RHEOLOGICAL AND THERMAL PROPERTIES OF SORGHUM DOUGH

ARUN KULAMARVA

Department of Bioresource Engineering
McGill University
Montreal, Canada

August 2005

A thesis submitted to McGill University in partial fulfilment of the requirements of the degree of Master of Science

Your file Votre référence
ISBN: 978-0-494-24710-5
Our file Notre référence
ISBN: 978-0-494-24710-5

For my parents....

ACKNOWLEDGEMENTS

I wish to express sincere appreciation to my advisor James McGill Professor Dr. Vijaya Raghavan for recommending this research topic and for his guidance, instruction and tremendous help throughout my research. I am also grateful to Professor Michael Ngadi for serving as my co-supervisor and for use of his laboratory equipment and supplies.

Generous support for these studies was provided through the Canadian International Development Agency (CIDA) and by my supervisor Dr. Raghavan. McGill University is thanked for the fellowship awarded. The University of Agricultural Sciences, Dharwar, India is thanked for providing the sorghum samples used in these studies.

My specials thanks to Dr. Venkatesh Sosle and Yvan Gariépy for their insightful and helpful comments at assorted stages of my project, and for making various issues clear to me. Yvan Gariépy and Dr. Lamin Kassama are thanked for their help with the Instron and DSC/ Rheometer respectively. Dr. Nirmala Yenagi and Dr. K.C. Shashidhar (University of Agricultural Sciences, Dharwar, India) are acknowledged for their valuable assistance in preparing and conducting the sensory evaluation tests.

Dr. Valerie Orsat and Dr. Samson Sotocinal are thanked for their support and encouragement during the period of my research.

I am grateful to the secretaries in the department, for helping the department run smoothly and for assisting me in many different ways. Ms. Susan Gregus, Ms. Abida Subhan and Ms. Patricia Singleton, deserve special mention.

Special thanks to my friend Jasmine Bhathena for her great help with this manuscript. Christopher Martoni is thanked for the translation of the thesis abstract into French.

Lastly, and most importantly, I wish to thank my parents, Prabha G. Bhat and K. Ganapathi Bhat. They bore me, raised me, supported me, taught me, and loved me. I am grateful to my brother Ashwin, for rendering me the sense and value of brotherhood. To them I dedicate this thesis.

ABSTRACT

Sorghum is a gluten free cereal and forms the staple diet of a majority of the populations living in the semi-arid tropics dough. It is usually consumed in the form of bread made from the grain flour. Dough made with sorghum flour has poor viscoelastic properties compared to wheat dough and mechanical methods for production of sorghum roti are scarce. This study was conducted to elucidate the rheological and thermal properties of sorghum dough to establish its behavior. The temperature and amount of water used for preparation of the dough and the composition of the flour were varied. Wheat, soya and black gram flours were used to prepare the composite doughs. Sensory characteristics of roti made with these dough samples by the traditional method and mechanical compression were studied. The results are presented and their implications are discussed.

RÉSUMÉ

Le sorgho est une céréale sans gluten qui forme le régime principal d'une majorité des populations vivant dans les régions tropiques. Il est habituellement consommé sous forme de pain préparer de la farine de grain. La pâte faite avec de la farine de sorgho a les propriétés viscoélastiques faibles comparées à la pâte de blé et les méthodes mécaniques pour la production du rôti de sorgho sont rares. Cette étude a été amenée pour élucider les propriétés rhéologiques et thermiques de la pâte de sorgho pour établir son comportement. La température et la quantité de l'eau utilisées pour la préparation de la pâte et la composition de la farine ont été variées. Des farines de blé, de soya et de black gram ont été employées pour préparer les pâtes composées. Des caractéristiques sensorielles du rôti faites avec ces échantillons de la pâte par la méthode traditionnelle et la compression mécanique a été étudiée. Les résultats sont présentés et leurs implications sont discutées.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

^0C	Degree Centigrade
A_1	Area under first compression curve
A_2	Area under second compression curve
ABEV	Apparent Biaxial Extensional Viscosity
Ca	Calcium
cal	Calories
CD	Celiac Disease
Cr	Chromium
Cu	Copper
cm	centimeter
dh/dt	Crosshead speed
DSC	Differential Scanning Calorimeter
e_r	Biaxial extensional rate
F	Peak force
FAO	Food and Agriculture Organization
Fe	Iron
G'	Storage modulus
G"	Loss modulus
G*	Complex modulus
g	Gram
h	Final height
h0	Initial height
kN	Kilo Newton
ha	hectares
HNIS	Human Nutrition Information Service
INPHO	Information Network on PostHarvest Operations
mg	MilliGram
Mg	Magnesium
mm	MilliMeter
Mn	Manganese
Mo	Molybdenum
N	Newton
P	Phosporous
p	Probability
Pa	Pascal
RCS	Refrigerated Cooling System
S	Sorghum
s	Second
SB	Sorghum-Blackgram
SB_c	Sorghum-Blackgram-Conventional
Sc	Sorghum-conventional
Sh	Sorghum-Boiling water

SS	Sorghum-Soya
SS_c	Sorghum-Soya-Conventional
SSh	Sorghum-Soya-Boiling water
Std. Dev	Standard Deviation
SW	Sorghum-Wheat
SW_c	Sorghum-Wheat-Conventional
SWh	Sorghum-Wheat-Boiling water
Tg	Glass transition temperature
TPA	Texture Profile Analysis
USDA	United States Department of Agriculture
UTM	Universal Testing Machine
WHO	World Health Organization

Chapter 1

INTRODUCTION

1.1 Background

Sorghum is a major cereal in the semi-arid regions of the world where it is an important food and feed crop. Sorghum species (*Sorghum vulgare* and *Sorghum bicolor*) are members of the grass family. Sorghum is known by a variety of names: great millet and guinea corn in West Africa, kafir corn in South Africa, dura in Sudan, mtama in eastern Africa, jowar in India and kaoliang in China (Purseglove, 1972). In the United States it is usually referred to as milo or milo-maize.

Sorghum was grown in over 44 million hectares around the world in 2004 and the total world production was 60 million tons (FAO Statistical database-FAOSTAT) and considered the fifth most important cereal in the world. Although this production is only about 11-12% of each of the major cereals such as maize, rice and wheat, the food potential of sorghum resides in the ability of the plant to grow well in the semi-arid regions of the world. It is a very hardy crop, which can survive under limiting conditions of water and alkaline soils. The USA is a major producer of sorghum but the grain is not consumed as human food except for a very small fraction, but as animal fodder, whilst in Africa and India the grain is a major food source.

Sorghum forms the staple diet for large populations living in the semi arid tropics of India and Africa, where nearly all the produce is used directly as human food. Sorghum, like other cereals, is an excellent source of starch and protein. It is a gluten free cereal which bears significance in the present day scenario where the occurrence of Celiac Disease (CD), an immunological response to gluten intolerance is on the rise. Grain sorghum contains phenolic compounds like flavonoids (Shahidi and Naczk, 1995) which have been found to inhibit tumour development (Huang and Ferraro, 1992). The starches and sugars in sorghum are released more slowly than in other cereals (Klopfenstein and Hoseney, 1995) and hence it could be beneficial to diabetics (Toomey, 1988).

Sorghum is consumed in various forms around the world like baked bread, porridge, tortillas, couscous, gruel, steam-cooked products, alcoholic and non-alcoholic beverages etc. The potential food and industrial applications of sorghum have been reported (Brannan et al., 2001; Obizoba, 1988). It has the potential to be processed into starch, flour, grits and flakes and used to produce a wide range of industrial products. It can also be malted and processed into malted foods, beverages and beer.

On account of its nutritional significance, easy adaptability to a wide range of growing conditions, lesser water requirements, sorghum has the potential to be incorporated in the diets of human populations around the world, more specifically to those intolerant to wheat.

In India, most of the sorghum produced is consumed in the form of 'roti' which is an unleavened, flat bread. It has been estimated that nearly 70% of the total sorghum produced in India is consumed in the form of roti (Murty and Subramanian, 1981). It forms the staple diet and source of nutrition for the farming communities and agricultural labourers in India.

The traditional method of preparing sorghum rotis is very laborious and cumbersome and is usually performed by the womenfolk in villages. Efforts to mechanize the production process of sorghum rotis have been rare. Sorghum, being a gluten free cereal behaves quite differently from wheat and has poor rheological properties in terms of its pliability, extensibility and rollability. Mechanization of the preparation of sorghum would require elucidation of the properties of sorghum dough which play a role in its behaviour.

The rheological properties of doughs describe how they deform, flow or rupture under applied stress and could be used as a tool in the selection and specification of appropriate raw materials. They are of importance in terms of product formulation and optimization, quality control, machining properties of the dough, scale-up of the process and automation (Bushuk, 1985; Hamann and Macdonald, 1992).

The thermal properties of dough help in characterizing the behaviour of dough during mixing and handling. Storage of doughs in frozen state is a common practise followed in the baking industry.

Sorghum could play a pivotal role in developments towards agricultural improvement in some of the poorest countries of the world if relevant scientific work is carried out to produce the yield, quality and knowledge required by locally-based industries. With the aid of proper processing technology, equipment and methods it would be possible to enhance the nutritional and aesthetic value of the products, providing sorghum an image make-over in the more affluent societies.

1.2 Hypothesis

It is hypothesized that the amount and temperature of water added to sorghum flour to prepare dough plays a role in its properties. Addition of other cereal and legume flours improves its rheological characteristics as well as enhances its nutritional and aesthetic value.

1.3 Research Objectives

This thesis aims to evaluate the rheological and thermal properties of sorghum dough in order to facilitate development of proper handling equipment for sorghum dough for mechanized production of rotis. It attempts to advance the knowledge of sorghum dough properties in the following ways:

1) Evaluate the rheological properties of sorghum dough at varying levels of temperature and quantity of water
2) Analyze the texture profile of dough samples
3) Elucidate the glass transition temperature
4) Study the effect of supplementing sorghum flour with wheat, soya and black gram flours
5) Compare the organoleptic properties of sorghum roti made by traditional and mechanical means

1.4 Outline of Thesis

The objectives of this research are stated in Chapter 1. Chapter 2 surveys the literature concerning the nutritional significance, properties of sorghum dough and means and methods of elucidating these characters. Chapter 3 outlines the experimental conditions, materials used, equipment set up performed in this study. Chapter 4 presents and summarizes the results obtained in this study. Detailed discussions of results are also included in this chapter. Conclusions (Chapter 5) are given at the end of this thesis.

Chapter 2

LITERATURE REVIEW

Sorghum is an important cereal crop in the semi-arid tropics. It is consumed in various forms and constitutes the staple diet of a majority of the population living in these parts of the world. It was grown in over 44million hectares of area around the world and the total production has been to the tune of 60million tons (FAO Statistical Database-FAOSTAT). The worldwide production of sorghum in 2004 is provided in Table 2.1.

Table 2.1: World sorghum production in the year 2004

Country	Area (million ha)	(% total)	Production (million tonnes)	(% total)
Argentina	0.47	1.07	2.16	3.59
Australia	0.63	1.41	1.90	3.15
Brazil	0.91	2.04	2.10	3.49
Burkina Faso	1.60	3.60	1.60	2.66
China	0.78	1.76	3.11	5.16
Ethiopia	1.17	2.64	1.40	2.32
India	9.20	20.72	6.50	10.79
Mali	1.00	2.25	0.65	1.08
Mexico	1.91	4.30	6.30	10.46
Niger	2.30	5.18	0.58	0.96
Nigeria	7.10	15.99	8.10	13.45
Sudan	7.08	15.95	5.19	8.61
United States	2.65	5.98	11.73	19.48
World	44.39	100.00	60.23	100.00

Source: FAOSTAT, (2004).

2.1 Sorghum as food

Sorghum is an important cereal crop in Africa and Asia and is consumed in different forms like tortillas (Bedolla et al., 1983; Choto et al., 1985), porridges (Bello et al., 1990; Rooney and Pflugfelder, 1986; Vivas et al., 1987), couscous (Anglani, 1998; Galiba et al., 1987; Purseglove, 1972) and baked goods (Badi and Hoseney, 1976; Perten, 1983). Anglani (1998) and Purseglove (1972) reviewed the use of sorghum as human food and has reported the various forms in which sorghum is being consumed. Youssef et al. (1990) have worked on preparation of extruded products from sorghum. The use of sorghum in pasta processing has been evaluated (Miche et al., 1977). It is also used in the brewing industry (Palmer, 1992) and as a raw material for glucose production (Devarajan and Pandit, 1996).

Sorghum products including expanded snacks, cookies and ethnic foods are gaining popularity in areas like Japan (Awika and Rooney, 2004). White sorghum products are used to a small extent in the US to substitute for wheat in products for people allergic to wheat gluten (Awika and Rooney, 2004).

In India, sorghum has been most commonly consumed in the form of *roti,* which is an unleavened, flat bread. It's been estimated that nearly 70% of the total sorghum produced in India is consumed in the form of roti (Murty and Subramanian, 1981). It forms the staple diet and source of nutrition for the farming communities and agricultural labourers in India. Rotis are also sun-dried and stored for more than a week. The nutritional composition of sorghum roti has been reported (Pushpamma and Geervani, 1981; Swaminathan et al., 1976) and is given in Table 2.2.

Table 2.2: Nutrient composition of sorghum roti

Nutrient composition of sorghum roti (per 100g)	
Calories	292
Protein (g)	8.0
Fat (g)	1.2
Carbohydrates (g)	61.8
Ash (g)	2.3
Fibre (g)	2.9
Calcium (mg)	67.8
Iron (mg)	5.3
Thiamine (mg)	0.17
Riboflavin (mg)	0.16
Niacin (mg)	0.80

Source: Pushpamma and Geervani, (1981)

Viraktamath et al. (1972) evaluated differences in chemical composition, physical properties and culinary qualities of sorghum varieties and demonstrated that all varieties studied except K-jowar were suitable for making Bhakri which is a dry pan cake, similar to roti.

The kneading characteristics, pliability, extensibility and rollability of dough play an important role in roti making. The lack of gluten leads to supposedly poor extensibility and viscoelastic properties. Despite the fact that most of the sorghum grown in India is used for the production of rotis, there is no suitable equipment for mass production of the same. Existing equipments designed for making a similar product from wheat flour is not suitable for sorghum flour doughs owing to the difference in their viscoelastic properties.

2.1.1 Traditional method of preparation of sorghum roti

Murty and Subramanian (1981) have reported the traditional method of roti preparation in which approximately 50 g of sorghum flour is mixed with 50 ml of warm water and kneaded into smooth dough on a wooden board. It is then rolled into a ball of around 6 cm diameter and flattened in the form of a circular disc which is then further tapped by the strokes of the hand into a flat, circular shape. The roti size could vary from 12 to 25 cm in diameter and 1.3 to 3.0 mm in thickness.

In some cases sugarcane juice, milk or jaggery water has been used instead of water to mix the dough (Subramanian et al., 1983). Use of composite flours comprising sorghum flour and flours from other cereals and pulses like wheat, chickpea, green gram and black gram is also followed. The flattened dough is then baked over a hot plate at temperatures around 300-325^{0}C, frequently turning it over to ensure proper cooking on either sides.

2.1.2 Chemical composition and nutrient value of sorghum

Sorghum is a gluten free cereal which bears significance in the present day scenario where the occurrence of Celiac Disease (CD), an immunological response to gluten intolerance is on the rise. It is reported that in the United States of America the prevalence of CD is 1:22 and 1:39 respectively in first and second degree relatives of CD patients,1:56 in patients having either gastrointestinal symptoms or a disorder associated with CD, and 1:133 in non-risk individuals (Accomando and Cataldo, 2004). Gujral et al. (2004) have reported the prevalence of this syndrome to an extent between 1 in 250 and 1 in 300 worldwide. Grain sorghum contains phenolic compounds like flavonoids (Shahidi and Naczk, 1995) which have been found to inhibit tumor development (Gomez-Cordoves et al., 2001; Huang and Ferraro, 1992). Awika and Rooney (2004) have reviewed the diversity of phenolic compounds in sorghum and their nutritional significance. The starches and sugars in sorghum are released more slowly than in other cereals (Klopfenstein and Hoseney, 1995) and hence it could be beneficial to diabetics (Toomey, 1988).

Studies of the mature sorghum grain structure show that the embryo constitutes roughly 10%, the bran layers (pericarp) about 8% and the endosperm more than 80% of the grain. The relative proportions may vary with genetic background, environment and degree of maturity. The composition of kernel fractions of sorghum is given in Table 2.3.

The largest part of the kernel, the endosperm, is relatively poor in mineral matter and oil content; however, it is a major contributor to the kernel's protein (80%), starch (94%) and B-complex vitamins (50 to 75%). The germ fraction of sorghum is rich in mineral (ash), protein and lipid content but meager in starch. It contains over 68% of the total mineral matter, 75% of the oil and 15% protein of the whole kernel. Sorghum germ is also rich in B-complex vitamins. Sorghum bran is low in ash, protein and rich in fiber

Table 2.3: Nutrient content of whole kernel and its fractions[a]

Kernel fraction	% of kernel weight	Protein[b] (%)	Mineral (%)	Lipid (%)bg	Starch (%)	Niacin (mg/100g)	Riboflavin (mg/100 g)	Pyridoxin (mg/100g)
Whole kernel	100	12.3	1.67	3.6	73.8	4.5	0.13	0.47
Endosperm	82.3	12.3	0.37	0.6	82.5	4.4	0.09	0.40
		(80)	(20)	(13)	(94)	(76)	(50)	(76)
Germ	9.8	18.9	10.4	28.1	13.4	8.1	0.39	0.72
		(15)	(69)	(76)	(20)	(17)	(28)	(16)
Bran	7 9	6.7	2.0	4.9	34.6	4.4	0.40	0.44
		(4 3)	(11)	(11)	(4)	(7)	(22)	(8)

[a] Values in parentheses represent percentage of whole kernel value.

[b] N × 6.25

Source: Hubbard et al., (1950)

(FAO / Information Network on Post-Harvest Operations (INPHO), 1995). Removal of the outer pericarp proportionally increases the protein and reduces the cellulose, lipid and mineral content of the residual grain.

2.1.3 Carbohydrate Content

Akin to other cereals, starch is the principal storage form of carbohydrate in sorghum. With values ranging from 56 to 73%, the average starch content of sorghum is 69.5 percent (FAO / Information Network on Post-Harvest Operations (INPHO), 1995). About 70 to 80% of the sorghum starch is amylopectin and the remaining 20 to 30% is amylose (Deatherage et al., 1955).

Arabinoxylans (pentosans) in cereals play an important role in the bread-making quality and have proven to influence the water balance and rheological properties of dough and starch retrogradation (Izydorczyk and Biliaderis, 1995; Vinkx and Delcour, 1996). They are complex polysaccharides with arabinose residues branching on a xylan backbone. Nandini and Salimath (2001a and 2001b) have worked on the carbohydrate composition and structural features of arabinoxylans of sorghum with good chapatti/roti making quality. Sorghum has been reported to have almost the same amount of starch as wheat flour, but with significantly lower α –amylase (40-50%) and amylolytic (10%) activity when compared to wheat flour (Zhumabekova et al., 1978).

2.1.4 Proteins

The second major component of sorghum grains is protein. Both genetic and environmental factors affect the protein content of sorghum. Fluctuations in the protein content of the grain are generally accompanied by changes in the amino acid composition of the protein (Waggle and Deyoe, 1966). The protein content of sorghum is equivalent to that of wheat and maize (Table 2.4). High fiber content and poor digestibility of nutrients is a characteristic feature of sorghum grains, which severely influences its consumer acceptability.

Sorghum cultivars have been proven to have reduced amounts of lysine, threonine and total sulphur amino acids (Khalil et al., 1984) It is reported that the leucine/isoleucine ratio was imbalanced in comparison with the FAO/WHO reference protein (FAO/WHO 1973) and baking reduced the tannin levels to zero in the cultivars studied. Breads fermented for 18h had higher vitamin B12 and pantothenic acid levels but lower P levels as compared to unfermented breads. There was a slight reduction in amino acid levels in fermented bread.

The nutrient composition of sorghum is at par with wheat and rice, but the poor protein quality due to its high leucine and tannin contents Nair, 1980 and hence it would be beneficial to incorporate other cereal or legume flours to enrich its nutritional quality. Dhingra et al. (1992) evaluated sorghum varieties based on their amino-acids, tannins and physico-chemical characteristics in relation to texture of chapaties.

Table 2.4: Nutrient composition of sorghum (per 100 g edible portion; 12 percent moisture)

Food	Protein[a] (g)	Fat (g)	Ash (g)	Crude fibre (g)	Carhohydrate (g)	Energy (kcal)	Ca (mg)	Fe (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)
Rice (brown)	7.9	2.7	1.3	1.0	76.0	362	33	1.8	0.41	0.04	4.3
Wheat	11.6	2.0	1.6	2.0	71.0	348	30	3.5	0.41	0.10	5.1
Maize	9.2	4.6	1.2	2.8	73.0	358	26	2.7	0.38	0.20	3.6
Sorghum	10.4	3.1	1.6	2.0	70.7	329	25	5.4	0.38	0.15	4.3

[a] N x 6.25

Sources: FAO / Information Network on Post-Harvest Operations (INPHO), (1995); Hulse et al., (1980); United States Department of Agriculture/Human Nutrition Information Service (USDA/HNIS)., (1984).

2.1.5 Starch & protein digestibility

Sorghum grain has been reported to have the lowest raw starch digestibility due to restrictions in accessibility to starch caused by endosperm proteins (Chandrashekar and Kirleis, 1988; Rooney and Pflugfelder, 1986; Waniska et al., 1990). The digestibility of the starch, dependent on hydrolysis by pancreatic enzymes, determines the available energy content of cereal grain. The digestibility of isolated starch of sorghum cultivars ranged from 33 to 48% as against 53 to 58% for corn starches (Sikabbubba,1989).

The texture of the grain endosperm, the particle size of the flour and starch digestibility were found to be strongly correlated with each other. The chemical nature of the starch, particularly the amylose and amylopectin content, is yet another factor that affects its digestibility. The starch digestibility was reported to be higher in low-amylose, i.e. waxy, sorghum than in normal sorghum (Hibberd et al., 1982). The presence of tannins in the grain contributes to the poor digestibility of starch in some varieties of sorghum (Dreher et al., 1984). Tannins isolated from sorghum grain were shown to inhibit the enzyme X-amylose, and they also bind to grain starches to varying degrees (Davis and Hoseney, 1979).

The low starch digestibility has also been attributed to a high content of dietary fiber (Bach Knudsen et al.; 1988a and 1988b). Zhang and Hamaker (1998) have reported lower starch digestibility in case of cooked sorghum flours than normal maize flour, irrespective of the endosperm type. Their results indicate that starch digestibility in cooked sorghum flour is affected by proteins and that this effect occurs during the cooking or cooling process.

Eggum et al. (1983), Elkhalifa et al. (1999) and Mitaru and Blair (1984) have reported a similar reduction in digestibility of sorghum after cooking and it has been estimated that the digestibility decreases by around 24 to 31% (Hamaker et al., 1987; Mitaru and Blair, 1984). The reduction has been attributed to the formation of disulphide bonds during cooking which leads to toughening at the surface and interior of protein bodies.

Protease inhibitors such as tannins are known to reduce in vitro digestibility of endogenous and exogenous proteins in sorghum flours (Navas and Garcia, 2000). It is suggested that the nutritional quality of sorghum flours in terms of protein content and in vitro digestibility could be improved by supplementation of the flour with dehydrated whey. The nutritional value of sorghum could also be improved by supplementing it with high quality protein sources like soya, groundnut or animal proteins from milk, eggs or fish (Ahmed et al., 1993; Delucci and Mastrodi, 1994; Sarode et al., 1983).

Both in vitro and in vivo studies have demonstrated wide variability in protein digestibility of sorghum varieties (Axtell et al., 1981). Values ranging from 49.5 to 70 percent (Nawar et al., 1970) and from 30 to 70 percent (Silano, 1977) have been reported. These values were lower than that observed for corn protein (78.5 percent). In certain sorghum varieties the presence of condensed polyphenols or tannins in the grains is another factor that adversely affects protein digestibility and amino acid availability

(Bach Knudsen et al., 1988a and 1988b; Whitaker and Tanner, 1989). A decrease in the protein digestibility of sorghum on cooking was attributed to reduced solubility of prolamin and its reduced digestibility by pepsin (Hamaker et al., 1986).

Processing of the grain by methods such as steaming, pressure-cooking, flaking, puffing or micronization of the starch increases the digestibility of sorghum starch. This has been attributed to a release of starch granules from the protein matrix rendering them more susceptible to enzymatic digestion (Harbers, 1975; McNeill et al., 1975). The in-vitro digestibilities of starch and protein in sorghum flours have been shown to be improved by cooking in the presence of reducing agents like cysteine, sodium metabisulphite or ascorbic acid (Arbab and El Tinay, 1997; Elkhalifa et al., 1999b; Hamaker et al., 1987; Rom et al., 1992) as the reducing agents minimize the formation of disulphide bonds. Yousif and El Tinay (2001) have shown that the in vitro digestibility of sorghum proteins could be improved by fermentation. Fermentation is also reported to have lead to an increase in lysine and methionine content (Kazanas and Fields, 1981).

Protein digestibility of sorghum could also be improved by malting the grain (Elkhalil et al., 2001). Malt pre-treatment also resulted in a reduction in phytic acid content, which is a significant anti-nutritional factor. Germinated sorghum extract had a very low paste viscosity while pretreatment of sorghum flour with small amounts of papain or trypsin enzymes lead to an improvement in the invitro protein digestibility of sorghum without affecting the paste viscosity (Elkhalifa et al., 1999a). Youssef and Abu-Foul (1998) have evaluated the effect of germination of sorghum on its tannin and starch content and the baking properties of germinated sorghum flour.

2.1.6 Other nutrients

The crude fat content of sorghum is 3 percent; higher than that of wheat and rice but lower than that of maize. The germ and aleurone layers are the main contributors to the lipid fraction. The germ provides about 80 percent of the total fat (Rooney and Serna-Saldivar, 1991). The mineral composition of sorghum grains (Table 2.5) is highly variable.

Table 2.5: Mineral composition of sorghum (mg %) [a]

Grain	Number of cultivars	P	Mg	Ca	Fe	Zn	Cu	Mn	Mo	Cr
Sorghum	6	352	171	15	4.2	2.5	0.44	1.15	0.06	0.017

[a] Expressed on a dry-weight basis.

Source: Sankara Rao and Deosthale, (1980)

In the sorghum kernel the mineral matter is unevenly distributed and is more concentrated in the germ and the seed-coat (Hubbard et al., 1950). Sorghum, in general, is a rich source of B-complex vitamins. Detectable amounts of other fat-soluble vitamins, namely D, E and K, have also been found in sorghum grain. Sorghum as it is generally consumed is not a source of vitamin C. Among B-group vitamins, concentrations of thiamin, riboflavin and niacin in sorghum were comparable to those in maize (Table 4). Sorghum does not contain vitamin A, although certain yellow endosperm varieties contain small amounts of β-carotene, a precursor of vitamin A.

Cellulose, the major insoluble fibre component of sorghum was, which varied from 1.19 to 5.23 percent in sorghum varieties (Kamath and Belavady, 1980).Grain sorghum does contain phenolic compounds other than tannin that affect its sensory and nutritional quality (Hahn et al., 1984). Brannan et al. (2001) have characterized the flavour properties of feed grain and food grain, whole and decorticated sorghum samples and evaluated samples for potential human use.

Soy flour has been incorporated into chapattis made with wheat flour to improve its nutritional quality (Lindell and Walker, 1984; Rajagopal et al., 1983). Organoleptic attributes of chapattis made from wheat flour supplemented with different levels of Bengal gram flour and soy protein concentrate were evaluated by Kaur and Hira (1989). The sensory and nutritional value of sorghum flakes on supplementation with wheat flour has been reported (Al-Kahtani, 1989). Keregero and Mtebe (1994) have evaluated the acceptability of food products including bread and buns made using wheat-sorghum composite flours. Enhancement of the nutritional profile of sorghum by supplementing it with flours from other cereals or legumes has been attempted (Mosha and Vicent, 2004). Khetarpaul et al. (2004) have evaluated the nutritional composition and sensory characteristics of porridges made with different combinations of soy and sorghum grits.

2.2 Rheological properties

Rheological studies are one of the most convenient methods for measuring indicators of quality and texture of food products. The rheological properties of doughs describe how they deform, flow or rupture under applied stress and could be used as a tool in the selection and specification of appropriate raw materials. Knowledge of the fundamental rheological properties of any dough can be an indication of how the dough is going to behave under various processing conditions. They are of importance in terms of product formulation and optimization, quality control, machining properties of the dough, scale-up of the process and automation (Bushuk, 1985; Hamann and Macdonald, 1992).

2.2.1 Dynamic Rheometry

Dynamic rheometry gives information on the flow and elastic properties of materials and has been widely used to elucidate the rheological characteristics of food materials including doughs. In a dynamic measurement the sample is usually put between two round plates or between a cone and a plate. The system is maintained at desired temperature and a sinusoidal deformation at different frequencies is applied. As a result we get storage and loss modulus as a function of frequency. Storage modulus, which represents the energy stored during deformation, is related to the elastic energy of the sample, while the loss modulus, which represents the energy lost during deformation, is related to the viscose energy. The measurement of the storage modulus (G') and the loss modulus (G"), together with the phase angle (δ), could provide a good indication of the stiffness and extensibility of the dough. A high value of G' and a low G'' indicates a stiff dough, while a lower G' indicates a softer and more extensible dough (Weipert, 1990).

The loss tangent (G''/G') represents the samples ability to dissipate energy and provides a measurement of the ratio of the viscous to elastic response of the material being tested. The complex modulus (G*) is usually calculated as a function of frequency using these parameters.

Dynamic rheometry has been successfully used to evaluate the effect of protein content (Hibberd, 1970a; Mita and Matsumoto, 1984; Navickis et al., 1982; Smith et al., 1970); addition of starch granules (Hibberd, 1970b); the effect of moisture content (Berland and Launay, 1995; Hibberd, 1970a; Masi et al., 1998; Phan-Thien and Safari-Ardi, 1998; Smith et al., 1970) on wheat flour dough properties as well as the different fractions of wheat flour (Addo et al., 2001). It has also been used to study the relationship between the quality of bread and the rheological characteristics of wheat flour dough (Autio et al., 2001).

The gluten proteins play a principal role in the rheological properties of wheat flour doughs (Faubian and Hoseney, 1990). The effect of the amount of water present in wheat flour doughs has been evaluated emipirically (Abdelrahman and Spies, 1986) and it is proved that both G' and G'' decrease with an increase in the water content of a dough (Dreese et al., 1988; Hibberd, 1970a; Hibberd and Parker, 1975; Navickis et al., 1982). Georgopoulos et al. (2004) have compared the rheological properties of wheat flour dough and its gluten alone. The effect of water content on the modulii was less significant in gluten as compared to dough.

Petrofsky and Hoseney (1995) have measured the range in modulii of dough made with starch and gluten and demonstrated the starch-gluten or starch-gluten-water interactions in dough.

The principal of dynamic rheometry has also been applied to a gluten free cereal like rice as well. Sivaramakrishnan et al. (2004) studied the rheological properties of two varieties of rice in comparison to wheat dough to assess its suitability for making bread.

Sorghum based composite flours have been evaluated in bread making over the years (Bhatia and Khetarpaul, 2002; Bugusu et al., 2001; Dendy, 1970; Kim and De Ruiter, 1968; Morad et al., 1984; Ortega-Ramirez et al., 1995; Subramanian et al., 1983). Bread baked with 0, 5, 10 and 15% wheat-sorghum composite flour showed good volume, good external and internal characteristics and a high percentage of acceptability (Zaparrart and Salgado, 1994). However, in all these studies, addition of sorghum flour to wheat flours at higher levels lead to poor dough rheological properties. Sorghum based composite flours yielded dough with a tough texture (Pringle et al., 1969; Subramanian et al., 1983) and breads with lower loaf volume (Hart et al., 1970). The water absorption and extensibility of wheat dough decreased on addition of sorghum flour and it also resulted in lesser loaf volume and weight of bread (Hussein et al., 1977).

The addition of wheat flour to sorghum flour improved the dough rheological properties (Foda et al., 1987; Rao and Rao, 1997). The rheological characteristics and breadmaking quality of sorghum composite flours can also be improved by the addition of exogenous gluten proteins (Carson and Sun, 2000), zein (Bugusu et al., 2001) or cysteine (Elkhalifa and El Tinay, 2002).

Chandrashekar and Desikachar (1983) analyzed the rolling quality of sorghum dough in relation to some of its physiochemical properties. They have correlated good rolling quality with lower gelatinization temperature, higher peak viscosities and set backs as determined by a Brabender Viscograph. Lower gelatinization temperatures lead to greater degree of gelatinization resulting in better adhesive doughs which would be easily rolled. Higher water uptake at 70^0C was correlated to starch damage in flour and the amylose, protein and prolamine content had no relation to the rolling quality, which was determined subjectively. Equal quantities of flour and boiling water for mixing have been recommended.

Addition of reducing agents to improve the digestibility of the starch and protein in sorghum has been discussed earlier. However, an increase in the gelatinization temperature and peak viscosity of sorghum has been reported due to the effect of reducing agents (Elkhalifa et al., 1999b).

Dreese et al. (1988a) reported that the storage modulus (G') of wheat flour-water doughs increased between 55 and 75^0C while the ratio of loss modulus to storage modulus decreased rapidly and the change was irreversible. The magnitude of the temperature-dependent change in the rheological characteristics was found to be proportional to the starch content in the dough. Addition of pre-gelatinized starch to gluten-starch blends yielded similar results.

Torres et al., (1994) have demonstrated an increase in the maximum stress peak, stress during relaxation period and dough viscosity when sorghum flour was used in 70:30 wheat-sorghum composite dough. Sorghum flour with smaller particle size distribution had greater water absorption and stress during relaxation. The rheological properties were evaluated by uniaxial compression tests.

The chemical, sensory and rheological properties of porridges made from blends of sprouted sorghum, bambara groundnuts and fermented sweet potatoes were examined by (Nnam, 2001).

2.2.2 Textural properties and texture profile analysis

The rheological properties of dough in relation to its texture measurements could help understand the behavior of dough during processing. The texture profile analysis (TPA) has been used for the textural evaluation of a wide range of foods. It was originally developed for the General Foods Texturometer (Szczesniak, 1963; Szczesniak et al., 1963). Bourne (1968, 1974 and 1978) has demonstrated a method to evaluate texture profile parameters from the force-deformation curves obtained by the Instron - Universal Testing Machine (UTM). The food sample is compressed twice, successively, between two parallel plates and the force-time curves are plotted. Some of the textural parameters derived from these curves are defined (Bourne, 1968a) as follows:

Hardness- the peak force during the first compression cycle.

Cohesiveness- the ratio of the positive force area during the second compression to that during the first compression.

Adhesiveness- the negative force area for the first compression, representing the work necessary to pull the compressing plunger away from the sample.

Springiness or elasticity – the height that the food recovers during the time that elapses between the end of the first compression and the start of the second compression.

Gumminess- the product of hardness and cohesiveness.

Chewiness- the product of gumminess and springiness.

Mechanical and textural properties of foods have been determined from the stress-strain relationships obtained through uniaxial compression tests (Bagley and Christianson, 1986; Bagley and Christianson, 1987; Casiraghi et al., 1985; Peleg, 1977). The elastic and viscous properties as functions of time and strain are necessary to characterize dough. Chatraei et al. (1981) have interpreted the results of the uniaxial compression procedure in terms of Apparent Biaxial Extensional Viscosity (ABEV) for application in flattening, sheeting and rolling of doughs.

The influence of the chemical composition, dough functional properties and the effect of surfactants on the ABEV and texture profile of wheat dough and the quality of *parotta* (a kind of flat bread) was evaluated by Indrani and Rao (2000 and 2003). The rheological characteristics, ABEV, hardness and cohesiveness were reported to have a high correlation with the overall quality score of *parotta*.

Padua and Whitney (1982) derived an expression for the deformation of corn dough under a constant load between two parallel plates. Diehl (1981) has reviewed rheological techniques for texture and quality measurement of solid and liquid food products made from sorghum. Bhattacharya et al. (1999) have evaluated the effect of incorporating different types of cereal flours on the viscoelastic properties of black gram dough in relation to the sensory textural attributes by using uniaxial compression method. They have reported higher resistance to compression when sorghum flour was added to black gram flour.

Black gram flour when added to wheat flour yielded greater extensibility (Gujral and Pathak, 2002). They used the Instron Universal Testing Machine to determine the tensile properties of chapaties prepared from composite flours. Stiffness, breaking strength and deformation of rectangular strips of chapaties were measured by a tensile test performed using an Instron by Waniska (1990). Kernels with waxy endosperm had lower strength and stiffness and a greater deformation to breakage than non-waxy types. The tensile test was used by Rizley and Suter (1977) to show that sorghum varieties with a corneous endosperm texture yielded stronger tortillas than those with an intermediate endosperm.

Subramanian et al. (1983) used a back extrusion cell mounted on an Instron to measure textural characteristics of sorghum dough and reported that the force and energy required for the extrusion were higher in case of good quality cohesive dough. The influence of flour-water-soluble components on dough cohesiveness has been discussed.

Stickiness of a food product depends on both the cohesive forces in the food and the adhesive forces between the food and with whatever it comes into contact (Sherman, 1969). By pulling two parallel plates apart at a constant rate, a measure of stickiness could be obtained (Kumar et al., 1976).

Dhingra et al. (1992) have reported that grain hardness had a positive correlation with the texture and the amylase content with overall acceptability of chapattis made from sorghum flour. They used the Instron Testing Machine for recording dough hardness. The peak force to compress dough samples to 75% of original thickness was considered as the hardness. They have confirmed the role of water soluble components in determining dough hardness. Subramanian and Jambunathan (1981) had earlier reported a similar observation. A higher yield of desirable sorghum couscous granules was reported when flours from hard grain sorghum were used (Aboubacar and Hamaker, 1999).

The textural characteristics of cooked sorghum grain as determined by texture profile analysis and rapid visco analyzer measurements were reported by Lee et al. (2002). They concluded that the kernel size had no consistent effect on the visco analyzer measurements (peak viscosity, holding strength and final viscosity) while a larger kernel size yielded a better texture profile in terms of higher values for hardness, less sticky and more cohesive product. The effect of raw and gelatinized sorghum flours on the structure and texture of baked corn and tortilla chips have been studied (Quintero-Fuentes et al., 1999) and a significant effect has been reported.

2.3 Thermo-physical properties

The physico-chemical properties of the starch affect the textural characteristics of the food preparations made from grain. The behavior of starch in water is temperature and concentration dependent (Whistler and Paschall, 1967). Grain starches in general show very little uptake of water at room temperature and their swelling power is also small. At higher temperatures, water uptake increases and starch granules collapse, which leads to solubilization of amylose and amylopectin to form a colloidal solution. This is the gelatinization stage. Heat treatment of starch in a limited amount of water leads to swelling of the granules with very little loss of soluble material and partial gelatinization of the starch.

On cooking, the gelatinized starch tends to return from the soluble, dispersed and amorphous state to an insoluble crystalline state. This phenomenon is known as retrogradation or setback; it is enhanced with low temperature and high concentration of starch. Amylose, the linear component of the starch, is more susceptible to retrogradation. The gelatinization temperature of isolated sorghum starch and that of finely ground flour of the corresponding endosperm has been reported to be the same. On the other hand the pasting temperature, i.e. the temperature at which starch attains peak viscosity when heated with water to form a paste, was found to be about 10°C higher for the sorghum flour than for the isolated starch (Akingbala and Rooney, 1987). Zhang and Hamaker (2003) have reported the interactions between sorghum starch, protein and free fatty acids by analyzing the paste viscosity profile in a Rapid ViscoAnalyzer.

The starch gelatinization range of sorghum (68-78^{0}C) is higher than that of wheat (58-64^{0}C) (Akingbala et al., 1988; Hoseney, 1994). This factor along with a low water holding capacity have been correlated with grittiness, dry mouthfeel and higher firming ratio of sorghum composite breads (Munck, 1995). Hugo et al. (2000) have evaluated the effect of malting of sorghum and wet-heat treating the malt in order to reduce the pasting temperature and increase the water holding capacity of sorghum flour so as to yield softer bread more resistant to crumbing when used with wheat flour.

Suhendro et al. (2000) have worked on the cooking characteristics of sorghum-flour noodles and reported better results when the flour water mixture was preheated. They have also stated that starch gelatinization occurred to a higher degree in finer flours than coarse flours and yielded better noodles. Steam pre-treatment of the flour has been suggested to induce faster gelatinization. Some characteristics of sorghum starches are presented in Table 2.6.

It has been suggested that, as with rice, the cooking characteristics of sorghum maybe influenced by the relative proportions of amylase and amylopectin present. The quality of cooked sorghum has been strongly associated with the total and soluble amylose content

Table 2.6: Characteristics of isolated starches of sorghum

Grain	Amylose (%)	Gelatinization temperature (°C)		Water-Binding capacity (%)	Swelling at 90°C (%)	Solubility at 90°C (%)	Viscosity (amylograph -- Brabender units)			
		Initial	Final				At 93°-95°C	After holding at 95 °C	Cooled to 35° or 50°C	After holding at 35°C or 50°C
Sorghum	24.0	68.5	75.0	105	22	22	600	400	580	520
Sorghum (waxy)	1.0	67.5	74.0	-	49	19	380	290	390	350

Source:FAO / Information Network on Post-Harvest Operations (INPHO), (1995) of the grain and also the soluble protein content (Cagampang and Kirleis, 1984). The availability of gelatinized starch and the amount of amylopectin and amylase affect the functionality of dough used for baked snacks. Increasing the free amylopectin content has been shown to yield softer, cohesive dough and provides film formation, sheet extensibility and better puffing when heated (Addesso et al., 1995).

The swelling power of starch and its solubility significantly influenced the cooking quality of sorghum (Subramanian and Jambunathan, 1982). The percentage weight increase of cooked grain was negatively correlated with starch solubility at 60°C, a temperature at which most of the starch granules will have reached gelatinization stage. The swelling power of starch at 60° and 90°C and solubility at 25° and 50°C were inversely correlated with gruel solid content, which directly depended on the starch content of the grain. The starch gelatinization temperature did not show any significant effect on the cooking quality of sorghum.

Plasticity of sorghum flour dough mostly arises from the gelatinization of starch when the dough is prepared in hot or boiling water. The stickiness of the cooked flour is a function of the starch gelatinization. Porridge prepared from hard endosperm of sorghum is less sticky than that prepared from grains with a larger proportion of floury endosperm (Cagampang et al., 1982).

Dough prepared with cold water has poor adhesiveness and is difficult to roll thin. Thus heat modification of the starch when the dough is prepared with hot water determines its rolling properties (Desikachar and Chandrashekhar, 1981). Higher water uptake, low gelatinization temperature, high peak paste viscosity and high setback are the starch properties that have been shown to be associated with good quality of roti, the unleavened bread that is the most common form in which sorghum is consumed on the Indian subcontinent. Almeida-dominguez et al. (1991) found that low-amylose or waxy sorghum produced sticky dough (masa) and was not suitable for preparation of tortillas. Desikachar and Chandrashekhar (1981) have stressed on the importance of hydration capacity of the grain as a factor that affects the cooking quality and sensory attributes of sorghum products.

2.3.1 Differential Scanning Calorimetry

The differential scanning calorimeter (DSC) has been used as an effective tool in determining the thermal properties of a wide range of food products. A quantitative measure of phenomena like gelatinization and glass transition is provided based on the heat flow associated with order-disorder transitions (Stevens and Elton, 1971). Abundant research has been done on the use of the DSC for measuring thermal characteristics of dough and flour samples.

The physical states of most foods are often related to the phase and state transitions occurring in them during preparation, processing and storage. Glass transition has been proved to be an important factor in the stability of foods (Elizalde and Pilosof, 1999;

Lemeste et al., 1992; Slade and Levine, 1995). The glass transition phenomenon has a significant effect on texture, stability, flavor release and other quality attributes of foods (Noel et al., 1990). It is a second-order time-temperature-moisture dependant phase transition and is generally characterized by a discontinuity in physical, mechanical, electrical, thermal and other properties of a material. Food materials are in an amorphous, rubbery state below the glass transition temperature and considered very stable at the glassy state. At this temperature there is an endothermic shift in the DSC curve corresponding to the increase in specific heat.

Several authors have studied the properties and phase transitions in frozen wheat dough (Laaksonen and Roos, 2000, 2001 and 2003; Rasanen et al., 1998). Doescher et al. (1987) have studied cookie dough setting during baking as related to the change in glass transition temperatures.

The influences of glassy and rubbery states, and of plasticization by water, on the thermal, mechanical, rheological, structural and textural properties of doughs and baked products has been studied by the food polymer science approach (Slade and Levine, 1995). The glass transition behaviour of starch and wheat glutens is well documented (Slade and Levine, 1995). The glass transition temperature of wheat gluten proteins have been reported by Noel et al. (1990).

Micard et al. (2001) studied the thermal properties (glass transition temperature and change in heat capacity) of raw and processed wheat gluten as a function of water content. Slade and Levine (1995) have reviewed the dependence of glass transition on the composition and chemical structure of wheat flour in relation to cookie baking. Theoretically, the plasticizing effect of water on Tg has been described by the Gordon-Taylor, Couchman-Karasz or Kwei equations (Couchman and Karasz, 1978; Gordon and Taylor, 1952; Kwei, 1984).

Akingbala et al. (1988) elucidated the gelatinization temperature of starches isolated from 24 non waxy varieties of sorghum using a Differential Scanning Calorimeter and have reported the onset, peak and end gelatinization temperatures to be 71.0 ± 1.0, 75.6 ± 0.9 and 81.1 ± 1.1 ^{0}C respectively and the gelatinization energies to be in the range of 2.51 to 3.96 cal/g. They found no significant relationship between the thermal properties and grain characteristics like endosperm texture and type, pericarp thickness and color, kernel mass and grain density. No significant relationship between the thermal properties of sorghum and physicochemical properties of their starches was reported (Akingbala et al., 1988; Akingbala and Rooney, 1987).

Zhang and Hamaker (1998a) evaluated the low alpha amylase starch digestibility of cooked sorghum flours using a DSC. Thermal transition temperatures of sorghum wax during storage was measured by differential scanning calorimetry (Hwang et al., 2004).

The literature cited emphasises the consequence of the rheological and thermal properties of cereal doughs with respect to their bread making characteristics. The importance of sorghum in terms of its nutritional significance and agronomic advantages especially with reference to developing countries in the semi-arid tropics is immense. An effort to evaluate the properties of sorghum dough in relation to roti making would therefore be beneficial. The supplementation of cereal or legume flours could lead to an improvement in its nutritional worth leading to value addition to the product.

Chapter 3

EXPERIMENTAL METHODS AND MATERIALS

3.1 General description

The rheological and thermal properties of sorghum dough made with different levels of water, composite flour and temperature of mixing water were evaluated in this study. The rheological and textural characteristics of storage modulus, loss modulus, Apparent Biaxial Extensional Viscosity (ABEV), cohesiveness, hardness, adhesiveness etc were measured by dynamic rheometry and an Instron Universal Testing Machine (UTM). The glass transition behaviour of the dough samples were studied with a DSC. A comparison of sorghum rotis made by traditional means and by compressing with the Instron was made by sensory evaluation.

Sorghum flour (12% moisture content, wet basis, variety M-54) was procured from the University of Agricultural Sciences, Dharwad, India. Wheat gluten (80% protein, 9% moisture, wet basis) was supplied by Sigma Aldrich, St. Louis, USA. and whole wheat flour, soya flour and blackgram flour (14% moisture content, wet basis) were obtained from a local store.

3.2 Rheological properties

3.2.1 Preparation of dough

Dough samples were made by mixing 50 g of sorghum flour with different proportions of water (35, 40, 45 and 50 ml). The temperature effect was checked by using water at 22 and 100^{0}C. The dough samples were thoroughly mixed and kneaded. Composite flours made by using 75% (of total flour mass) of sorghum flour and 25% of wheat, soya or black gram flours were also used for the study.

3.2.2 Instron – Universal Testing Machine measurements

Dough was sheeted by compressing a ball of dough between two parallel plates made of acrylic separated by spacers to yield a sheet of 1.0 cm thickness. Circular discs of 4.0 cm diameter were cut using a cutter. Each disc was equilibrated to 25^{0}C in a covered petri dish for a period of 30 min.

The Instron- Universal Testing Machine (M 4502, Instron Corp., Canton, MA) was used to perform the texture profile analysis and measure the apparent biaxial extensional viscosity (ABEV) of the prepared dough samples. The textural properties of hardness, cohesiveness and gumminess were measured using the method of Peleg (1976) and Bourne (1978) under the following conditions –

Plunger diameter - 8.5cm

Load cell - 500 N

Crosshead speed - 50mm.min^{-1}

Compression level - 60%.

This method has been successfully used by researchers to determine the rheological properties of a parotta, a flat, baked bread made from wheat (Indrani and Rao, 2000 and 2003). The textural parameters studied were defined as follows:

Hardness- the peak force (F) measured during the first compression cycle

Cohesiveness- A_2/A_1 the ratio of the positive force area (A_2) during the second compression to that during the first compression (A_1)

Gumminess- the product of hardness and cohesiveness.

The uniaxial compression method of Bagley and Christianson (1986) was used to measure the ABEV. The following conditions were used –

Plunger diameter - 8.5cm

Load cell - 500 N

Crosshead speed - 50mm.min^{-1}

Compression level - 50%

Relaxation time – 60s.

The sample-geometry interface was lubricated with a thin layer of vegetable oil to minimise the frictional losses at the interface during compression (Casiraghi et al., 1985). Sprinkling a very thin layer of flour on the interface was found to be beneficial.

ABEV of the dough was computed as,

$$ABEV = (Fh) / (\pi R_o^2 h_o e_r), \qquad \text{- - - (1)}$$

where,

F: is the peak force in N

h: is the final height in m

R_o: is the initial radius in m

h_o: is the initial height in m

e_r = [dh/dt] [1/(2h)] in s^{-1} is the biaxial extensional rate

dh/dt is the crosshead speed in $m.s^{-1}$ and

ABEV: is the Apparent Biaxial Extensional Viscosity in Pa.s.

All measurements were conducted at 25^0C and in triplicate.

3.2.3 Dynamic rheological measurements

An AR2000 Dynamic Rheometer (TA Instruments, Texas, USA) was used for rheological measurements. Oscillatory tests were conducted using the 40 mm parallel plate geometry. The instrument gap was set at 2 mm. Dough samples were loaded between the parallel plates and the edges were trimmed with a knife. A solvent trap was used to prevent dehydration. The samples were rested between the plates for 5 min to attain equilibrium.

The samples were initially tested for the linear range of shear stress. Subsequent oscillatory tests were done at a constant oscillatory stress value of 6 Pa and to a frequency range of 0.1 and 100 Hz which corresponds to the linear range of shear stress. All measurements were conducted at 25^0C and in triplicate. The results were analyzed on the TA Rheology Advantage data analysis software.

3.3 Differential Scanning Calorimetry

3.3.1 Preparation of dough

About 50 g of sorghum flour was mixed with different proportions of boiling water (45, 50, 55 and 60 mL). Once the optimum water requirement was established, then the temperature effect was checked (two temperature levels: 22 and 100^0C).

The dough samples supplemented with gluten at the rates of 5 and 10% (of total mass) and wheat flour at the rates of 10, 20 and 30% (of total mass) were also analyzed. The dough samples were mixed thoroughly and kneaded.

3.3.2 DSC measurements

A TA Instruments Q-100 DSC (TA Instruments, Texas, USA) was used to determine the phase transition in the samples. The Refrigerated Cooling System (RCS) was used for this instrument. The instrument was calibrated using sapphire and indium. Nitrogen at the rate of $50mL.min^{-1}$ was used as the purge gas.

Around 10 mg of sample was taken in hermetically sealed aluminium pans for analysis. An empty pan was taken as reference. Samples were heated between -80 to120^0C. The ramp rate employed was 10^0C per minute. The samples were studied in triplicate. Results were analyzed and the glass transition temperature determined using the Universal Analysis software from TA Instruments.

3.4 Sensory evaluation of rotis

Sensory evaluation of rotis made by the traditional method and rotis prepared by unilateral compression in an Instron Universal Testing Machine was carried out by an expert panel consisting of 11 members to evaluate the organoleptic properties.

3.4.1 Determination of optimum water level for dough preparation

Ten grams of sorghum flour was taken in a beaker and water was added from a pipette drop wise, with consistent mixing of the dough mixture until a dough of desired consistency was reached. A similar procedure was followed for complex flour doughs constituting 75% sorghum flour and 25% of wheat, soya or black gram flours. A 1:1 ratio of water and flour was shown to be the ideal proportion in terms of consistency, kneading characteristics and texture as evaluated by observation.

3.4.2 Preparation of rotis

Dough samples for roti preparation were prepared by mixing a 1:1 ratio of flour and water and kneading thoroughly. Fifty grams of dough was rolled into a ball and then tapped with fingers to form a circular disc 20 cm in diameter and 2 mm thick. It was then baked on a Teflon hot plate by turning over frequently until it was cooked well. The baking temperature was around 350^0C.

The Instron was used to prepare rotis by mechanical means. Fifty grams of dough was compressed to a thickness of 2 mm using a 500 N load cell between two circular parallel plates around 23 cm in diameter. The peak force required for every sample was recorded.

3.4.3 Sensory evaluation

The rotis were scored for the following characteristics: appearance, color, taste, flavour, pliability, texture and mouthfeel. A nine point hedonic scale was used with a score of 1 representing 'dislike extremely' and a score of 9 representing 'like extremely'. Samples were given to the panelists in a random order.

3.5 Statistical methods

Statistical analysis of the data was carried out using the General Linear Model (GLM) procedure in SAS (SAS Institute, Cary, North Carolina) and the means were separated by the Duncan's multiple range test. In all statistical tests the difference between variables was considered to be significant at a 95% confidence level ($p<0.05$). The samples were evaluated in triplicates.

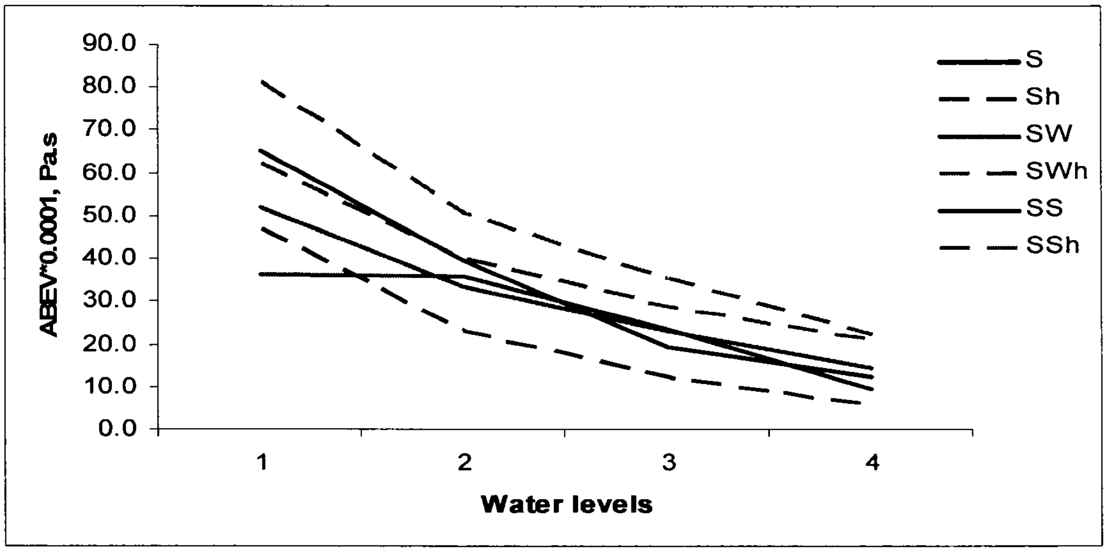
Chapter 4

Results and Discussion

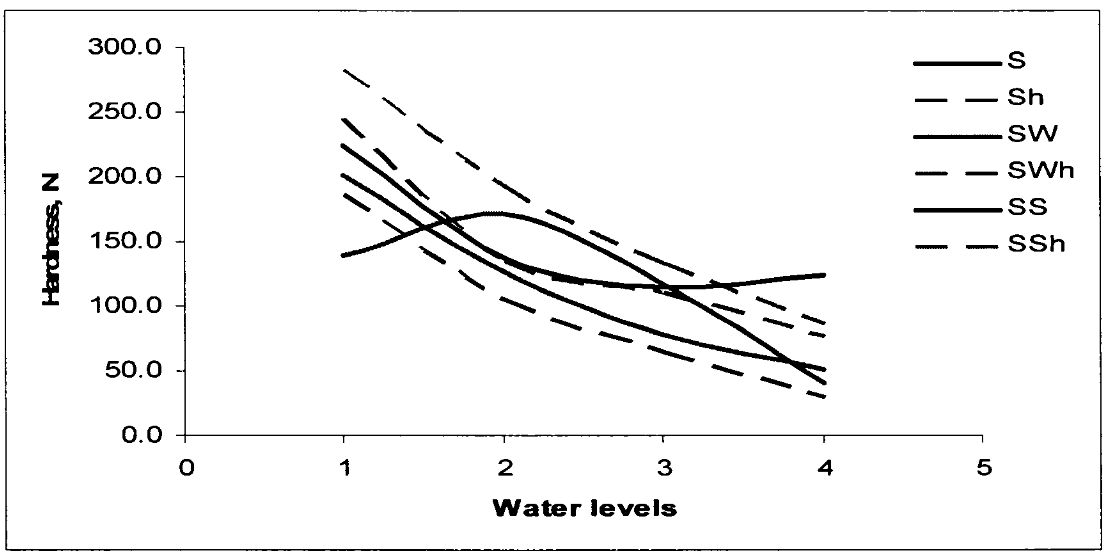
4.1 Texture Profile Analysis

The apparent biaxial extensional viscosity (ABEV) of the doughs, as defined in equation 1, decreased with increase in water level, indicating that a ratio closer to 1:1 for amount of flour and water used for mixing, yielded doughs with better extensibility. The sorghum flour doughs had lesser ABEV values when boiling water was used for dough mixing. This could be explained by the gelatinization of the starch which improves the adhesivity of dough rendering them more suitable for rolling/flattening. Chandrashekar and Desikachar (1983) have reported similar results. The effect of water level and temperature of mixing water on ABEV and hardness is shown in Figure 4.1.

Dough samples made with composite flours had significantly smaller ABEV values only at lower water levels. At higher cold water levels the difference between the samples was minimal. Addition of boiling water had a contrary effect on composite flours as compared to sorghum flour doughs. The ABEV values were significantly higher for composite flour doughs when boiling water was used. Sorghum-soya composite flour doughs made with boiling water had the highest ABEV values, while, plain sorghum flour dough made with boiling water had the least ABEV values among all the combinations. This could be explained by the higher protein content in case of composite flours.



(a)



(b)

Figure 4.1: (a) ABEV, Pa.s and (b) Hardness, N, of dough samples made at different water levels.

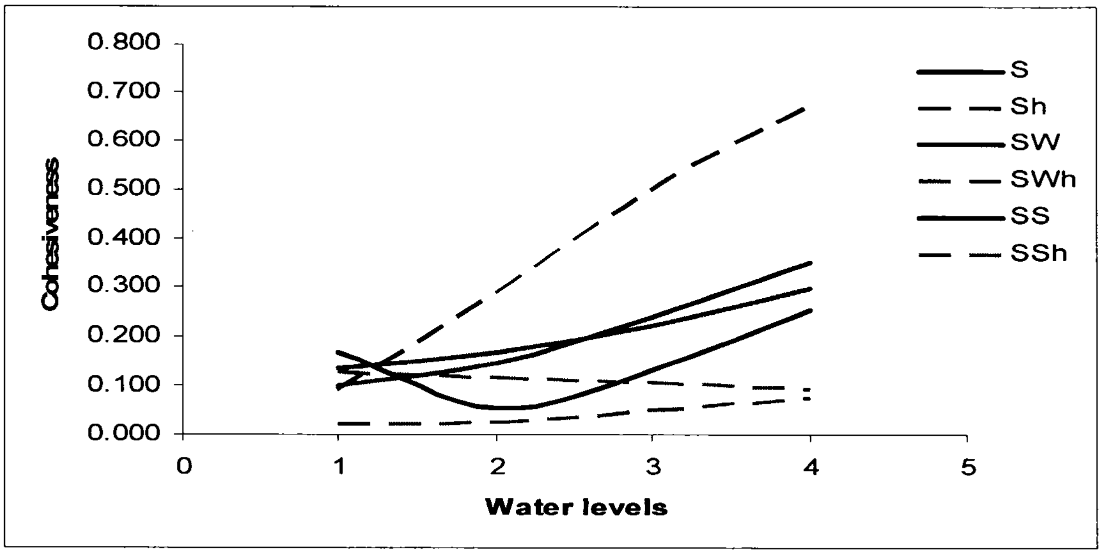
Flour types used to make dough samples - S: Sorghum (100%), SW: Sorghum (75%) + wheat (25%), SS: Sorghum (75%) + Soya (25%). Numbers 1,2,3,4 on X-axis refer to 35, 40, 45 and 50ml respectively, of water used for mixing 50g of flour. "h" represents the use of water at 100^0C for dough mixing, the rest refer to water at 22^0C.

Similar trends were observed in hardness values of dough samples. The hardness of dough samples generally decreased with increase in water. Boiling water reduced the hardness of sorghum flour doughs significantly compared to doughs made with cold water; while, it had the opposite effect in case of composite flour doughs. The cohesiveness of dough samples generally increased with water level (Figure 4.2). Plain sorghum flour dough seemed to have lowest value for a water level of 40 ml per 50 g of dough.

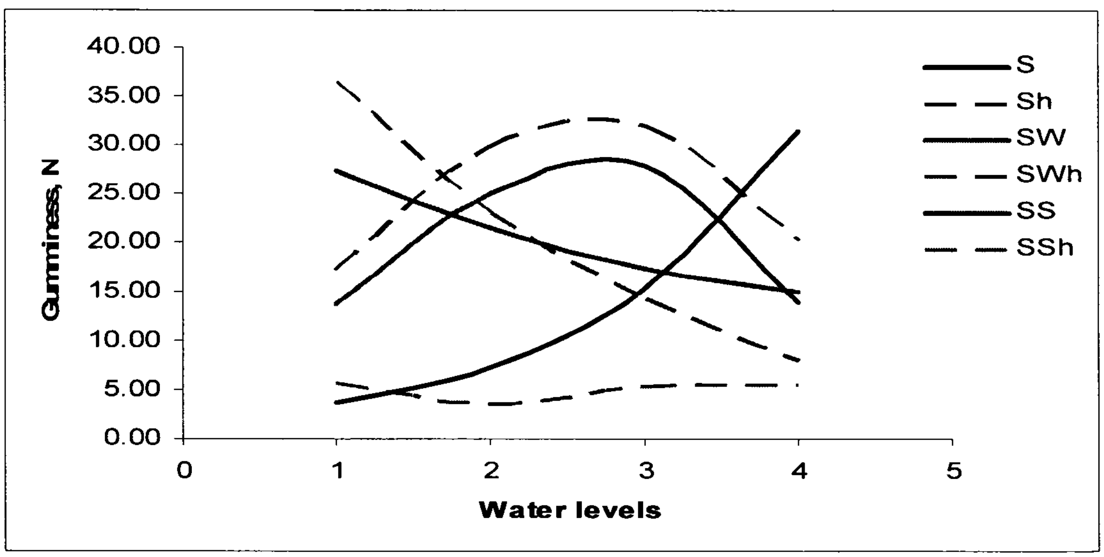
Boiling water seemed to improve the cohesiveness of sorghum flour dough which could be due to starch gelatinization and the difference was more significant at higher water levels. The increase in this attribute implies the improvement in elastic nature of the dough and better extensibility. The cohesiveness of sorghum-soya composite flour dough made with boiling water, reduced with increase in water level.

Gumminess values of sorghum flour dough increased with water level. Boiling water lead to higher values, but, at higher water levels, it tends to decrease. The interactions were more complex for this attribute. Sorghum-wheat composite flour dough showed reduction in gumminess with increase in water level as well as temperature. Sorghum-soya composite flour dough had higher gumminess at low water level and boiling water combination, but at higher water levels, the gumminess reduced significantly.

The rheological properties measured by the Instron are summarized in Table 4.1.



(a)



(b)

Figure 4.2: (a) Cohesiveness and (b) Gumminess of dough samples made at different water levels.

Flour types used to make dough samples - S: Sorghum (100%), SW: Sorghum (75%) + wheat (25%), SS: Sorghum (75%) + Soya (25%). Numbers 1,2,3,4 on X-axis refer to 35, 40, 45 and 50ml respectively, of water used for mixing 50g of flour. "h" represents the use of water at 100^0C for dough mixing, the rest refer to water at 22^0C.

Table 4.1: Rheological properties of dough samples measured by the Instron.

	Characteristics							
	ABEV*10^{-4}, Pa.s		Hardness, N		Cohesiveness		Gumminess	
Flour type	22^{0}C	100^{0}C	22^{0}C	100^{0}C	22^{0}C	100^{0}C	22^{0}C	100^{0}C
S1	65.2b	47.0c	224c	187d	0.167k	0.092hij	3.68j	17.1hi
S2	39.7d	23.3g	138f	105i	0.053jk	0.288d	7.30j	29.9bc
S3	19.5gh	12.4i	115hi	64.3kl	0.133fgh	0.499b	15.3i	31.9b
S4	12.3i	5.89j	125fgh	30n	0.254de	0.670a	31.5bc	20.1gh
SW1	51.9c	62.3b	202d	244b	0.136fgh	0.023k	27.3cde	5.66j
SW2	33.3ef	40.2d	127fgh	135f	0.168f	0.026k	21.4fgh	3.50j
SW3	23.3g	28.8f	78jk	111hi	0.223e	0.049jk	17.4hi	5.44j
SW4	14.6hi	20.9g	51lm	76.7jk	0.297d	0.074ij	15.0i	5.58j
SS1	36.3de	81.3a	139f	283a	0.100ghi	0.129fgh	13.8i	36.5a
SS2	36.2de	50.8c	171e	193t	0.147fg	0.119ghi	25.0def	23.1efg
SS3	23.6g	35.4de	117ghi	134fg	0.239e	0.107ghi	27.9bcd	14.3i
SS4	9.56ij	22.1g	40mn	86j	0.352c	0.094hij	13.9i	8.04j

Flour types used to make dough samples - S: Sorghum (100%), SW: Sorghum (75%) + wheat (25%), SS: Sorghum (75%) + Soya (25%). Numbers 1,2,3,4 refers to 35, 40, 45 and 50ml respectively, of water used for mixing 50g of flour. Means in adjacent columns under every parameter followed by a different letter differ significantly ($p<0.05$).

4.2 Dynamic rheological measurements

The dynamic moduli of the dough samples increased with the frequency, which refers to a more viscous behavior of the samples. The trends were fairly linear for the sorghum flour dough samples for the frequency range studied, while sorghum-wheat composite flour dough samples showed some variability at higher values of frequency. The higher dynamic moduli at higher frequencies imply more bonds involved in the mechanical response of the system due to a stress or strain applied over a shorter time.

The G' values were more than the G'' (loss modulus) values in all cases (Figures 4.3 & 4.4), as expected for highly structured materials, which implies that the doughs were more elastic than viscous. The slope of the frequency curve is relatively flat, characteristic of the viscoelastic behavior in the rubbery plateau region (Graessley, 1984). A typical variation in moduli with frequency for the dough combinations at a mixing ratio of 1:1 is shown in Figure 4.4. The Tan δ values for all samples were less than one, indicating a more elastic than viscous characteristic.

The softening effect of water on sorghum flour dough was obvious by the decrease in G' (storage modulus) values with increase in water levels (Figure 4.3). The trends were similar to earlier reports (Berland and Launay, 1995). The G' values of the composite flour doughs increased with water content contrary to the behavior of sorghum flour dough (Figures 4.7 & 4.6).

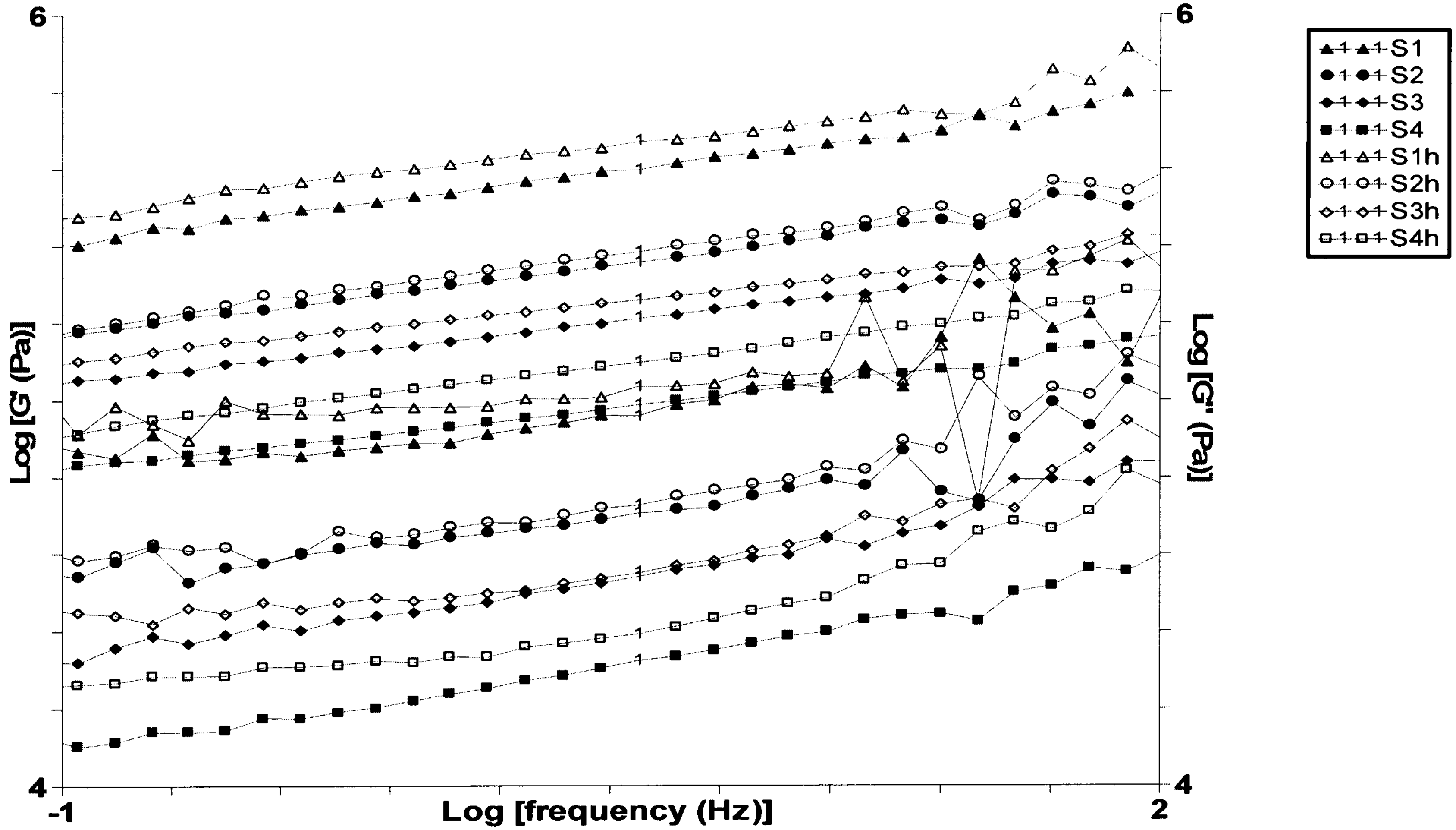


Figure 4.3: Comparison of G' and G" values for sorghum flour doughs.

- Numbers 1,2,3,4 refers to 35, 40, 45 and 50ml respectively, of water used for mixing 50g of flour
- "h" represents the use of water at 100^0C for dough mixing, the rest refer to water at 22^0C

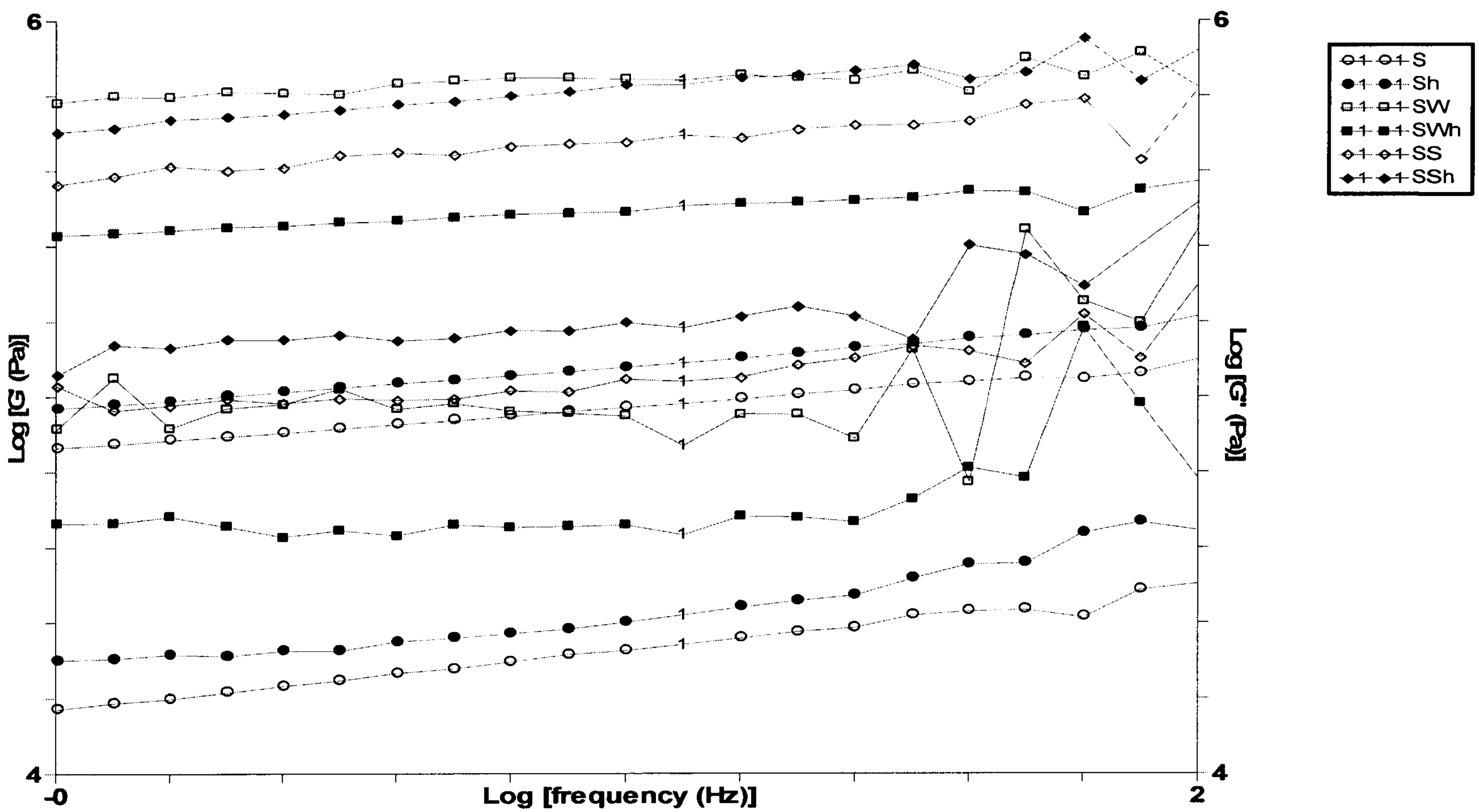


Figure 4.4: Comparison of G' and G" values for doughs made with a 1:1 flour-water ratio

- Flour types used to make dough samples - S: Sorghum (100%), SW: Sorghum (75%) + wheat (25%), SS: Sorghum (75%) + Soya (25%).
- "h" represents the use of water at 100^{0}C for dough mixing, the rest refer to water at 22^{0}C

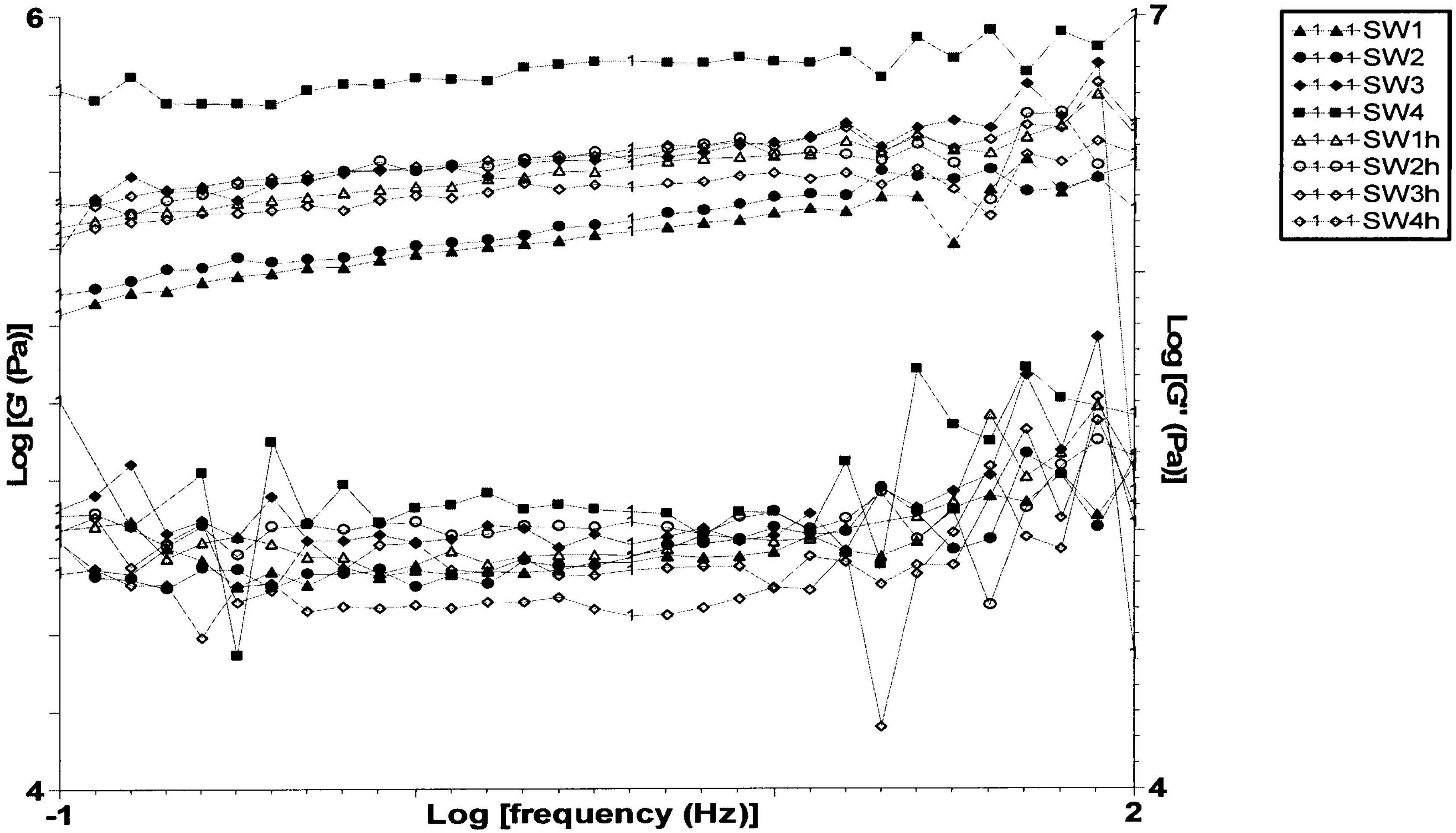


Figure 4.5: Variation of G' and G" for sorghum-wheat composite flour doughs

- Numbers 1,2,3,4 refers to 35, 40, 45 and 50ml respectively, of water used for mixing 50g of flour
- "h" represents the use of water at 100^0C for dough mixing, the rest refer to water at 22^0C

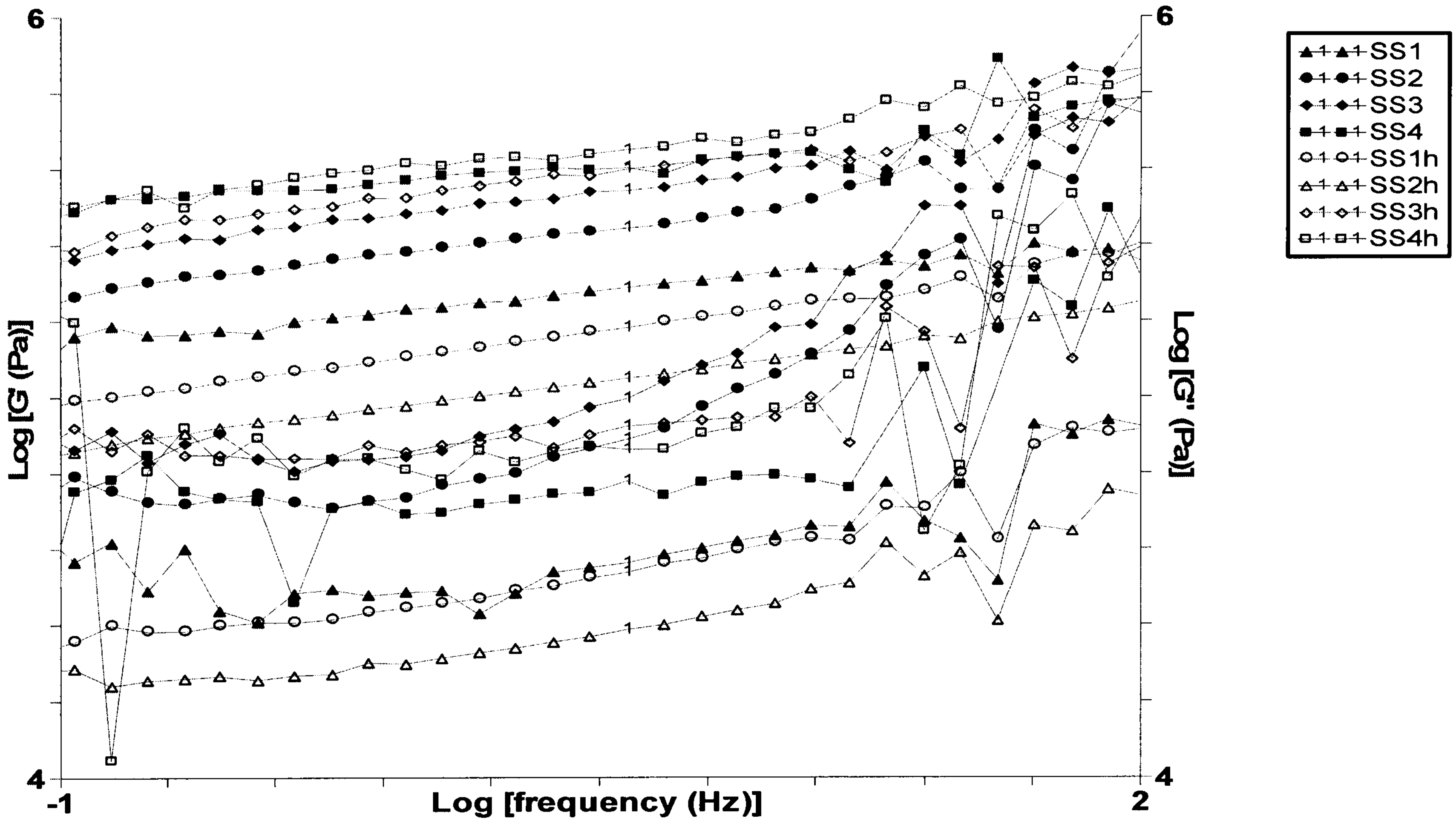


Figure 4.6: Variation of G 'and G" of sorghum-soya composite flour doughs.

- Numbers 1,2,3,4 refers to 35, 40, 45 and 50ml respectively, of water used for mixing 50g of flour
- "h" represents the use of water at 100^0C for dough mixing, the rest refer to water at 22^0C

It is a known fact that the rheological properties of doughs are largely governed by the contribution of starch, protein and water. The viscoelastic behavior of doughs is shaped by the capability of starch and proteins to form a continuous network. Addition of wheat or soya alters the composition of the starches and proteins in the dough samples as compared to sorghum flour doughs. Supplementation with wheat or soya flours leads to a higher protein content and lesser carbohydrate content than pure sorghum flour dough. Figure 4.7 compares the complex modulus (G^*) of the dough samples and it is seen that the G^* values are higher for dough samples made with composite flours which could be explained by the increasing starch-protein interactions when a higher protein content cereal flour like wheat and soya flours are added. Earlier workers have reported similar behavior when comparing flours with different protein content (Amemiya and Menjivar, 1992). The starch granules in the dough samples act as fillers, reinforcing the gluten to produce strong bonds yielding a higher modulus. The values were highest for sorghum-wheat composite flours, while sorghum-soya flours had values in between the standard and sorghum-wheat flours.

Doughs made with boiling water generally had higher G' values compared to those made with cold water which could be due to the gelatinization of starch. The water uptake by starch molecules tends to reduce the plasticizing effect of water.

Composite flour doughs when made with boiling water had lower values for the moduli compared to those made with cold water (Figures 4.5 & 4.6). This behavior is contrary to

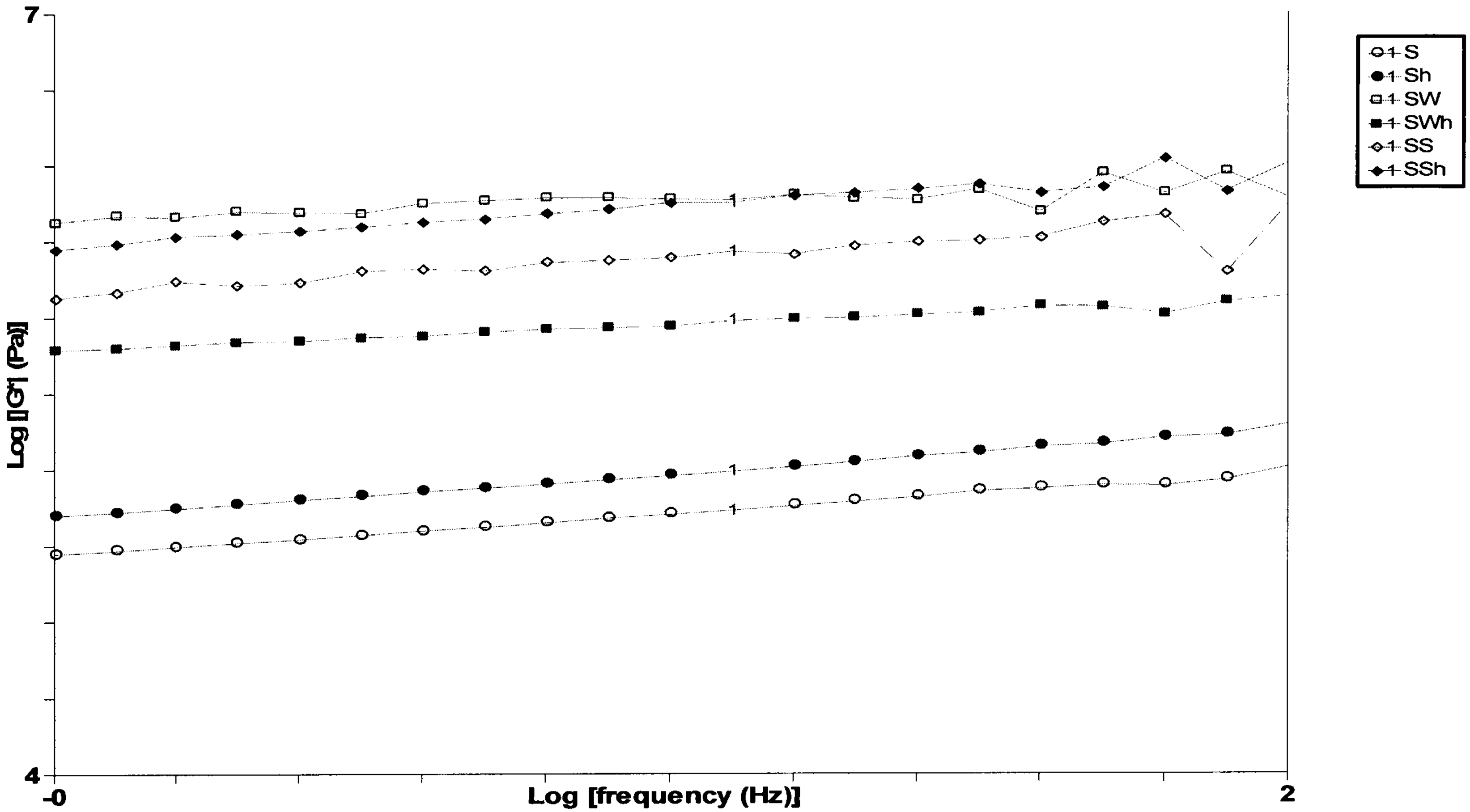


Figure 4.7: Comparison of complex viscosity (*G**) values for doughs made at a 1:1 flour-water ratio

- Flour types used to make dough samples - S: Sorghum (100%), SW: Sorghum (75%) + wheat (25%), SS: Sorghum (75%) + Soya (25%).
- "h" represents the use of water at 100^0C for dough mixing, the rest refer to water at 22^0C

that of the standard sorghum flour dough and could be explained by the lesser starch content in the doughs when compared to pure sorghum flour doughs. These results are in agreement with those generated by the Instron measurements.

From the results it could be generalized that, for the range of water levels selected, 1:1 ratio of flour and mixing water, gave better results in terms of viscoelastic properties. Addition of wheat or soya flours has an improving effect as well. Similar results have been reported by Cheong and Sun (1997). But, their behavior is significant at lower water levels. The poor viscoelastic properties of sorghum dough are in agreement with earlier reports (Bhattacharya et al., 1999).

Addition of boiling water had contrary effects on most properties of plain sorgum flour and composite flour doughs. While, the gelatinization of starch in case of plain sorghum flour doughs did improve the characteristics, similar results were not to be found when composite flours were used. The differences in the behavior of the composite flours could be due to the nature of proteins and starch in wheat and soya flours. Further investigation on this aspect will be able to explain their interaction with sorghum flour.

4.3 Glass transition temperature

The DSC results showed a transition in the thermograms for the dough samples in the temperature range of -23 to -27^{0}C. Levine and Slade (1990) have reported glass transition in dough systems to occur between -10 to -30^{0}C and the results seem to be in agreement with this. The average of the midpoint of inflection for the three replicates has been reported in Tables 4.2 and 4.3. There was only a small change in the heat capacity of the systems across the transition. However, the transition was slightly steeper when faster cooling rates were used. The glass transition was immediately followed by melting (Figure 4.8).

Water has a plasticizing effect on the glass transition behavior in polymeric systems (Slade and Levine, 1995). There is a depression in the glass transition temperature with increasing volumes of water in the dough (Figure 4.9). Increased amounts of water lead to greater mobility of the molecules. The relationship between Tg and water-flour ratio was fairly linear according to the data.

Table 4.2: Glass transition temperatures of sorghum dough at different levels of water

Water (mL) per 50g flour	**Glass transition temperature, Tg (^{0}C)**
45	-23.68 $\pm$ 0.05
50	-23.80 $\pm$ 0.08
55	-25.45 $\pm$ 0.09
60	-26.94 $\pm$ 0.02

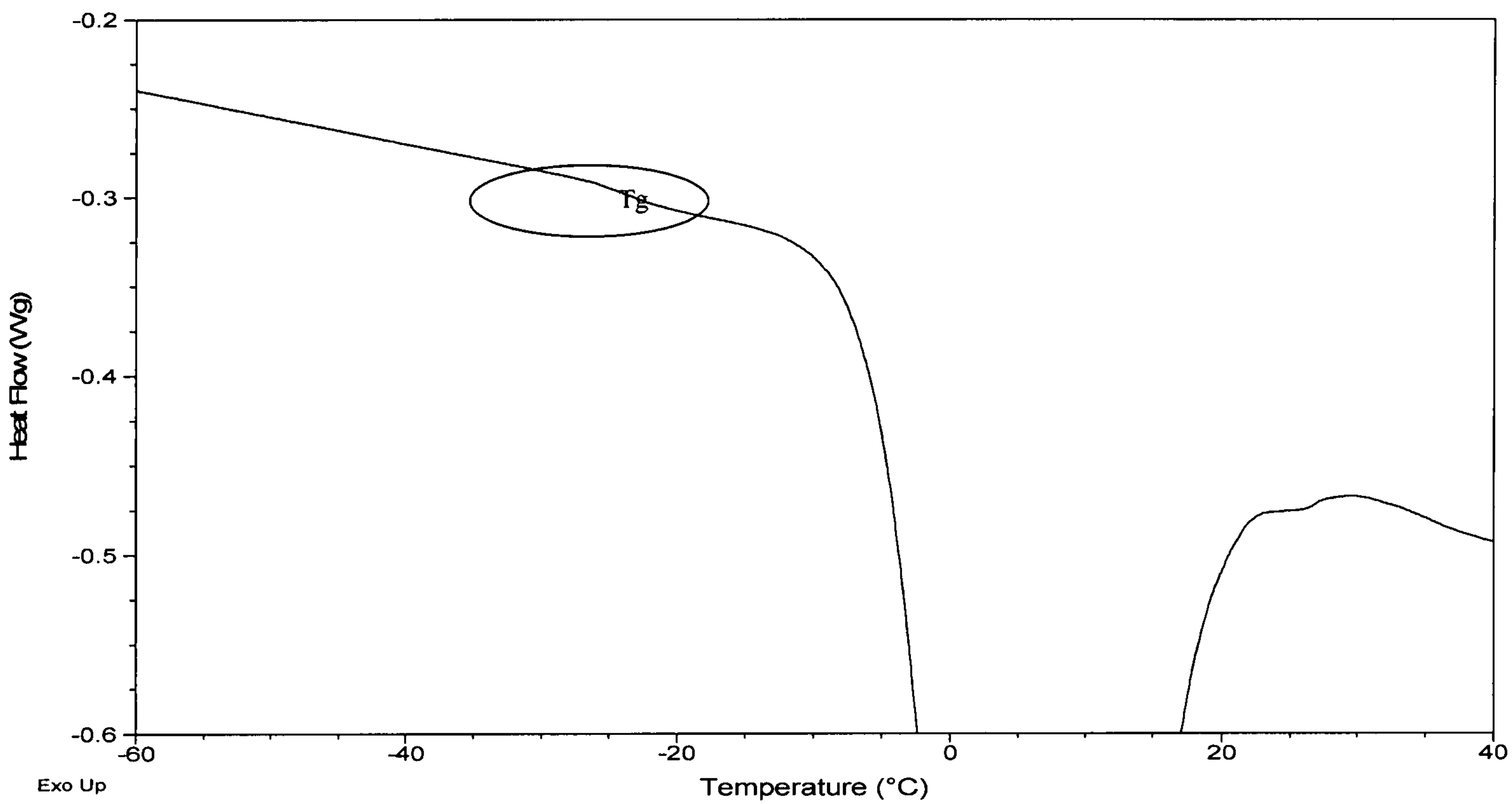


Figure 4.8: Typical DSC thermogram of sorghum flour dough showing regions of glass transition

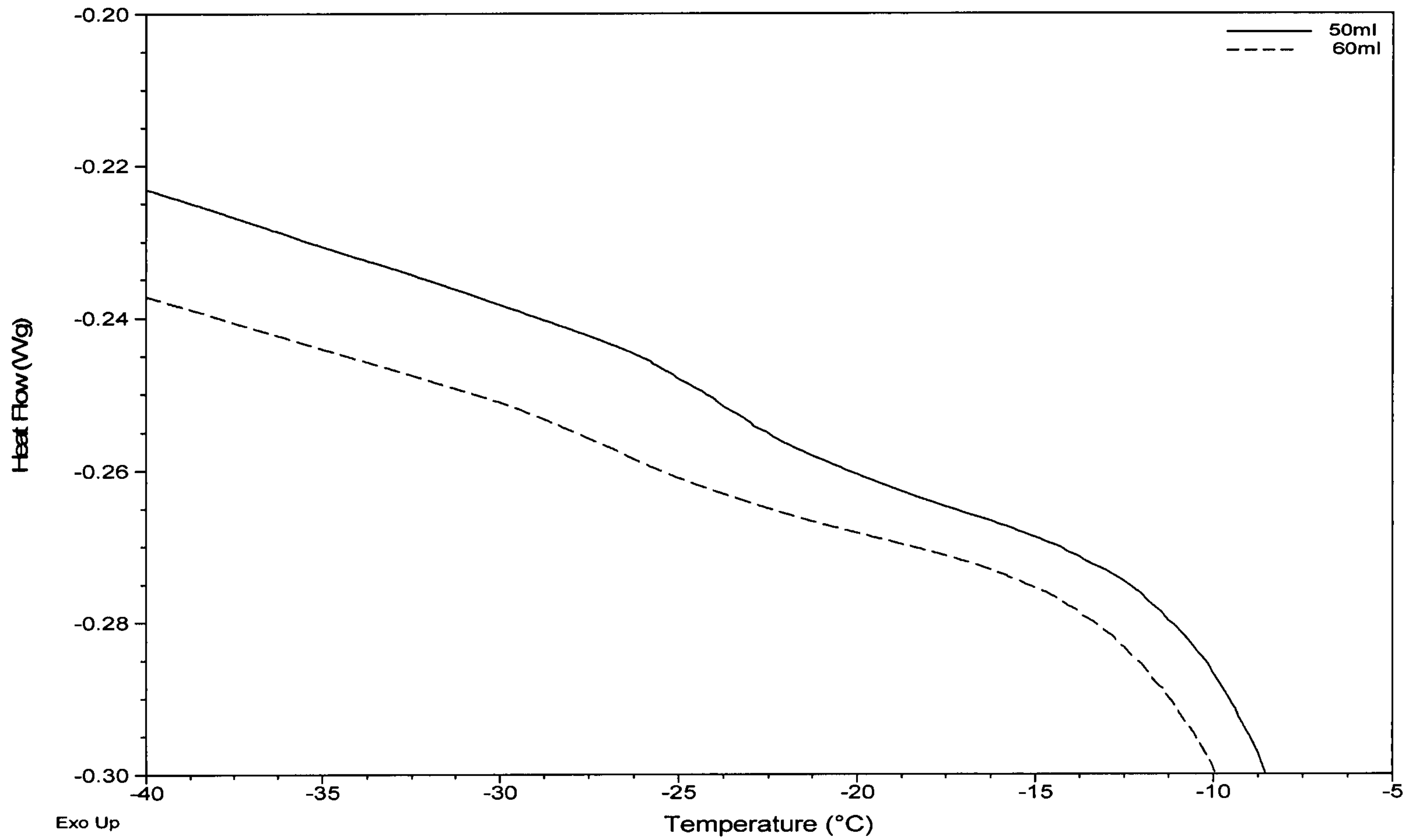


Figure 4.9: Typical DSC thermogram of sorghum flour dough made with different water levels

Table 4.3: Glass transition temperatures of sorghum dough samples supplemented with wheat flour and gluten

Water temperature (^0C)	With wheat flour (%)			With gluten (%)	
	10	20	30	5	10
100	-25.31 ± 0.56	-24.27 ± 0.03	-24.11 ± 0.03	-25.34 ± 0.26	-24.51 ± 0.04
22	-24.08 ± 0.39	-24.51 ± 0.12	-25.22 ± 0.49	-25.46 ± 0.24	-25.06 ± 0.34

The Tg is observed to be higher when boiling water was used for dough making as compared to water at ambient temperature (Figure 4.10). Also, there appeared to be a distinct difference in the viscoelastic characteristics of the doughs. This might be explained by the gelatinization of the starch molecules taking place. Akingbala and Rooney (1987) have reported that the apparent gelatinization temperature of sorghum flours was 10^0C greater than that observed for sorghum starch. From the DSC thermograms, a small transition around the temperature range of 70 to 80^0C is observed which correlates well with their study.

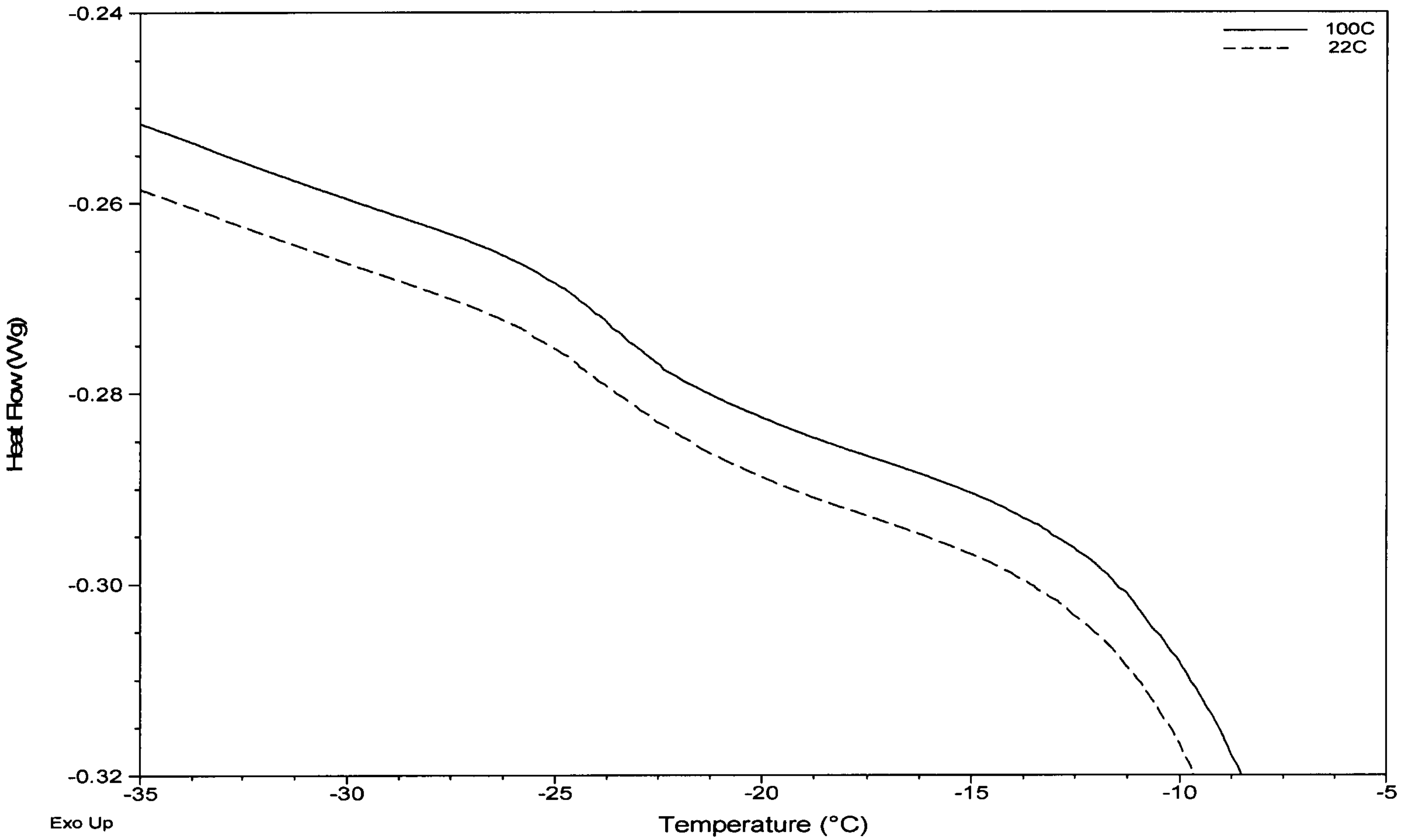


Figure 4.10: Typical DSC thermogram of sorghum flour dough made with water at different temperatures

Laaksonen and Roos (2001) have reported gluten to have a significant role in the glass transition behavior of frozen wheat doughs. Addition of gluten also had a positive effect on the viscoelastic properties of the dough, rendering it more pliable and rollable. Carson and Sun (2000) have reported on the importance of exogenous gluten proteins in doughs made from sorghum composite flour. The Tg values of dough supplemented with gluten were lower than plain sorghum flour dough (Figure 4.11). This can be explained by the fact that Tg values of gluten are lower than that of starch. Gluten forms a network in the presence of moisture and acts as a water-binding agent and less water is available for the starch system in doughs (Hoseney, 1984). A similar trend was observed in case of addition of wheat flour to the dough as well (Figure 4.12). The gluten and protein content of wheat play an active role interacting with the water present and lower the Tg.

4.4 Sensory evaluation

Comparison of the sensory score of rotis made by conventional method of hand tapping and compression by the Instron did not show any significant difference between the two methods. The scores are reported in Table 4.4.

Rotis made using composite flour doughs had a similar sensory value as those made by pure sorghum flour alone. The acceptability of the roti samples was good. Supplementing sorghum flour with wheat flour yielded a marginally better roti in terms of appearance, color, pliability and texture. It could be safely summarized that composite flours do not

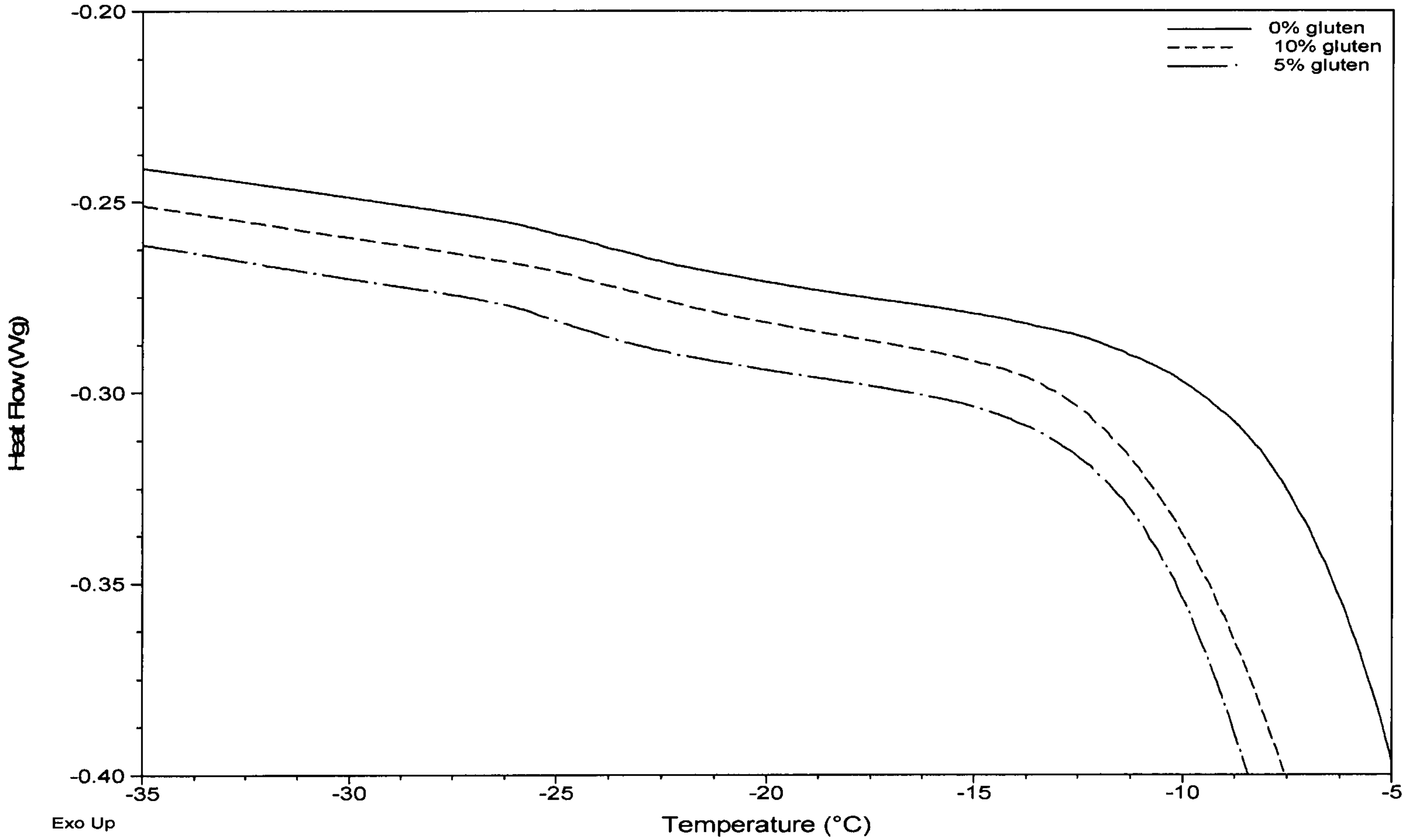


Figure 4.11: Typical DSC thermogram of sorghum flour dough supplemented with varying levels of gluten

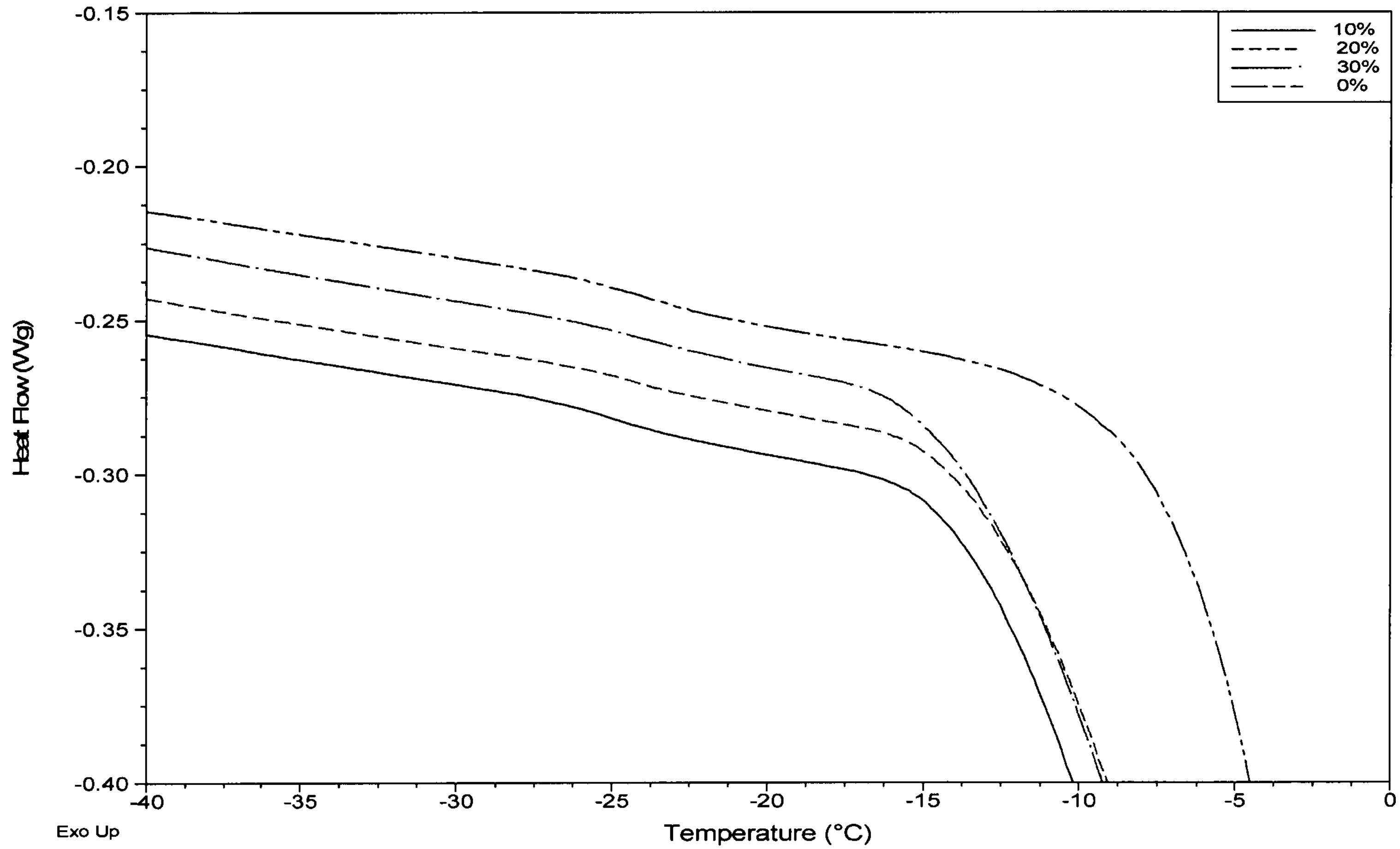


Figure 4.12: Typical DSC thermogram of sorghum-wheat flour composite doughs

have a negative effect on the sensory qualities of sorghum roti and using mechanical means to make roti could give similar results as the traditional method of roti preparation.

Table 4.4: Sensory evaluation score for roti samples made using Instron and conventional method.

Attribute	S	S_c	SW	SW_c	SS	SS_c	SB	SB_c
Appearance	6	6	7	7	6	6	6	7
Color	6	6	7	7	7	6	6	7
Taste	6	5	6	6	5	5	6	6
Flavor	6	5	6	6	5	4	5	6
Pliability	6	6	7	7	6	6	6	6
Texture	6	5	7	7	6	6	6	6
Mouthfeel	6	5	6	6	6	6	6	5

Abbreviations S, SW, SS and SB refer to rotis made from sorghum, sorghum-wheat, sorghum-soya and sorghum-blackgram composite flours respectively. Subscript "c" indicates samples prepared by conventional method.

The Instron peak force measurements for compressing the dough samples to a flat circular shape for roti making is given in Table 4.5.

Table 4.5: Force measurements from the Instron during compression of dough samples

Sample	Force, kN	Std. Dev.
Sorghum	1.064	0.006
Sorghum -wheat	0.433	0.062
Sorghum - soya	1.304	0.049
Sorghum – black gram	0.974	0.031

Dough samples made with sorghum flour recorded the highest force values, which is in agreement with its texture profile analysis and rheological data. Sorghum-wheat composite flours yielded doughs which needed the least force. Although the process of preparing rotis by the traditional method is more intricate and delicate than unilateral compression, these measurements do give an idea of the force required for a machine to achieve the same thickness as achieved by manual methods.

Chapter 5

CONCLUSIONS

The rheological properties of sorghum dough are better at near 1:1 ratio of flour to mixing water. Starch gelatinization due to addition of boiling water for dough mixing improves the viscoelastic properties of sorghum dough. Composite flour doughs, made by adding wheat or soya flours to sorghum flour gave better results and their performance is significantly better when cold water is used for dough mixing.

The glass transition temperature of the sorghum flour and composite flour dough samples lie in the temperature range of -23 to -27^{0}C. Water has a plasticizing effect on both thermal and rheological properties of the dough samples studied. The difference between interaction of starch-gluten in composite flour and the starch interaction in pure sorghum flour might be a major factor in determining the rheological and thermal properties of sorghum doughs.

Composite flours and mechanical compression of dough for roti preparation yielded rotis with good sensory values, resembling those made with pure sorghum flour and the traditional method of preparation.

In summary,

1. The rheological properties of sorghum dough vary with the water content and using boiling water for mixing the dough yields better results.

2. The textural properties of sorghum flour dough have been established.
3. The glass transition temperature of sorghum dough ranges between -23 and -79^{0}C.
4. Addition of wheat, soya or black gram flours to sorghum flour yields better results in terms of its viscoelastic properties and bears no negative effect on its sensory characteristics.
5. Mechanical methods could be favourably employed to prepare sorghum rotis without any significant ill effect.

It would be beneficial to further study the biochemical interaction between the starches and proteins of the cereal flours upon mixing in relation to its effect on the properties of dough samples. Successive correlation between its biochemical properties and rheological properties could be used to design suitable equipment for roti making. Value addition and efficient means of production could lead to a great turn around in the fortunes of this grain and help remove the tag of a "poor man's cereal" attached to it and present it to the world as a healthy, wholesome grain.

References

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

Aboubacar, A. and Hamaker, B. R. (1999) Physicochemical properties of flours that relate to sorghum couscous quality *Cereal Chemistry* **76** (2), 308-313

Accomando, S. and Cataldo, F. (2004) The global village of celiac disease *Digestive and Liver Disease* **36** (7), 492-498

Addesso, K. R, Dzurenko, T. E, and Plains, M 1995 Production of chip-like starch based snacks

Addo,K., Xiong,Y.L., and Blanchard,S.P. (2001) Thermal and dynamic rheological properties of wheat flour fractions Food Research International **34**, 329-335

Ahmed, A. M., Singh, B., and Singh, U. (1993) Improvement of Sensory and Nutritional Qualities of Sorghum-Based Kisra by Supplementation with Groundnut *Journal of Food Science and Technology-Mysore* **30** (2), 121-126

Akingbala, J. O., Gomez, M. H., Rooney, L. W., and Sweat, V. E. (1988) Thermal-Properties of Sorghum Starch *Starch-Starke* **40** (10), 375-378

Akingbala, J. O. and Rooney, L. W. (1987) Paste Properties of Sorghum Flour and Starches *Journal of Food Processing and Preservation* **11** (1), 13-24

Al-Kahtani, H. A. (1989) Processing of Different Wheat Flour-Supplemented Sorghum Flakes (Sorghum and Wheat of Saudi-Arabia) - Sensory, Nutritional, and Microbiological Evaluation *Food Chemistry* **33** (2), 133-149

Almeidadominguez, H. D., Sernasaldivar, S. O., and Rooney, L. W. (1991) Properties of New and Commercial Sorghum Hybrids for Use in Alkaline-Cooked Foods *Cereal Chemistry* **68** (1), 25-30

Amemiya, J. I. and Menjivar, J. A. (1992) Comparison of Small and Large Deformation Measurements to Characterize the Rheology of Wheat-Flour Doughs *Journal of Food Engineering* **16** (1-2), 91-108

Anglani, C. (1998) Sorghum for human food - A review *Plant Foods for Human Nutrition* **52** (1), 85-95

Arbab, M. E. and ElTinay, A. H. (1997) Effect of cooking and treatment with sodium bisulphite or ascorbic acid on the in vitro protein digestibility of two sorghum cultivars *Food Chemistry* **59** (3), 339-343

Autio, K., Flander, L., Kinnunen, A., and Heinonen, R. (2001) Bread quality relationship with rheological measurements of wheat flour dough *Cereal Chemistry* **78** (6), 654-657

Awika, J. M. and Rooney, L. W. (2004) Sorghum phytochemicals and their potential impact on human health *Phytochemistry* **65** (9), 1199-1221

Axtell,J.D., Kirleis,A.W., Hassen,M.M., D'Croz Mason,N.et al. (1981) Digestibility of sorghum proteins. Proc . Natl. Acad. Sci . USA **78** (1333-1335

Bach Knudsen, K. E., Kirleis, A. W., Eggum, B. O., and Munck, L. (1988) Carbohydrate composition and nutritional quality for rats of sorghum *To* prepared from decorticated white and whole grain red flour *J. Nutr.* **118** (5), 588-597

Bach Knudsen, K. E., Munck, L., and Eggum, B. O. (1988) Effect of cooking, pH and polyphenol level on carbohydrate composition and nutritional quality of a sorghum (Sorghum bicolor (L.) Moench) food, ugali *Br. J. Nutr.* **59** (1), 31-47

Badi, S. M. and Hoseney, R. C. (1976) Use of Sorghum and Pearl Millet Flours in Cookies *Cereal Chemistry* **53** (5), 733-738

Bagley, E. B. and Christianson, D. D. (1986) Response of Doughs to Uniaxial Compression *Cereal Foods World* **31** (8), 585-585

Bagley, E. B. and Christianson, D. D. (1987) Measurement and Interpretation of Rheological Properties of Foods *Food Technology* **41** (3), 96-99

Bedolla, S., Depalacios, M. G., Rooney, L. W., Diehl, K. C., and Khan, M. N. (1983) Cooking Characteristics of Sorghum and Corn for Tortilla Preparation by Several Cooking Methods *Cereal Chemistry* **60** (4), 263-268

Bello, A. B., Rooney, L. W., and Waniska, R. D. (1990) Factors Affecting Quality of Sorghum Toflex, A Thick Porridge *Cereal Chemistry* **67** (1), 20-25

Berland, S. and Launay, B. (1995) Rheological Properties of Wheat-Flour Doughs in Steady and Dynamic Shear - Effect of Water-Content and Some Additives *Cereal Chemistry* **72** (1), 48-52

Bhatia, A. and Khetarpaul, N. (2002) Effect of fermentation on phytic acid and in vitro availability of calcium and iron of 'Doli ki roti' - An indigenously fermented Indian bread *Ecology of Food and Nutrition* **41** (3), 243-253

Bhattacharya, S., Bhattacharya, S., and Narasimha, H. V. (1999) Uniaxial compressibility of blackgram doughs blended with cereal flours *Journal of Texture Studies* **30** (6), 659-675

Bourne, M. C. (1968a) Texture Profile of Ripening Pears *Journal of Food Science* **33** (2), 223

Bourne, M. C. (1974) Textural Changes in Ripening Peaches *Canadian Institute of Food Science and Technology Journal-Journal de l Institut Canadien de Science et Technologie Alimentaires* **7** (1), 11-15

Bourne, M. C. (1978b) Texture Profile Analysis *Food Technology* **32** (7), 62-

Brannan, G. L., Setser, C. S., Kemp, K. E., Seib, P. A., and Roozeboom, K. (2001) Sensory characteristics of grain sorghum hybrids with potential for use in human food *Cereal Chemistry* **78** (6), 693-700

Bugusu, B. A., Campanella, O., and Hamaker, B. R. (2001) Improvement of sorghum-wheat composite dough rheological properties and breadmaking quality through zein addition *Cereal Chemistry* **78** (1), 31-35

Bushuk, W 1985 Rheology: Theory and application to wheat flour dough Faridi, H American Association of Cereal Chemists, Inc., St Paul, Minnesota 1-26

Cagampang, G. B., Griffith, J. E., and Kirleis, A. W. (1982) Modified Adhesion Test for Measuring Stickiness of Sorghum Porridges *Cereal Chemistry* **59** (3), 234-235

Cagampang, G. B. and Kirleis, A. W. (1984) Relationship of Sorghum Grain Hardness to Selected Physical and Chemical Measurements of Grain Quality *Cereal Chemistry* **61** (2), 100-105

Carson, L. C. and Sun, X. S. (2000) Breads from white grain sorghum: Rheological properties and baking volume with exogenous gluten protein *Applied Engineering in Agriculture* **16** (4), 423-429

Casiraghi,E.M., Bagley,E.B., and Christianson,D.D. (1985) Behaviour of mozzarella, cheddar and processed cheese spread in lubricated and bonded uniaxial compression J. Texture Studies **16,** 281-301

Chandrashekar, A. and Desikachar, H. S. R. (1983) Sorghum Quality Studies .1. Rolling Quality of Sorghum Dough in Relation to Some Physicochemical Properties *Journal of Food Science and Technology-Mysore* **20** (6), 281-284

Chandrashekar, A. and Kirleis, A. W. (1988) Influence of Protein on Starch Gelatinization in Sorghum *Cereal Chemistry* **65** (6), 457-462

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

Cheong,M.L. and Sun,X.S. (1997) Sorghum based composite flour for breadmaking Cereal Food World **42** (8), 631-

Choto, C. E., Morad, M. M., and Rooney, L. W. (1985) The Quality of Tortillas Containing Whole Sorghum and Pearled Sorghum Alone and Blended with Yellow Maize *Cereal Chemistry* **62** (1), 51-55

Couchman, P. R. and Karasz, F. E. (1978) Classical Thermodynamic Discussion of Effect of Composition on Glass-Transition Temperatures *Macromolecules* **11** (1), 117-119

Davis, A. B. and Hoseney, R. C. (1979) Grain-Sorghum Condensed Tannins .1. Isolation, Estimation, and Selective Adsorption by Starch *Cereal Chemistry* **56** (4), 310-314

Deatherage,W.L., McMasters,M.M., and Rist,C.E. (1955) A partial survey of amylose content in starch from domestic and foreign varieties of corn, wheat and sorghum and from some other starch-bearing plants. Trans. Am. Assoc. Cereal Chem **13** (31-42

Delucci,M.Y. and Mastrodi,J. (1994) Availacao quimica e nutrotional de farhina de sorgo integral (*Sorghum bicolor* L. Moench), complementacao con feijao e soro de leite, aplicacao em panificacao Archivos Latinoamericanos de Nutricion **44** (3), 151-157

Dendy, D. A. V 1970 Composite Flours Food and Agricultural Organisation (FAO): Rome

Desikachar, H. S. R and Chandrashekhar, A. 1981 Quality of sorghum for use in Indian foods. ICRISAT 262-

Devarajan,B. and Pandit,A.B. (1996) Sorghum flour as raw material for glucose production Journal of Maharashtra Agricultural Universities **21** (1), 86-90

Dhingra, M., Srivastava, S., and Chauhan, G. S. (1992) Nutrient Composition and Relationship Between Physicochemical and Sensory Qualities of Sorghum Genotypes *Journal of Food Science and Technology-Mysore* **29** (2), 97-100

Diehl, K. C. 1981 Rheological Techniques for Texture and Quality Measurement of Sorghum Food Products ICRISAT Proceedings of the International Symposium on Sorghum Grain Quality 312-322.

Doescher, L. C., Hoseney, R. C., and Milliken, G. A. (1987) A Mechanism for Cookie Dough Setting *Cereal Chemistry* **64** (3), 158-163

Dreese, P. C., Faubion, J. M., and Hoseney, R. C. (1988) Dynamic Rheological Properties of Flour, Gluten, and Gluten-Starch Doughs .1. Temperature-Dependent Changes During Heating *Cereal Chemistry* **65** (4), 348-353

Dreese, P. C., Faubion, J. M., and Hoseney, R. C. (1988) Dynamic Rheological Properties of Flour, Gluten, and Gluten-Starch Doughs .2. Effect of Various Processing and Ingredient Changes *Cereal Chemistry* **65** (4), 354-359

Dreher,M.L., Dreher,C.J., and Berry,J.W. (1984) Starch digestibility of foods. A nutritional perspective. CRC Crit. Rev. Food Sci. Nutr **20** (47-71

Eggum, B. O., Monowar, L., Knudsen, K. E. B., Munck, L., and Axtell, J. (1983) Nutritional Quality of Sorghum and Sorghum Foods from Sudan *Journal of Cereal Science* **1** (2), 127-137

Elizalde, B. E. and Pilosof, A. M. R. (1999) Kinetics of physico-chemical changes in wheat gluten in the vicinity of the glass transition temperature *Journal of Food Engineering* **42** (2), 97-102

Elkhalifa, A. E. O. and El Tinay, A. H. (2002) Effect of cysteine on bakery products from wheat-sorghum blends *Food Chemistry* **77** (2), 133-137

Elkhalifa, A. O., Chandrashekar, A., and El Tinay, A. H. (1999a) Effect of preincubation of sorghum flour with enzymes on the digestibility of sorghum gruel *Food Chemistry* **66** (3), 339-343

Elkhalifa, A. O., Chandrashekar, A., Mohamed, B. E., and El Tinay, A. H. (1999b) Effect of reducing agents on the in vitro protein and starch digestibilities of cooked sorghum *Food Chemistry* **66** (3), 323-326

Elkhalil, E. A. I., El Tinay, A. H., Mohamed, B. E., and Elsheikh, E. A. E. (2001) Effect of malt pretreatment on phytic acid and in vitro protein digestibility of sorghum flour *Food Chemistry* **72** (1), 29-32

FAO / Information Network on Post-Harvest Operations (INPHO), FAO 1995 1995 Sorghum and millets in human nutrition 27 FAO Food and Nutrition Series Rome Food and Agriculture Organization of the United Nations

FAO/WHO 1973 Energy and Protein Requirements Food and Agricultural Organisation of the United Nations

Faubian, J. M and Hoseney, R. C. 1990 <[03] Book Title> <[15] Volume> Faridi, H and Faubian, J. M AVI Publishing: New York ,

Foda,Y.H., Ramy,A., Rasmy,N.M., Abu-Salem,F.M.A.et al. (1987) Rheological and sensory characteristics of doughs and balady bread based on wheat, sorghum, millet and defatted soy flours Annals of Agricultural Science, Ain Shams University **32** (1), 381-395

Galiba, M., Rooney, L. W., Waniska, R. D., and Miller, F. R. (1987) The Preparation of Sorghum and Millet Couscous in West-Africa *Cereal Foods World* **32** (12), 878-&

Georgopoulos, T., Larsson, H., and Eliasson, A. C. (2004) A comparison of the rheological properties of wheat flour dough and its gluten prepared by ultracentrifugation *Food Hydrocolloids* **18** (1), 143-151

Gomez-Cordoves, C., Bartolome, B., Vieira, W., and Virador, V. M. (2001) Effects of wine phenolics and sorghum tannins on tyrosinase activity and growth of melanoma cells *Journal of Agricultural and Food Chemistry* **49** (3), 1620-1624

Gordon, M. and Taylor, J. S. (1952) Ideal Copolymers and the 2Nd-Order Transitions of Synthetic Rubbers .1. Non-Crystalline Copolymers *Journal of Applied Chemistry* **2** (9), 493-500

Graessley, W. W 1984 <[03] Book Title> <[15] Volume> Mark, J. E, Eisenberg, A, Graessley, W. W, Mandelkern, L, and Koenig, J. L American Chemical Society, Washington D.C. 97-153.

Gujral, H. S. and Pathak, A. (2002) Effect of composite flours and additives on the texture of chapati *Journal of Food Engineering* **55** (2), 173-179

Gujral, Hardeep Singh, Haros, Monica, and Rosell, Cristina M. (2004) Improving the texture and delaying staling in rice flour chapati with hydrocolloids and [alpha]-amylase *Journal of Food Engineering* **65** (1), 89-94

Hahn, D. H., Rooney, L. W., and Earp, C. F. (1984) Tannins and Phenols of Sorghum *Cereal Foods World* **29** (12), 776-779

Hamaker,B.R., Kirleis,A.W., Butler,L.G., Axtell,J.et al. (1987) Improving the in-vitro protein digestibility of sorghum with reducing agents Proceedings of the National Academy of Sciences **84** (626-628

Hamaker, B. R., Kirleis, A. W., Mertz, E. T., and Axtell, J. D. (1986) Effect of Cooking on the Protein Profiles and Invitro Digestibility of Sorghum and Maize *Journal of Agricultural and Food Chemistry* **34** (4), 647-649

Hamann, D. D. and Macdonald, G. A. 1992 Rheology and texture properties of surimi based food Lanie, T. C and Lee, C. M Marcel Dekker, New York 429-500

Harbers,L.H. (1975) Starch granule structural changes and amylolytic patterns in processed sorghum grain. J. Anim. Sci **41** (1496-1501

Hart,M.R., Graham,R.P., Gee,M., and Morgan,A.I. (1970) Bread from sorghum and barley flours Journal of Food Science **35** (5), 661-665

Hibberd,C.A., Wagner,D.G., Schemm,R.L., Mitchell,F.et al. (1982) Digestibility characteristics of isolated starch from sorghum and corn grain. J. Anim. Sci. **55** (1490-1497

Hibberd,G.E. (1970a) Dynamic viscoelastic behaviour of wheat flour doughs. Part II. Effects of water content in the linear region Rheologica Acta **9** (497-500

Hibberd,G.E. (1970b) Dynamic viscoelastic behaviour of wheat flour doughs. Part III. The influence of starch granules Rheologica Acta **9** (501-505

Hibberd, G. E. and Parker, N. S. (1975) Measurement of Fundamental Rheological Properties of Wheat-Flour Doughs *Cereal Chemistry* **52** (3), R1-R23

Hoseney,R.C. (1984) Differential scanning calorimetry of starch Journal of Food Quality **6** (169-182

Hoseney, R. C. 1994 Principles of Cereal Science and Technology 2nd Am. Assoc. Cereal Chem, St Paul, MN

Huang, M. T and Ferraro, T 1992 Phenolics compounds in food and cancer prevention Huang, M. T, Ho, C. T, and Lee, C. Y. American Chemical Society, Washington D.C.

Hubbard,J.E., Hall,H.H., and Earle,F.R. (1950) Composition of the component parts of the sorghum kernel Cereal Chem. **27** (415-420

Hugo, L. F., Rooney, L. W., and Taylor, J. R. N. (2000) Malted sorghum as a functional ingredient in composite bread *Cereal Chemistry* **77** (4), 428-432

Hulse, J. H., Laing, E. M., and Pearson, O. E 1980 Sorghum and the millets: their composition and nutritive value. New York, Academic Press 997-

Hussein, M. A., Saleh, A., and Noaman, M. (1977) Effect of Adding Sorghum Flour on Physical and Chemical Properties of Bread *Periodica Polytechnica-Chemical Engineering* **21** (4), 343-354

Hwang, Keum Taek, Weller, Curtis L., Cuppett, Susan L., and Hanna, Milford A. (2004) Changes in composition and thermal transition temperatures of grain sorghum wax during storage *Industrial Crops and Products* **19** (2), 125-132

Indrani, D. and Rao, G. V. (2000) Effect of chemical composition of wheat flour and functional properties of dough on the quality of south Indian parotta *Food Research International* **33** (10), 875-881

Indrani, D. and Rao, G. V. (2003) Influence of surfactants on rheological characteristics of dough and quality of parotta *International Journal of Food Science and Technology* **38** (1), 47-54

Izydorczyk, M. S. and Biliaderis, C. G. (1995) Cereal arabinoxylans: Advances in structure and physicochemical properties *Carbohydrate Polymers* **28** (1), 33-48

Kamath, M. V. and Belavady, B. (1980) Unavailable Carbohydrates of Commonly Consumed Indian Foods *Journal of the Science of Food and Agriculture* **31** (2), 194-202

Kaur, R. D. and Hira, C. K. (1989) Supplementary Effect of Aestivum Wheat (Triticum-Aestivum L), Bengal Gram (Cicer-Arietinum-L) and Soya Bean (Glycine-Max L) on Protein-Quality of Durum-Wheat (Triticum-Durum Desf) *Journal of the Science of Food and Agriculture* **46** (2), 201-209

Kazanas, N. and Fields, M. L. (1981) Nutritional Improvement of Sorghum by Fermentation *Journal of Food Science* **46** (3), 819-821

Keregero, M. M. and Mtebe, K. (1994) Acceptability of Wheat Sorghum Composite Flour Products - An Assessment *Plant Foods for Human Nutrition* **46** (4), 305-312

Khalil, J. K., Sawaya, W. N., Safi, W. J., and Almohammad, H. M. (1984) Chemical-Composition and Nutritional Quality of Sorghum Flour and Bread *Qualitas Plantarum-Plant Foods for Human Nutrition* **34** (2), 141-150

Khetarpaul,N., Goyal,R., and Garg,R. (2004) Nutritional and sensory evaluation of nutritious porridge prepared using combinations of soy and sorghum grits Nutr Health. **17** (4), 309-315

Kim,J.C. and De Ruiter,D. (1968) Bread from non-wheat flours Food Technology **22** (897-878

Klopfenstein, C. F. and Hoseney, R. C. 1995 Nutritional properties of sorghum and millets Dendy, D. A. V 125 St Paul, Minn.: American Association of Cereal Chemistry

Kumar,B.M., Upadhyay,J.K., and Bhattacharya,K.R. (1976) Objective test for the stickiness of rice J. Texture Studies **7** (271-278

Kwei, T. K. (1984) The Effect of Hydrogen-Bonding on the Glass-Transition Temperatures of Polymer Mixtures *Journal of Polymer Science Part C-Polymer Letters* **22** (6), 307-313

Laaksonen, T. J. and Roos, Y. H. (2000a) Thermal, dynamic-mechanical, and dielectric analysis of phase and state transitions of frozen wheat doughs *Journal of Cereal Science* **32** (3), 281-292

Laaksonen, T. J. and Roos, Y. H. (2001b) Dielectric relaxations of frozen wheat doughs containing sucrose, NaCl, ascorbic acid and their mixtures *Journal of Cereal Science* **33** (3), 331-339

Laaksonen, T. J. and Roos, Y. H. (2003) Water sorption and dielectric relaxations of wheat dough (containing sucrose, NaCl, and their mixtures) *Journal of Cereal Science* **37** (3), 319-326

Lee, W. J., Pedersen, J. F., and Shelton, D. R. (2002) Relationship of Sorghum kernel size to physiochemical, milling, pasting, and cooking properties *Food Research International* **35** (7), 643-649

Lemeste, M., Huang, V. T., Panama, J., Anderson, G., and Lentz, R. (1992) Glass-Transition of Bread *Cereal Foods World* **37** (3), 264-267

Levine, H. and Slade, L. 1990 <[03] Book Title> <[15] Volume> Ma, C. Y and Harwalkar, V. R London: Elsevier Applied Science , 221-305.

Lindell, M. J. and Walker, C. E. (1984) Soy Enrichment of Chapaties Made from Wheat and Nonwheat Flours *Cereal Chemistry* **61** (5), 435-438

Masi, P., Cavella, S., and Sepe, M. (1998) Characterization of dynamic viscoelastic behavior of wheat flour doughs at different moisture contents *Cereal Chemistry* **75** (4), 428-432

McNeill,J.W., Potter,G.D., and & Rooney,L.W. (1975) Chemical and physical properties of processed sorghum grain carbohydrates J. Anim. . Sci. **40** (335-341

Micard, V., Morel, M. H., Bonicel, J., and Guilbert, S. (2001) Thermal properties of raw and processed wheat gluten in relation with protein aggregation *Polymer* **42** (2), 477-485

Miche, J. C, Alary, R, Jeanjean, M. F, and Abecassis, J 1977 Potential use of sorghum grains in pasta processing Proc. Symp. Sorghum Millets Hum. Food Dendy, D. A. V Trop. Prod. Inst., London, England

Mita, T. and Matsumoto, H. (1984) Dynamic Viscoelastic Properties of Concentrated Dispersions of Gluten and Gluten Methyl-Ester - Contributions of Glutamine Side-Chain *Cereal Chemistry* **61** (2), 169-173

Mitaru,B.N. and Blair,R. (1984) Comparative effects of cooking and high moisture storage of sorghums on protein digestibility in rats Nutrition Reports International **30** (397-400

Morad, M. M., Doherty, C. A., and Rooney, L. W. (1984) Effect of Sorghum Variety on Baking Properties of United-States Conventional Bread, Egyptian Pita Balady Bread and Cookies *Journal of Food Science* **49** (4), 1070-1074

Mosha, T. C. E. and Vicent, M. M. (2004) Nutritional value and acceptability of homemade maize/sorghum-based weaning mixtures supplemented with rojo bean flour, ground sardines and peanut paste *International Journal of Food Sciences and Nutrition* **55** (4), 301-315

Munck, L. 1995 New Milling Technologies and Products: Whole plant utilisation by milling and separation of the botanical and chemical components Dendy, D. A. V Am. Assoc. Cereal Chem., St Paul, MN 223-281

Murty, D. S. and Subramanian, V 1981 Sorghum *Roti*: I. Traditional methods of consumption and standard procedures for evaluation 73-78.

Nair, K. B. 1980 Jowar Indian Council of Agricultural Research, New Delhi 89-

Nandini, C. D. and Salimath, P. V. (2001) Carbohydrate composition of wheat, wheat bran, sorghum and bajra with good chapati/roti (Indian flat bread) making quality *Food Chemistry* **73** (2), 197-203

Nandini, C. D. and Salimath, P. V. (2001) Structural features of arabinoxylans from sorghum having good roti-making quality *Food Chemistry* **74** (4), 417-422

Navas, P. B. and Garcia, L. (2000) Nutritional evaluation of sorghum flour on supplementation with whey proteins *Journal of Food Science and Technology-Mysore* **37** (2), 144-148

Navickis, L. L., Anderson, R. A., Bagley, E. B., and Jasberg, B. K. (1982) Viscoelastic Properties of Wheat-Flour Doughs - Variation of Dynamic Moduli with Water and Protein-Content *Journal of Texture Studies* **13** (2), 249-264

Nawar,I.A., Clark,H.E., Pickett,R.C., and Hegsted,D.M. (1970) Protein quality of selected lines of Sorghum vulgare for the growing rat Nutr Rep. Int. **1** (75),

Nnam, N. M. (2001) Chemical, sensory and rheological properties of porridges from processed sorghum (Sorghum bicolor, bambara groundnut (Vigna subterranea L. Verdc) and sweet potato (Ipomoea batatas) flours *Plant Foods for Human Nutrition* **56** (3), 251-264

Noel,T.R., Ring,S.G., and Whittam,M.A. (1990) Glass transition in low moisture foods Trends in food science and technology **1** (62-67

Obizoba, I. C. (1988) Nutritive-Value of Malted, Dry-Milled Or Wet-Milled Sorghum and Corn *Cereal Chemistry* **65** (6), 447-449

Ortega-Ramirez, R, Siqueiros, M. G, Hernandez, R, and Ramirez-Wong, B 1995 Evaluation of rheological and bread making properties of composite wheat and decorticated sorghum flours Anaheim, Calif. Poster 294 Chicago, Ill.: Institute of Food Technol.

Padua, G. W. and Whitney, R. M. (1982) Application of the Instron Tester for Investigation of Rheology of Corn Dough *Cereal Chemistry* **59** (5), 361-366

Palmer, G. H. (1992) Sorghum - Food, Beverage and Brewing Potentials *Process Biochemistry* **27** (3), 145-153

Peleg,M. (1977) Operational conditions and the stress-strain relationship of solid foods-theoretical evaluation J. Texture Studies **8** (283-295

Peleg, M. (1976) Texture Profile Analysis Parameters Obtained by An Instron Universal Testing Machine *Journal of Food Science* **41** (3), 721-722

Perten, H. (1983) Practical Experience in Processing and Use of Millet and Sorghum in Senegal and Sudan *Cereal Foods World* **28** (11), 680-683

Petrofsky, K. E. and Hoseney, R. C. (1995) Rheological Properties of Dough Made with Starch and Gluten from Several Cereal Sources *Cereal Chemistry* **72** (1), 53-58

Phan-Thien, N. and Safari-Ardi, M. (1998) Linear viscoelastic properties of flour-water doughs at different water concentrations *Journal of Non-Newtonian Fluid Mechanics* **74** (1-3), 137-150

Pringle,W., Williams,A.A., and Hulse,J.H. (1969) Mechanical developed doughs from composite flours Cereal Sci. Today **14** (114-129

Purseglove, J. W. 1972 Tropical crops: monocotyledons 1 Longres Longman Group Limited 334-

Pushpamma, P and Geervani, P 1981 Nutritive value of traditional recipes of Andhra Pradesh. College of Home Science, Andhra Pradesh Agricultural University, Hyderabad, India 159-

Quintero-Fuentes, X., McDonough, C. M., Rooney, L. W., and Almeida-Dominguez, H. (1999) Functionality of rice and sorghum flours in baked tortilla and corn chips *Cereal Chemistry* **76** (5), 705-710

Rajagopal, M. V., Mudambi, S. R, and Pasi, S 1983 Composite flour for chapati Proceedings of the 6th International Congress of Food Science and Technology 55-

Rao, S. J. and Rao, G. V. (1997) Effect of incorporation of sorghum flour to wheat flour on chemical, rheological and bread characteristics *Journal of Food Science and Technology* **34** (3), 251-254

Rasanen, J., Blanshard, J. M. V., Mitchell, J. R., Derbyshire, W., and Autio, K. (1998) Properties of frozen wheat doughs at subzero temperatures *Journal of Cereal Science* **28** (1), 1-14

Rizley, N. F. and Suter, D. A. (1977) Sorghum Tortillas - Process and Product Attributes *Journal of Food Science* **42** (6), 1435-1438

Rom,D.L., Shull,J.M., Chandrashekar,A., and Kirleis,A. (1992) Effect of cooking and treatment with sodium bisulphite on the in vitro protein digestibility and microstructure of sorghum flour Cereal Chemistry **69** (178-181

Rooney, L. W. and Pflugfelder, R. L. (1986) Factors Affecting Starch Digestibility with Special Emphasis on Sorghum and Corn *Journal of Animal Science* **63** (5), 1607-1623

Rooney, L. W. and Serna-Saldivar, S. 0. 1991 Sorghum Lorenz, K. J and Kulp, K New York, Marcel Dekker. 233-269

Sankara Rao,D.S. and Deosthale,Y.G. (1980) Effect of pearling on mineral and trace element composition and ionizable iron content of sorghum. Nutr. Rep. Int. **22** (723-728

Sarode,R.N., Shastri,P.N., and Rao,B.Y. (1983) Studies on utilization of sorghum flour for biscuits Indian J. Nutri. Dietet **20** (7), 213-215

Shahidi, F and Naczk, M 1995 Phenolics in cereals and legumes Lancaster, Pa.: Technomic Publishing Co. 9-52

Sherman,P. (1969) A texture profile of food stuffs based on well defined rheological properties Journal of Food Science **34** (458-462

Sikabbubba, R.M.(1989) The effect of alcohol soluble proteins an the digestibility of sorghum Kansas State University, Manhattan, Kansas, Etats-Unis. Thèse de maîtrise.

Silano, V. 1977 Factors affecting digestibility and availability of protein in cereals. Proceedings of the Advisory Group Meeting on a Nutritional Evaluation of Cereal Mutants Vienne, Agence internationale de l'énergie atomique 13-46.

Sivaramakrishnan, H. P., Senge, B., and Chattopadhyay, P. K. (2004) Rheological properties of rice dough for making rice bread *Journal of Food Engineering* **62** (1), 37-45

Slade, L. and Levine, H. (1995) Water and the Class Transition - Dependence of the Glass-Transition on Composition and Chemical-Structure - Special Implications for Flour Functionality in Cookie Baking *Journal of Food Engineering* **24** (4), 431-509

Slade, L. and Levine, H. (1995) Water and the Glass Transition - Dependence of the Glass-Transition on Composition and Chemical-Structure - Special Implications for Flour Functionality in Cookie Baking *Journal of Food Engineering* **24** (4), 431-509

Smith, J. R., Smith, T. L., and Tschoegl, N. W. (1970) Rheological Properties of Wheat Flour Doughs .Part III. Dynamic shear modulus and its dependence on amplitude, frequency, and dough composition *Rheologica Acta* **9** (239-252

Stevens, D. J. and Elton, G. A. (1971) Thermal Properties of Starch/Water System .1. Measurement of Heat of Gelatinisation by Differential Scanning Calorimetry *Starke* **23** (1), 8-

Subramanian, V and Jambunathan, R 1981 Properties of sorghum grain and their relationship to roti quality. ICRISAT. 280-

Subramanian, V and Jambunathan, R 1982 Properties of sorghum grain and their relationship to roti quality Rooney, L. W. and Murthy, D. S. 280-288.

Subramanian, V., Jambunathan, R., and Rao, N. S. (1983) Textural Properties of Sorghum Dough *Journal of Food Science* **48** (6), 1650-&

Suhendro, E. L., Kunetz, C. F., McDonough, C. M., Rooney, L. W., and Waniska, R. D. (2000) Cooking characteristics and quality of noodles from food sorghum *Cereal Chemistry* **77** (2), 96-100

Swaminathan, M, Kantha, J, Rao, M. N, Chandiramani, S. V., Lalitha, S, and Indira, K 1976 Nutrient composition of sorghum Mysore, India: Central Food Technological Research Institute 86-87

Szczesniak, A. S. (1963) Classification of Textural Characteristics *Journal of Food Science* **28** (4), 385-

Szczesniak,A.S., Brandt,M.A., and Friedman,H.H. (1963) Development of standard rating scales for mechanical parameters of texture and correlation between the objective and sensory methods of texture evaluation Journal of Food Science **28** (397-

Toomey,G. (1988) Sorghum as substitute. Food enterprises for Indian woman. Int. Develop. Res. Centre Reports **17** (3), 20-21

Torres, P. I., Ramirezwong, B., Sernasaldivar, S. O., and Rooney, L. W. (1994) Effect of Decorticated Sorghum Addition on the Rheological Properties of Wheat Tortilla Dough *Cereal Chemistry* **71** (5), 509-512

United States Department of Agriculture/Human Nutrition Information Service (USDA/HNIS). 1984 Composition of foods: cereal grains and pasta. Washington, DC.

Vinkx, C. J. A. and Delcour, J. A. (1996) Rye (Secale cereale L) arabinoxylans: A critical review *Journal of Cereal Science* **24** (1), 1-14

Viraktamath,CS, Raghavendra,G, and Desikachar,HSR (1972) Varietal differences in chemical composition, physical properties and culinary qualities of some recently developed sorghum strains *<[11] Journal Name>* **9** (73-76

Vivas, N. E., Waniska, R. D., and Rooney, L. W. (1987) Thin Porridges (Atole) Prepared from Maize and Sorghum *Cereal Chemistry* **64** (6), 390-394

Waggle,D.H. and Deyoe,C.W. (1966) Relationship between protein level and amino acid composition of sorghum grain. Feedstuffs **38** (1819-

Waniska, R.A.(1990) Methods to assess quality of boiled sorghum, gruel and chapaties from sorghums with different kernel characteristics College Station, Texas, USA: Texas A&M University M.S thesis

Waniska, R. A., Kotarski, S., and Thurn, K. 1990 Starch digestibility of sorghum Ejeta, G. et. al. Purdue University, West Lafayette, IN 177-190.

Weipert, D. (1990) The Benefits of Basic Rheometry in Studying Dough Rheology *Cereal Chemistry* **67** (4), 311-317

Whistler, R. L and Paschall, E. F. 1967 Starch chemistry and technology 2 New York et Londres, Academic Press

Whitaker, M. E. and Tanner, M. 1989 Methods of determining the bioavailability of amino acids for poultry. 3 M.Friedman Boca Raton, Floride, Etats-Unis, CRC Press 129-141

Yousif, N. E. and El Tinay, A. H. (2001) Effect of fermentation on sorghum protein fractions and in vitro protein digestibility *Plant Foods for Human Nutrition* **56** (2), 175-182

Youssef,A.M. and Abu-Foul,N.S. (1998) Influence of germination on tannins, phytic acid, starch, fat and baking properties of germinated sorghum flour Alexandria Science Exchange **19** (2), 353-368

Youssef, A. M. M., Moharram, Y. G., Moustaffa, E. K., Bolling, H., Elbaya, A., and Harmuth, A. E. (1990) New Extruded Products from Sorghum *Food Chemistry* **37** (3), 189-199

Zaparrart, M. I. D. and Salgado, J. M. (1994) Chemical and Nutritional-Evaluation of Whole Sorghum Flour, Complementation with Phaseolus-Vulgaris and Dried Milk Whey - Application in Baking *Archivos Latinoamericanos de Nutricion* **44** (3), 151-157

Zhang, G. Y. and Hamaker, B. R. (1998a) Low alpha-amylase starch digestibility of cooked sorghum flours and the effect of protein *Cereal Chemistry* **75** (5), 710-713

Zhang, G. Y. and Hamaker, B. R. (23-4-2003b) A three component interaction among starch, protein, and free fatty acids revealed by pasting profiles *Journal of Agricultural and Food Chemistry* **51** (9), 2797-2800

Zhumabekova,Z.Z., Darkanbaev,T.B., and Ostrovskaya,L.K. (1978) Characteristics of the carbohydrate-amylase complex of sorghum grain flour Seriya Biologicheskaya **16** (1), 11-17