dough formulation. However, deciding on the appropriate water adjustment is not straightforward. Adding bran increased the overall water absorption as measured by the SRC test and increased the SRC indicator damaged starch while the indicators of gluten quality and pentosane effects decreased with increased bran levels. Wheat bran AX and sugarcane bagasse AX had higher water absorption capacities, with a larger increase observed with sugarcane bagasse AX. Wheat bran AX and bagasse AX both resulted in a decline in the SRC parameter that indicates gluten quality, this makes sense, as AX can interfere with gluten development. However, opposite behaviours were observed in relation to effects on the measure of damaged starch, with wheat

bran AX increasing this measure and bagasse AX decreasing it; this is less expected, as there is no mechanism by which addition of AX ought to affect damaged starch. This indicates that the conventional interpretation of the SRC may be incomplete when it comes to extending its use from white flours to fibre-rich flours.

### **8.2.3 Effect of wheat bran on bread dough rheology**

The DDD system and creep-recovery measurements were used to investigate the effects of bran level and particle size on dough rheology and gas expansion. Increasing the amount of wheat bran in the formulations reduced the expansion capacity of the dough, more so for fine bran than for coarse bran. Creep compliance reduced as the amount of fine bran added was increased, while the opposite behaviour was observed for coarse bran dough formulations. Higher recovery compliance was observed for fine bran dough formulations, compared to coarse bran dough formulations. Loaf volumes higher than the control loaf were produced when doughs were baked using 5% and 10% fine wheat bran and all WBAX levels and some of SCBAX levels (0.5% and 1%), while the other loaves had lower volumes. The increase in the level of AX resulted in a lower loaf volume.

### **8.2.4 Effect of fibre on bread dough expansion**

Bread doughs prepared using the Minorpin mixer and Tweedy 1 mixer were analysed to determine the expansion capacity using the Dynamic Dough Density system (DDD). Addition of fibre decreased the expansion capacity of dough samples prepared in both the Minorpin mixer and the Tweedy 1 mixer,

with fine bran having a more detrimental effect than coarse bran. Doughs containing wheat bran AX expanded better than those containing sugarcane bagasse AX. Wheat bran AX showed expansion capabilities similar to the control dough produced from the Tweedy 1 mixer while bagasse AX showed a continuous decrease as the level used increased. This behaviour was also observed using the MinorPin mixer and undissolved AX samples. It illustrates the subtle link between aeration and rheology: aeration not only affects the rheology of the static dough through the physical presence of bubbles following mixing, but it also affects the mechanical development of the gluten rheology within the mixer, both by affecting the rate of work input that develops the gluten structure, and also through the turnover of air that supplies oxygen to facilitate this development.

The work presented in this thesis has tackled the difficult issue of how to adjust the water level in dough formulations to account for the addition of fibre, either in the form of bran or in the form of arabinoxylans. It has approached this by using the SRC test, which has previously been applied mainly to white flours. The work has shown the limitations of this test for high-fibre doughs, that the conventional interpretation of effects does not seem to be valid when bran or fibre is added. For example, addition of AX affected the SRC measure that reflects starch damage, although there is no mechanism by which AX could influence starch damage, showing that this measure is not a “pure” indication of starch damage effects, but is influenced by other factors.

The work also extended the use of the DDD system, firstly to demonstrate its sensitivity by investigating effects of ethanol and retardation, demonstrating that the effect of retardation on dough expansion and bread quality is not due to production of ethanol by yeast; this is a new finding and increases our understanding of retarding of doughs. The DDD system was then applied to understand effects of bran and fibre on dough expansion, confirming previous work on the effects of bran (Campbell *et al.*, 2008b,c), and extending that work to begin to understand the effects of isolated AX fibres. In particular, this is the first time that AX from sugarcane bagasse has been considered as a bread dough ingredient. Bran and fibre interfere with gluten development; use of a high-speed mixer was investigated to enhance gluten development in order, at least to some extent, to counter the damaging effects of fibre.

More generally, the current thesis represents the first attempt to bring together both aeration and rheology perspectives to investigate effects of fibre in bread dough formulations. The inherent challenge of the system and the limitations of the work are recognised; however, the work has led to new insights as well as some clear directions that research in this area should pursue, which are described in the next section.

### **8.3 Recommendations for future works**

Measurements of the bubble size distributions in bread dough is challenging, especially with the addition of fibre ingredients; however, such studies are required for a full understanding of how fibre particles affect the initial creation of bubbles during mixing and their subsequent growth and evolution during

proving and baking. X-ray microtomography is a relatively new method that would be valuable to apply to such studies (Cornish, 2019).

The Stable MicroSystems Dough Inflation System is designed for quantifying dough rheology under large strain deformation (Charalambides *et al.*, 2002; Dobraszczyk & Morgenstern, 2003; Sroan & MacRitchie, 2009), and would be a useful tool to apply to understand more fully the effects of fibre on dough rheology.

AX is a potential new class of fibre ingredients that are likely to be beneficial in bread formulations (Campbell *et al.*, 2019; Courtin & Delcour, 2002); there is a need to understand in greater detail the effects of AX from different sources on bread quality, in terms of its effects on the aeration and rheology of the dough that are the basis for bread quality. In particular, AX needs to be extracted and characterised from different feedstocks, its effect on water absorption clarified, and then its use optimised in dough formulations with respect to quality parameters such as loaf volume, crumb structure and texture, and effects on staling.

The work presented in this thesis highlights, to a greater extent than previously acknowledged or demonstrated, the multi-faceted and intimate nature of the interactions between dough aeration and rheology in high-fibre breads. It demonstrates opportunities for the application of fundamental scientific principles of aeration and rheology to better describe, predict and control the bread dough mixing process. A better understanding of the aeration and mixing process of bread dough offers opportunities for optimising existing product

quality and designing new products, and in quality control, product development, sensory assessment, process design and standardisation, and process scale-up.

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