A comprehensive review on wheat flour dough rheology

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ABSTRACT

The applications of rheology to the main processes encountered during bread making (mixing, fermentation and baking) are reviewed. Factors affecting dough rheology and influences of various additives on the rheological properties of flour doughs are illustrated and the component interactions are emphasized. The most commonly used rheological test methods and their relationships to product functionality are reviewed. Rheological testing has become a powerful and preferred approach for examining the structure and the fundamental properties of wheat flour doughs because of its characteristic and sensitive response to the structure variation of wheat flour doughs. It is shown that the most commonly used method for rheological testing of doughs, shear oscillation dynamic rheology, is generally used under deformation conditions inappropriate for bread making and shows little relationship with end-use performance. The frequency range used in conventional shear oscillation tests is limited to the plateau region, which is insensitive to changes in the HMW glutenin polymers thought to be responsible for variations in baking quality. Molecular size and structure of the gluten polymers that make up the major structural components of wheat are related to their rheological properties via modern polymer rheology concepts. Interactions between polymer chain entanglements and branching are seen to be the key mechanisms determining the rheology of HMW polymers.

Introduction – what is rheology?

Rheology can be defined as the study of how materials deform, flow or fail when force is applied. The name is derivated from Greek word: rheos, meaning the river, flowing, streaming. Therefore rheology means “flow science”. Rheological investigations not only include flow behaviour of liquids, but also deformation behaviour of solids. Normally, to measure rheological properties, the material is subjected to a controlled, precised and quantifiable distortion or strain over a given time and the material parameters such as stiffness, modulus, viscosity, hardness, strength or toughness are determined by considering the subsequent forces or stresses (Dobraszczyk and Morgenstern, 2003).

Food rheology focuses on the flow properties of single food components, which might already display a complex rheological response function, the flow of a composite food matrix, and the effect of processing on the food structure and its properties. For processed food the composition and the addition of ingredients to obtain a certain food quality and product performance requires deep rheological understanding of single ingredients their relation to food processing, and their final discernment (Fischer and Windhab, 2011).

Rheology is another valuable tool that gives a quantitative measure for the amount of stress in the dough, which is closely related to the quality of the molecular gluten network (Bloksma and Bushuk 1988b). Rheological measurements on dough are used to define its physical properties. The primary objectives of rheological measurements are:

- To get a quantitative description of the material’s mechanical properties.
- To gain information related to the molecular structure and composition of the material.
- To characterise and guess the material’s performance during processing and for quality control (Dobraszczyk, 2003).

Rheological measurements are an important tool to aid in process control and process design, it tells us how dough will behave under a given set of conditions and can be used to describe and guess its performance during practical processing (Scott and Richardson, 1997), e.g., during mixing, sheeting (Love et al., 2002; Morgenstern et al., 2002; Binding et al., 2003), proofing (Shah et al., 1999), and baking of dough (Fan et al., 1994). Moreover, it can also be related to product functionality. Many rheological tests are used to predict end product quality such as mixing behaviour, sheeting and baking performance (Dobraszczyk, 2004a). In order to examine process conditions and expect product performance and consumer acceptance, rheological instrumentation and measurements have become essential tools in analytical laboratories (Herh et al., 2005). Herh et al., (2000) studied that in predicting storage and stability measurements and in understanding and designing
Rheological properties should be independent of size, shape and how they are measured; in other words, they are worldwide, rather like the speed of light or density of water, which do not depend on how much light or water is being measured or how it is being measured. It would be encouraging to know that the stiffness of bread or viscosity of dough measured in a laboratory in Faisalabad (Pakistan) will be the same measured in any laboratory in the world, even if they are measured using different tests, sample sizes or shapes. In short, the rheological approach is that the properties that are measured are reproducible and can be compared between different samples, test sizes and shapes, and test methods (Dobraszczyk, 2004b).

Full understanding of the rheological behaviour of flour dough is of great importance from the practical point of view. Dough rheology directly affects the baking performance of flours, and rheological analyses have been made in order to optimize dough formulation. Although dough rheology has long been investigated, there remains a significant lack of understanding. This lacks of progress is due to the complexity of this biological system (Masi et al., 2001).

**Historical Background**

Humankind has always been a perceptive feel for rheological testing, e.g. in physical and visual evaluations of material properties such as hardness, stiffness, flexibility, and viscosity, and their relation to end-use quality characteristics. People often naturally measure the quality of solid foods by gently squeezing them, or liquid viscosity is measured by gently rotating the liquid in its container. These intuitive measurements gradually became formalised into quantitative descriptions of material properties by scientists such as Newton (1687), Boyle (1662), Pascal (1663), Hooke (1678), Young (1807) and Cauchy (1827) (Tanner and Walters, 1998).

Modern rheology as an independent discipline can be dated back to 1929, when The Society of Rheology was set up by a number of scientists working in matching fields to secure an absolute standard for viscosity, and the name rheology was suggested by Bingham and Reiner to describe the study of flow and deformation of all forms of matter. The targets of rheologists are measurement, characterization and interpretation of the flow and deformation behaviour of materials. Since then rheology has developed quickly as a science and contributed to a number of applications such as colloids, suspensions and emulsions, polymer processing, extrusion and polymer modelling. Recent developments in polymer rheology have established a quantitative link between the molecular size and structure of polymers to their rheology and end-use performance (de Gennes, 1979; Doi and Edwards, 1986).

Rheological measurements are more and more being used as rapid, sensitive indicators of polymer molecular structure and forecasters of end-use performance and are being applied to bread doughs as indicators of the gluten polymer molecular structure and predictors of its functional behaviour in breadmaking (Marin and Montfort, 1996).

**Rheological measurements**

There are many test methods used to measure rheological properties. It is not feasible to explain all the available testing methods here, and referred to general reviews of rheology (Ferry, 1980; Barnes et al., 1989; Whorlhow, 1992), rheological testing of foods (Sherman, 1970; Carter, 1990; Rao and Steffe, 1992; Dobraszczyk and Vincent, 1999; van Vliet et al., 1992) and cereal products (Bloksma and Bushuk, 1988a; Faridi and Faubion, 1986; Faridi and Faubion, 1990; Muller, 1975). It is common to classify rheological techniques according to the type of strain imposed: e.g. compression, extension, shear, torsion, and also the relative magnitude of the imposed deformation, e.g. small or large deformation. The main techniques used for measuring cereal properties have conventionally been divided into descriptive empirical techniques and fundamental measurements (Dobraszczyk, 2004b).

### 1. Descriptive empirical rheological measurements

Within the cereals industry there has been a long history of using descriptive empirical measurements of rheological properties, with instruments such as the penetrometer, texturometer, consistometer, amylograph, farinograph, mixograph, extensigraph, alveograph, various flow viscometers and fermentation recording devices (Muller, 1975) and (Shuey, 1975) (Table 1).

Empirical tests are easy to carry out and are often used in practical factory situations, providing data that are useful in assessing performance during processing and for quality control. The instruments are often vigorous and capable of resisting demanding factory environments, and do not require highly skilled or technically trained personnel. Simply because they do not provide data in fundamental units does not mean that these tests are valueless: in fact, they have provided a great deal of information on the quality and performance of cereal products such as consistency, hardness, texture, viscosity, etc. However, these measurements are not strictly ‘rheological’ tests since:
• The sample geometry is variable and not well defined.
• The stress and strain states are uncontrolled, complex and non-uniform.
• It is not possible to define any rheological parameters such as stress, strain, strain rate, modulus or viscosity.

Therefore, these tests are entirely descriptive and dependent on the type of instrument, size and geometry of the test sample and the specific conditions under which the test was performed. For example, empirical tests have been used to characterise the behaviour of bread doughs during processing, such as the Farinograph and Mixograph. The problem with the use of these instruments for rheological studies is that we cannot define the stress on the sample at any moment of time during the test. For example, in a mixograph bowl, only a small part of the dough is in contact with a pin at any given time, and the shape of the sample (dough) changes in a very complicated and unpredictable ways. Thus, it is impossible to determine the stress on the dough, as we do not know the geometry of our test piece. As a result, the measurement made using a mixograph is valid only for the mixograph, and measurements made using the farinograph are relevant only to the farinograph. Moreover, many of these are used as ‘single point’ tests, where a single parameter is often arbitrarily selected from a whole range of data acquired during the test as, for example, in selecting the peak torque from a mixing trace and then using this to correlate with performance. This neglects a large part of the recorded data, and is appropriate only to the set of conditions under which that test was performed and is generally not applicable to any other deformation conditions (Dobraszczyk and Schofield, 2002; Wikstrom and Bohlin, 1996). Since dough experiences a wide range of conditions of stress states and strain rates during processing and baking, and the rheological properties of dough are dependent both on time and strain, there is often a difference between such single point type tests and actual performance on the plant, where conditions of strain and strain rate may be poorly defined and very different from those in the laboratory test (Blokşma, 1990a; Stojceska et al., 2007). While this may give satisfactory correlations with a textural or processing parameter, it is impossible to compare results between different testing machines, or to extrapolate the results to other deformation conditions (Dobraszczyk, 2004b).

Most food materials are viscoelastic and therefore their properties depend on how quickly the test is performed (the strain rate or frequency). This is important in many aspects of dough processing: if the dough is deformed quickly, such as in mixing or sheeting, then the rheological properties of the dough will be very different when measured at the typically slower rates of deformation found in conventional testing machines. Alternatively, during processing dough will experience strains very different in magnitude and nature than those generally available in a rheological test. Many food processes operate under extensional flow, while most rheological tests on foods are performed in shear. Tests under only one particular set of conditions of rate, temperature and strain will almost certainly not be applicable to another set of deformation conditions. What is necessary is to define the set of deformation conditions that the food endures in practice and perform tests under similar conditions (Dobraszczyk and Morgenstern, 2003).

2. Fundamental rheological measurements

Fundamental rheological tests determine well-defined physical properties independent of size, shape and how they are measured, and can be used for process design calculations and to model complex processing situations not amenable to direct measurement. Problems encountered with such fundamental tests are: complex instrumentation which is expensive, time consuming, difficult to maintain in an industrial environment and requires high levels of technical skill; often inappropriate deformation conditions; difficulty in interpretation of results; and slip and edge effects during testing (Dobraszczyk, 2003).

The main types of fundamental rheological tests used in cereal testing are: (i) dynamic oscillation, (ii) creep and stress relaxation, (iii) extensional measurements, (iv) flow viscometry (Dobraszczyk, 2004b) (Table 1).

Factors affecting dough rheology

There are a wide variety of substances added to the dough mix that might be generally classed as processing aids and which may have secondary effects on dough rheology. Stear (1990) gives a useful summary of these. But here, our main concern is those substances that have a primary effect on rheology and throw light on the factors controlling the response to the input of mechanical energy.

The substances of interest are listed below:

- Water
- D₂O (deuterium oxide – heavy water)
- Esterifying agents for glutamine residues
- Urea
- Salts
- Agents affecting disulfide bonding
- The protein subunits present

Water is of course a prerequisite for making dough: water plasticises dough, and the control of water content is of critical importance in mixing. It
determines the ratio of loops to trains and hence the ability of the dough to be extended and to resist extension (Belton, 2003). The actual level of hydration in dough is quite low; typically the level of added water to flour is in the order of 0.6 g of water per gram of flour. Since the intrinsic level of water in the flour is of the order of 14%, the total water is about 0.75 g per gram. If the water is equally partitioned between the components of the flour this will mean that there is about 0.75 g of water per gram of gluten. In molecular terms this means that there will be about 5.5 water molecules per amino acid residue. This represents a highly concentrated protein system. Results reported using nuclear magnetic resonance (NMR) to measure the amount of mobile protein in preparation of high-molecular-weight (HMW) subunits of gluten (Belton et al., 1994), indicates that in this region of water to protein ratio, the quantity of mobile material is highly sensitive to water content (Fig. 1). In breadmaking, the water content of dough is thus chosen to be in a region where small changes in water content are likely to make a large change in the behaviour of the proteins.

Changing H_2O to D_2O has the effect of strengthening the dough (Tkachuk and Hlynka, 1968). This must indicate a role for hydrogen bonding in the dough, as the hydrogen bonds formed by D_2O are significantly stronger than those formed by H_2O and there seem to be no other significant differences between the two isotopic forms that could have an effect. Whereas strengthening hydrogen bonds strengthens the dough, treatment to esterify glutamines residues, thus removing their hydrogen bonding ability weakens the dough (Beckwith et al., 1963; Mita and Matsumoto, 1981). The indication of this effect is that the glutamine amino side chains are involved in some hydrogen-bonding network that is important in controlling dough

### Table 1: Rheological methods used for cereal products

<table>
<thead>
<tr>
<th>Methods</th>
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<td>Alveograph</td>
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<td>Amylograph RVA</td>
<td>Pastes, Suspensions</td>
<td>Apparent Viscosity, Gelatinisation temperature</td>
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<tr>
<td>Consistometer</td>
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<td>Fluids, Sauces, Batters</td>
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<td>Falling ball</td>
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<td>Flow viscometers</td>
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<td>Texturometer, TPA</td>
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<td><strong>Fundamental methods:</strong></td>
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<tr>
<td>Dynamic oscillation, Concentric cylinders, Parallel plates</td>
<td>Fluids, Pastes, Batters, Doughs</td>
<td>Dynamic shear moduli, Dynamic viscosity</td>
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<td>Tube viscometers: Capillary, Pressure, Extrusion, Pipe flow</td>
<td>Fluids, Sauces, Pastes, Dough</td>
<td>Viscosity, In-line viscosity</td>
<td>(Rouille et al., 2005)</td>
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<tr>
<td>Transient flow: Concentric cylinders, Parallel plates</td>
<td>Semi-solid viscoelastic Material</td>
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<tr>
<td>Extrusion: Uniaxial, Biaxial, Dough inflation system, Lubricated compression</td>
<td>Solid foods, Doughs</td>
<td>Extensional viscosity, Strain hardening</td>
<td>(Dobraszczyk, 2004a)</td>
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Fig. 1: A plot for the variation in the mobile fraction of high molecular weight subunits with water content.

Fig. 2: Relationship between G of gluten (stress 25 Pa, frequency 1 Hz) and loaf volume for flours.
rheology. In a similar manner, the weakening effects of urea on dough rheology (Wrigley et al., 1998) have been interpreted as being due to disruption of hydrogen bonding.

The molecular effects of salts can be quite subtle and the details of the mechanisms of the interactions of salts with proteins are not completely understood. Salts can affect both hydrogen bonding and protein solubility, both of which will affect the cohesiveness of the system. Eliasson and Larsson (1993) have reviewed the effects of salts on the behaviour of dough. The addition of sodium chloride to dough influences gas retention, increases the time to optimum dough development and increases the stability of the dough. These effects may arise from a variety of causes not directly linked to the interactions of the proteins. There may be effects on enzymes and yeast; however, more extensive studies have shown that both gluten strength (Preston, 1989) and extractability of proteins (Preston, 1985) are modified by the addition of salts.

For metal chloride salts, the gluten strength is increased with the charge density of the metal ion. Since generally higher charge densities result in a more hydrogen bonded water structure, this may be taken to imply that increasing the hydrogen bonding capacity of the solvent increases the gluten strength. Conversely, the extraction data for a series of sodium salts showed that the greater the capacity of the counter-ion to break down hydrogen bonding structure, the more it facilitated protein extraction. Apart from the obvious effects of shielding electrostatic charge interactions, the role of salts in protein is difficult to understand and much discussion has gone on in the literature. However spectroscopic results on gluten at constant water content (Wellner et al., 2003) indicate that for the series NaCl, NaBr and NaI, increasing counter-ion size, and hence water structure breaking capacity, cause an increase in the amount of beta turn present and the amount of mobile protein present. This result is consistent with those of Preston (1985, 1989).

The role of disulfide linkages in the control of dough rheology is of the utmost importance. If disulfide bonds are reduced by a chemical agent, such as dithiothreitol, a dramatic reduction in dough strength is observed (Wrigley et al., 1998) which is recovered on re-oxidation. The additions of various oxidizing and reducing agents that can affect the interchange of disulfide bonds also have major effects (Eliasson and Larsson, 1993). The actual mode of action of the various agents that can affect both the interchange among, and the number of disulfide bonds, is not entirely clear till now (Weegels et al., 1994). However, their effect is profound. Indeed, the role of disulfide interchange in dough rheology has led Bushuk (1998) to remark that “The importance of the disulfide interchange reaction in the development and stress relaxation of bread doughs cannot be overemphasised”.

Fig. 3: Dynamic responses of durum dough enriched with 2 % gluten, gliadin and glutelin, respectively (Edwards et al., 2001)
The role of the nature of the various protein subunits in dough rheology and loaf quality has been the subject of intensive research. Gliadins are generally agreed to contribute to the viscous nature of the dough and glutenins to the elastic nature of the dough. Of the glutenins the most important are the HMW subunits even though they only constitute 12 % of the total flour proteins or 1-1.7 % of the flour dry weight (Shewry et al., 2001).

Wheat grains and rheology

The physicochemical and rheological properties of flour differ significantly among wheat varieties which have far reaching effects on the end use quality of wheat. The rheological characteristics of flour vary between varieties (Stathopoulos et al., 2008). Actual quality of wheat is the summation of effects of soil, climate and seed stock on the wheat plant and kernel components. The wheat grains are milled into flour and used in different end use products. The quality of the end product depends upon quality of wheat grain. The wheat suitable for one particular use may have certain properties that are totally unsatisfactory for other use (Faridi et al., 1989; Anjum et al., 2008).

Wheat flours from various classes and cultivars display great diversity in their functional properties. The variations in functional properties of a wheat cultivar are attributed largely to its gluten quality and quantity (Rao et al., 2000). The farinograph test is one of the water hydrates the flour components and the dough is developed (Fu et al., 2008). Mixing time define as the time in minutes taken by the curve to reach the peak. Peak height is the height attained by the curve at peak in cm as measured from the center of the peak to the base line and mixing tolerance measured as the angle in degrees formed by the ascending and descending curves at the apex, located in the center of the curve (Singh et al., 2003).

Gluten is rich in gliadins and glutenins. Dynamic rheological parameters of gliadins are able to indicate the wheat quality. Gluten from poor quality reconstituted using gliadins of different wheat cultivars and a content source of starch and water soluble (Khatkar and Schofield, 2002a). Wheat are rheologically characterized as less elastic and more viscous than those from good quality wheat (Khatkar et al., 1995). Glutens from good bread making wheat are cross linked in a higher degree so that the frequency dependence of G is smaller than that of glutens from poor bread making wheat (Janssen et al., 1996b). Storage and loss moduli G and G’ of glutens show most commonly used flour quality tests in the world. The results are used as parameters in formulation to estimate the amount of water required to make dough, to evaluate the effects of ingredients on mixing properties, to evaluate flour blending requirements and to check flour uniformity. The results are also used to predict processing effects, including mixing requirements for dough development, tolerance to over-mixing and dough consistency during production. Farinograph results are also useful for predicting finished product texture characteristics. For example, strong dough mixing properties are related to firm product texture. Brabender farinograph has been used to predict doughing properties of flours. Dough is prepared during mixing and resistance to shear is recorded. Graph for strong wheat flour gives high water absorption, shows rapid development and minimal breakdown. Weak wheat flours also exhibit rapid development but their breakdown is greater as well as has low water absorption capacity. Farinographic water absorption of flour provides an indication of the potential of the protein molecules to absorb moisture (Dobraszczyk and Salmanowicz, 2008).

Dough stability is defined as the time difference between the point where the top of the curve first intercepts the 500 BU line and the point where the top of the curve leaves the 500 BU line (Sim et al., 2011). Dough development time is the time from water addition to the flour until the dough reaches the point of the greatest torque. During this phase of mixing, the significant positive correlations with loaf volume (Khatkar et al., 2002). Especially, G of gluten doughs can be directly related to the bread making performance, explaining 73 % of variation in loaf volume (Fig. 2) (Khatkar and Schofield, 2002a). The tan δ values of glutens are ranked as weak glutens > strong glutens > extra strong glutens while the G and G’ values show the reverse tendency. The weak glutens especially undergo a substantial structural change from solid-like to liquid-like behaviours with increasing frequency while the strong glutens maintain their elastic characters to a great extent (Khatkar, 2004).

Wheat flour water absorption 57.5 % in farinograph is observed. Canadian wheat cultivars have 60.7-65.9 % water absorption, 2.25-13 minutes development time and 5-25 minutes stability time in farinograph (Indrani and Rao, 2007). Water absorption of different wheat varieties were ranges from 58.1-66.4 % and the dough development time with average value of 6 minutes (Hruskova et al., 2006). In another experiment, wheat with 53.6 % water absorption, 1.53 minutes dough development time and 1.40 minutes dough stability is determined (Paraskevopoulou et al., 2010). Studies
showed that the Irish, Greek and Canadian wheat varieties had water absorption, dough development time and dough stability ranges from 50.7-61.5 %, 1.5-6 minutes 1-5 minutes respectively. In 2010, it is reported that the Irish wheat varieties had the water absorption, development time and stability ranges from 50-65.5 %, 1.5-6 minutes and 1-9 minutes respectively (Ktenioudaki et al., 2010). Mixograph test was the best predictors for chewiness and firmness because it is simple, requires relatively small sample size and the results obtained are highly correlated with sensory data. It is the most useful test to predict the end use quality (Kovacs et al., 1997). In mixograph, the mixing time varies from 2.3-7.9 minutes and peak dough resistance from 52.3-65.2 AU showed by Rao et al., (2000). The values for dough development time and dough stability decreased with reduced protein content, but the value of mixing tolerance index increased (Fu et al., 2008).

Both quantity and quality of protein influence water absorption (Kenny et al., 2001; Akubor and Ukwuru, 2003; Paraskevopoulou et al., 2010). Hefnawy et al., (2012) reported that the increase in protein content increased the water absorption. Water absorption is an important characteristic of the wheat flour and in Indo-Pakistan wheat varieties ranged from 60-76 % water absorption (Sila, 2010).

**Composite flour technology and rheology**

There is a growing interest in fortifying wheat flour with high lysine material, such as dry beans to improve the essential amino acid balance of baked food products. Using composite flours may be advantageous in developing countries where adequate technology for the production dry protein concentrates/isolates is not available or affordable in order to utilize the bean proteins. Also the development of such blends could lead to improved utilization of indigenous food crops in countries where import of wheat flour is a necessity and dry bean production is more than adequate. Increasing levels of cowpea flour in the blends affected most dough properties and resulted in changed farinograph and extensograph characteristics, mainly by increased water absorption. Increased water absorption of wheat-bean composite flours may provide more water for starch gelatinization in the doughs during baking and may prevent stretching and tearing of gluten strands (Hallen et al., 2004).

In the case of wheat dough, rheological analysis has been successfully applied as indicator of the molecular structure of gluten and starch, and as predictors of their functionality in baking performance (Collar and Bollain, 2005; Bollain et al., 2006). Despite gluten free matrixes are structurally different than gluten dough; rheological assessment of the gluten free matrixes might give an indication of its further functionality. The cohesiveness was significantly affected only by soybean protein content (Marco and Rosell, 2008). Legumes such as soybean and chickpea proteins shows higher emulsifying activity and emulsion stability (Tömösközi et al., 2001). They are used in food technology for supplying desirable functional properties such as emulsification, fat absorption, moisture holding capacity, thickening, and foaming (Marco and Rosell, 2008). The addition of 20 % soy flour to wheat produced a significant positive effect on the emulsifying activity of the samples (Ahn et al., 2005).

Farinograph characteristics of flour blends showed that as the proportion of soy flour increased there was a slight increase in water absorption and decrease in dough stability. The results showed that incorporation of soy flour increased the water absorption capacity. At 20 % level of soy flour the water absorption was 77 % and at 40 % level, it was 80 %. The stability of the dough was found to decrease from 4.5 to 3.0 minutes when the soy flour content increased from 20 to 40 %. Dough development time and mixing tolerance index remained almost same for all flour blends that are 4.5 minutes and 110 BU respectively (Senthil et al., 2002). In another trail as the percentage of soy flour increased from 5 to 10 %, water absorption increase from 57.2 to 57.9 %. As the level of flour blends in composite doughs increased, farinograph absorption and mixing tolerance index increased, but mixing time and dough stability decreased (Doxastakis et al., 2002).

Rheological characteristics in different wheat varieties of Pakistan showed 55.20- 62.13 % water absorption, 3.33-16.42 minutes dough stability time and 3.58-9.92 minutes dough development time (Huma, 2004). Further studies reported that water absorption of wheat is 61.24 %. As percentage of chickpea increase, water absorption increased. Water absorption in 10 % chickpea is higher than 7.5 % and 5 % that is 67.85, 67.45 and 66.85 % respectively. Similarly increased in the dough development time and dough stability time as the concentration of chickpea increased. While rheological behaviour of the composite flours prepared by blending commercial wheat flour with lentil, chickpea and guar gum showed decrease in water absorption and increase in dough development time in a storage period of 60 days (Shahzadi et al., 2005). In contrast, studied showed that at 5, 10, 15, 20 and 30 % replacement of chickpea with wheat the water absorption decreased from 62, 60, 57, 56.6 and 53.3 % respectively. In replacement of corn flour at the same percentage the water absorption increased from 63.3,
Ingredients and rheology

Rheological testing, especially in the linear viscoelastic region, has been used to follow the structure and properties of doughs and to study the functions of dough ingredients (Janssen et al., 1996a). This testing simultaneously measures the viscous and elastic characters of dough expressed in storage and loss moduli, $G'$ and $G''$, and loss tangent $\tan \delta$. It is generally found that doughs made from good quality flour have $\tan \delta$ values lower than doughs made from poor quality flour. The magnitude of modulus at intermediate and high strains is in the order of extra strong > strong > medium > weak (Safari-Ardi and Phan-Thien, 1998). Nevertheless, dynamic rheological tests on flour dough fail to predict the baking potential of wheat cultivars (Autio et al., 2001).

Influence of water

Dough is a macroscopically homogeneous mixture of starch, protein, fat, salt, yeast, and other components. At optimum mixing, the dough is fully hydrated and has the highest elasticity. Water plays an important role in determining the viscoelastic properties of dough. Both $G'$ and $G''$ decrease as water content increases. The dynamic viscoelastic behaviour of flour doughs can be understood by taking into account the dual role of water that behaves as inert filler reducing the dynamic properties proportionally and as a lubricant enhancing the relaxation (Masi et al., 1998).

Influence of starch

Starch, making up ~80 % of wheat flour on dry basis, is able to form a continuous network of particles together with the macromolecular network of hydrated gluten. These two independent networks and their interaction give rise to the rheological properties of doughs. Though the interaction plays an important role, the relative contributions of the two sources are difficult to resolve. The component interactions depend on stress level. The starch – starch interactions dominate over protein – protein interactions at low stresses while the protein – protein interactions play dominant role at large deformations (Khatkar and Schofield, 2002b). The nonlinear rheological behaviour of starch is largely responsible for the behaviour of dough (Watanabe et al., 2002).

In starch/gluten blend with constant water content, $G'$ increases rapidly with increasing protein content. The reconstituted doughs behave qualitatively like flour doughs with comparable compositions. When starch granules are apparently homogeneously dispersed in the gluten network, increasing starch content gives rise to an increase in $G'$ value (Watanabe et al., 2002) thus enhancing the elasticity (Edwards et al., 2002). Flour doughs cannot be viewed simply as a concentrated suspension of starch granules in hydrated gluten matrix. Mixing starches from different wheat cultivars into dough with constant gluten content leads to large rheological differences, indicating an active role of starch (Petrofsky and Hoseney, 1995).

Influence of proteins

The protein content of flours shows an inverse relationship with $G'$ and $G''$ up to ~14 % protein (Khatkar, 2005). Gluten contributes to the viscoelastic properties of dough to varying degrees depending on its source differing with both gliadin/gliutenin ratio and LMW-GS (Edwards et al., 2001; Edwards et al., 2003). Gliadin enhances viscous flow of dough. An addition of 2 % gliadin results in increased dough extensibility and $\tan \delta$ as compared to gluten and glutenin additions. Glutenin addition, on the other hand, results in more elastic dough in comparison with gluten and gliadin additions (Fig. 3) (Edwards et al., 2001). Addition of glutenins at constant protein basis contributes to the dough strength with marked differences among donor cultivars (Edwards et al., 2003). Increasing the glutenin/gliadin ratio improves maximum shear viscosity and dough strength (Uthayakumar et al., 2000).

Both low molecular weight glutenin subunits (LMW-GS) and high molecular weight glutenin subunits (HMW-GS) contribute to overall dough strength but LMW-GS enrichment improves the elasticity by introducing greater number of physical crosslinks (Edwards et al., 2001). The source of LMW-GS influences the viscoelastic characteristics of doughs while source of HMW-GS does not show such an effect (Edwards et al., 2003).

Influence of other additives

Rheological properties of materials depend on the structure and also on the arrangement of ingredients and the forces between them (Singh et al., 2003). The importance of the soluble fraction of flour in determining the rheological properties of dough subjected to large deformations and its possible consequence for breadmaking performances was demonstrated by measuring shear and extensional viscosities of native wheat flour and reconstituted doughs using creep-recovery tests and lubricated squeezing flow tests (LSF). The viscosity plateau decreases with increasing additions of soluble fractions. They showed poor discriminating properties compared
with results of lubricating squeezing flow tests (Rouille et al., 2005). Dairy ingredients are added to bakery products to increase nutritional and functional properties. Dynamic oscillation testing determined the effects of the ingredients on fundamental rheological properties. Adding 4% sodium casianate (SC) decreased resistance to extension, while adding 4% whey protein concentrate (WPC) increased extensibility (Kenny et al., 2001). Functional food additives such as surfactants are widely used to improve the quality of bread. The percent water absorption increased significantly with the addition of surfactants (monodiglyceride and lecithin) alone or in combination. Moreover, the overall dough rheological characteristics and baking quality improved and further these surfactants retarded the rate of staling in bread (Azizi et al., 2003). The performance of different fat replacers at various levels (Inulin powder, Inulin gel and Simplesse) in wheat bread and dough compared to a control containing block fat was examined. Empirical and fundamental rheological tests were carried out on the doughs. The addition of inulin gel was found to increase water absorption. Moreover complex modulus for doughs containing fat was significantly lower than the doughs containing the fat replacers. The addition of simplesse and inulin increased the dough complex modulus significantly (O’Brien et al., 2003).

Dynamic rheological testing has become a powerful and preferred approach for examining the structure and the fundamental properties of wheat flour doughs and proteins because of its characteristic and sensitive response to the structure variation of wheat flour doughs and proteins (Song and Zheng, 2007). Addition of carbohydrates such as arabinoxylans, β-glucans (Izydorczyk et al., 2001), carrageenan, alginate (Howell et al., 1998) and guar gum (Yu and Ngadi, 2006) improve the functional properties of wheat bread through associative interactions with gluten proteins that significantly increases $G'$ of doughs at the same water content.

Defatting improves protein interaction thus increases $G'$ and $G''$ significantly (Georgopoulos et al., 2006). Addition of nonpolar lipids to the defatted flour at their natural level might partially restore the rheological behavior while higher levels of addition have no further effect. On the other hand, addition of polar lipids has a more pronounced beneficial effect (Papantoniou et al., 2004). Addition of water-solubles dramatically shortens the optimum mixing time of the reconstituted flour and decreases $G'$ of the resultant dough (Miller and Hoseney, 1999).

Enzymes are used in baking to improve dough handling properties and the quality of baked products. Glucose oxidase (GO) is an enzyme with oxidizing effect due to the hydrogen peroxide released from its catalytic reaction. A reinforcement or strengthening of wheat dough and an improvement of bread quality can be obtained with the addition of GO, although inverse effects were obtained when excessive enzyme levels were added. The GO treatment modified gluten proteins (gliadins and glutenins) through the formation of disulfide and non-disulfide crosslinks. Excessive addition of GO produced an excessive crosslinking in the gluten network, responsible of the negative effect on the breadmaking properties. Rheological characteristics such as water absorption and dough tolerance showed a significant enhancement when added the higher concentration of glucose oxidase. Thus, the addition of GO promotes an increase in dough stability when over-mixing (Bonet et al., 2006).

### Processing conditions and rheology

Dough processing is an important factor determining the quality of bread. The most important mechanical steps in industrial dough processing are kneading, extrusion, and molding. In all of these processing steps, considerable changes in the structure and properties of the dough can occur. On a laboratory-scale level, these (structural) effects are well characterized but, so far, a little data is available for large-scale industrial dough processing line. The molecular and microstructural changes that can take place during the kneading step revealed that the dough shows a well-developed gluten network with a homogeneous dispersion of starch particles (at optimum kneading time). After the extrusion step (a sheeting procedure), the structure of the dough becomes coarser and the dough gluten network is oriented and partially disrupted. This is accompanied with an increase in both rheological stress and water mobility. After molding, the network structure is restored and both the rheological stress and the mobility of water decrease. These findings helps in optimization of industrial dough processing lines (Esselink et al., 2003).

Dough rheological techniques are frequently used for the analysis of wheat flour baking value. When dough is subjected to mechanical perturbation it shows viscoelastic behaviour. That is, the mechanical force applied to the dough results in dimensional changes that are partially but not fully reversed when the force is removed. The observation of a maximum of resistance during the mixing process implies that the dough stores some of the mechanical energy expended as elastic potential energy. (Hruskova et al., 2006). The distinctive rheological features of dough can predict...
about their expected behaviour under various processing conditions that in turn may help to select suitable raw materials and their proportions, and to decide the appropriate process equipment. As a result, the quality of the finished product including texture, and hence, consumer acceptability is affected. The role of water content in this condition plays an important role as it acts as a plasticizer that affect the rheological behaviour markedly (Bhattacharya et al., 2006).

Among the cereal flours, only wheat flour can form three-dimensional viscoelastic dough when mixed with water. Characterization of rheological properties of dough ispressive in predicting the processing behaviour and in controlling the quality of food products. Farinograph, mixograph and extensograph are the most common empirical instruments used for characterizing dough rheology (Song and Zheng, 2007) and in evaluating the performance during processing and for quality control. Tests based on these instruments are useful for providing practical information for the baking industries while they are not sufficient for interpreting the fundamental behaviour of dough processing and baking quality (Dobraszczyk, 2003). The water absorption capacity of flour often defines its quality and its tendency to form viscoelastic dough. The hydration of flour is severe in the food industry, because it affects its functional properties and the quality of cooking products (Berton et al., 2002).

It is studied that mild heating improves the strength of substandard bread flour such as soft wheat flour. Heating soft wheat flour at 80 °C for 15 min. improved its bread-making potential (Gelinas et al., 2001). The gluten fractions in the different wheat varieties varied in the proportion of HMW glutenins and LMW gliadins. The fractions containing a higher proportion of HMW glutenins were associated with a predominantly elastic character, whereas fractions containing mostly gliadins exhibited a viscous-like behaviour. The frequency dependent rheological behaviour of fractions containing HMW proteins was less susceptible to heat, and their elastic character was maintained after heating, whereas the rheology of intermediate fractions and fractions containing mostly gliadins was more susceptible to heating, indicating a rapid change from viscous to elastic behaviour after heating. Moreover gluten was easier to extract and its texture was slacker after heating, it significantly increased dough-mixing stability and development time (Gelinas and McKinnon, 2004; Stathopoulos et al., 2006).

**Rheological effect on mixing**

Mixing is a critical operation in food processing where, apart from the obvious function of mixing ingredients, the structure of the food is often formed. It is well known that in order to optimize bread quality, mixing must be stopped at the correct level of mechanical input. The actual process called mixing in reality has two separate processes going on within it: one is the homogenization of the various ingredients of the dough, which is a true mixing process, and the other is the development of dough structure by the mechanics of mixing energy into the system. Although the former is of vital importance, it is a process common to most food preparation processes; it is the latter process that demonstrates the uniqueness of wheat flour dough. As mechanical energy is put into the dough, its resistance to extension increases and then after some critical point decreases again. Optimum bread quality is achieved by choosing to stop mixing at the appropriate point on the mixing curve (usually close to, but not at, the maximum resistance) (Belton, 2003). For example, in the production of batters, pastes and doughs, the nature of the mixing action results in the hydration of flour particles leading to development of the viscoelastic properties gluten matrix and also incorporates air, which has a major effect on their rheology and texture (Dobraszczyk and Morgenstern, 2003; Singh et al., 2003; Dobraszczyk et al., 2006).

Most of the studies on doughs have been on the relationships between mixing, rheology and baking performance, because rheological changes occur in the gluten viscoelastic network during mixing and have importance for product quality. There is an intimate relationship between mixing, aeration and rheology: the design and operation of the mixer will develop texture, aeration and rheology to different extents (Campbell and Shah, 1999), and conversely the rheology of the food will affect the time and energy input required to achieve optimal development. This is seen in the great variety of mixers used in the food industry and the fact that certain mixers are required to produce a desired texture or rheology in a food (Campbell, 1995).

Studies on the rheology of mixing have focused on a number of areas: (i) the effects of mixer design and operation on the development of rheology and texture; (ii) empirical measurement of rheology during mixing from mixer torque or power consumption; (iii) effect of rheology on mixing patterns and performance; and (iv) simulation and prediction of mixing flow deformation patterns as functions of mixer geometry and rheology. Despite the obvious importance of mixing in the development of rheology and texture in doughs, there is very little information in the literature on these changes.
During the different stages in the mixing process. Most work has either concentrated on empirical measurement of mixer motor torque, voltage or power consumption during mixing as a qualitative indication of changing rheology, or measurement of rheological changes at some time after mixing. Problems associated with these approaches are: failure to take into account motor and drive losses, frictional and surface effects between the dough and the mixer, varying signal damping and data acquisition rates, effects of aeration on rheology, and rheological relaxation effects. Since dough is a viscoelastic material which shows rapid relaxation after deformation, which varies between different flours, such measurements are not ideal and run the risk of giving misleading information. Nevertheless, much useful information has been obtained about the effect of mixing on gluten structure, rheology and baking performance (Weegels et al., 1996; Skerrit et al., 1999). Extensive work on dough mixing has shown that mixing speed and energy (work input) must be above a certain value to develop the gluten network and to produce satisfactory breadmaking (Kilborn and Tipples, 1972), and an optimum in work input or mixing time has been related to optimum breadmaking performance (Skeggs, 1985), which varies depending on mixer type, flour composition and ingredients (Mani et al., 1992). For example, mixing doughs by elongational flow in sheeting to achieve optimum development required only 10-15 % of the energy normally used in conventional high speed shear mixers (Kilborn and Tipples, 1974), suggesting that much higher rates of work input can be achieved due to the enhanced strain hardening of doughs under extension. Numerous studies have shown that rheological measurements after mixing parallel changes in mixer torque and power consumption (Mani et al., 1992; Zheng et al., 2000; Anderssen et al., 1998), especially if rheological measurements are made under large, non-linear deformation conditions closer to those experienced in the mixer (Mani et al., 1992; Hwang and Gunasekaran, 2001). Recent studies have suggested that qualitative elongational rheological information during mixing can be derived directly from the torque/power consumption of a dough mixer (Gras et al., 2000).

Extensive work on dough mixing has shown that mixing speed and energy (work input) must be above a certain value to develop the gluten network and to produce satisfactory breadmaking, and an optimum in work input or mixing time (peak development) has been related to optimum bread-making performance, which varies depending on mixer type, flour composition, and ingredients. If dough is under-mixed or mixed well beyond its peak development, then bread of inferior quality is produced. Kilborn and Tipples in a series of papers from 1972-77 investigated factors affecting dough development. Their results indicated that: (i) for a given flour, there is a minimum mixing speed and energy input (the critical mixing speed or energy) below which development could not be achieved, resulting in a loaf of poor volume, colour, and texture; (ii) the total energy input required for peak development differs between flour types; and (iii) both the total energy required and the critical mixing speed for a given flour differ between mixers with different mixing actions. Moreover both aeration and rheological characteristics of dough are dependent on both the total work input and the work input rate (Chin and Campbell, 2005).

**Rheological effect on proofing, baking and final texture of bread**

Proofing (fermentation) is an important step in the breadmaking process, where the expansion of air bubbles previously incorporated during mixing provides the characteristic aerated structure of bread, which is central to its appeal (Dobraszczyk et al., 2000). Dough expansion during fermentation process (proofing) is greatly influenced by main components of flour and rheological properties of dough. Basically it depends on the optimum development of the gluten proteins network into a cohesive dough mass, encapsulating starch granules and other filler materials or components and air nuclei (Bloksma, 1990b). Although fermentation is clearly important in breadmaking, most rheological tests are performed on doughs without yeast and at room temperature. Few studies have been made on the changing rheological properties during fermentation and baking. Direct rheological measurements have been made on yeasted bread doughs (Kilborn and Preston, 1981), cake batters (Massey, 2002; Sahi, 1999), sour doughs (Wehrle and Arendt, 1998), and cracker sponge and dough (Oliver and Brock, 1997). Such measurements suffer from the problem of the evolving gas volume and metabolites from fermentation confounding the rheological data. The decrease in density as a result of increasing gas volume would be expected to have the effect of decreasing modulus and viscosity, but the compressibility of air may counteract this effect, especially at higher gas volumes and low densities where the moduli of the solid and gas phases converge, such as in cake batters, where shear modulus is directly related to the air content (Massey, 2002). Fermentation metabolites such as lactic and acetic acid may also exert rheological effects through changes in pH (Wehrle et al., 1997).

Other approaches have been to measure the increase in height or volume of the fermenting product using
devices such as the rheofermentometer or risograph, but these provide no direct information about the rheology of the material, since they do not measure force or deformation per change in unit dimensions. Changes in aeration have been predicted from modelling the increase in dough height (Shah et al., 1999), or by directly measuring internal gas pressure during fermentation (Matsumoto et al., 1975). Another approach has been to prevent fermentation by inactivating the yeast by freezing and thawing (Newberry et al., 2002), or by mixing under oxygen to rapidly deactivate the yeast activity (Chamberlain and Collins, 1979).

During proof and baking the growth and stability of gas bubbles within the dough determines the expansion of the dough and therefore the ultimate volume and texture of the baked product (He and Hoseney, 1991). The limit of expansion of these bubbles is related directly to their stability, due to coalescence and the eventual loss of gas when the bubbles fail. The rheological properties of the expanding bubble walls will therefore be important in maintaining stability against premature failure during baking, and also in relation to gas cell stabilization and gas retention during proof, and thus to the final structure and volume of the baked product (Dobraszczyk et al., 2000). The relevant rheological conditions around an expanding gas cell during proof and baking are biaxial extension, large strain, and low strain rate. Any rheological tests which seek to relate to baking performance should therefore be performed under conditions similar to those of baking expansion. Methods such as bubble inflation and lubricated compression offer the most appropriate method for measuring rheological properties of doughs. The major advantage of these tests is that the deformation closely resembles practical conditions experienced by the cell walls around the expanding gas cells within the dough during proof and oven rise, i.e., large deformation biaxial extension can be carried out at the low strain rates and elevated temperatures relevant to baking (Dobraszczyk et al., 2003).

Recent work has shown that bread doughs exhibit strain hardening under large extensional deformations, and that these extensional rheological properties are important in baking performance (van Vliet et al., 1992; Dobraszczyk and Roberts, 1994; Janssen et al., 1996b; Dobraszczyk, 1997; Wikstrom and Bohlin, 1999; Dobraszczyk et al., 2003). Strain hardening allows the expanding gas cell walls to resist failure by locally increasing resistance to extension as the bubble walls become thinner, and provides the bubble walls greater stability against early coalescence and better gas retention. It is therefore expected that doughs with good strain hardening characteristics should result in a finer crumb texture (e.g., smaller gas cells, thinner cell walls, and an even distribution of bubble sizes) and larger baked volume than doughs with poor strain hardening properties. It has been shown that good breadmaking doughs have good strain-hardening properties and inflate to larger single bubble volume before rupture, whereas poor bread-making doughs inflate to lower volumes and have much lower strain hardening (Dobraszczyk and Roberts, 1994; Dobraszczyk, 1997). Loaf volume for a number of commercial white flour doughs has been related directly to the failure strain and strain hardening properties of single dough bubbles measured at elevated temperatures in biaxial extension (Dobraszczyk et al., 2003). Strain hardening and failure strain of cell walls were both seen to decrease with temperature, with cell walls in good breadmaking doughs remaining stable and retaining their strain hardening properties to higher temperatures (60 °C), whilst the cell walls of poor bread-making doughs became unstable at lower temperatures (45-50 °C) and had lower strain hardening. Bubble wall stability is increased to progressively higher temperatures with increasing baking volume, allowing the bubbles to resist coalescence and retain gas for much longer. Bubble wall instability in poorer breadmaking varieties occurs at much lower temperatures, giving earlier bubble coalescence and release of gas, resulting in lower loaf volumes and poorer texture (Dobraszczyk et al., 2003).

The steaming of wheat flour for various periods weakened the gluten network structure whilst Prakash and Rao, (1999) have studied the effects of heat processing of cereal grains on the paste viscosity of cereal flours.

End product quality and rheology

The link between dough rheology and baking quality is long established, mainly due to empirical evidence from manual assessments such as kneading or stretching of dough by bakers after mixing. However, the results from conventional descriptive methods and fundamental rheological studies on doughs have often given disappointing correlations with baking quality, mainly because the deformation conditions in these tests are very different than those occurring during proof and baking.

Dough rheology is of considerable importance in bread and biscuit manufacturing as it influences the machinability of dough and the quality of end product (Indrani and Rao, 2007). Dough is the intermediate product between flour and biscuits. Dough which is too firm or too soft will not process satisfactorily on the
appropriate dough-forming equipment and will not yield a suitable product. Doughs that are too strong do not allow proper development of the bubbles and result in the formation of dense, unpalatable loaves of small volume, while doughs that are too weak cannot retain the bubbles and result in large holes in the loaf or in the collapse of the loaf. It is reported that dough consistency influences the quality of biscuits (Manohar and Haridas Rao, 2002; Angioloni and Collar, 2008).

The quality of baked products is governed by rheological properties of dough (Statikopoulos et al., 2006). This preceding rheological evaluation of the dough is a good indicator of dough handling properties. Dough rheology characterization is an important parameter in the evaluation of biscuit wheat quality and indicates dough-handling properties and the tendency of the dough to contract (Pedersen et al., 2004). Several methods including mixograph, farinograph and extensograph are used for characterization of the rheological properties of biscuit dough (Ross et al., 2004) and proteins present in wheat flour governed these rheological properties. Molecular size and structure of the gluten polymers that make up the major structural components of wheat are related to their rheological properties via modern polymer rheology concepts. Interactions between polymer chain entanglements and branching are seen to be the key mechanisms determining the rheology of HMW polymers. These structural and rheological properties of the insoluble polymer fraction are mainly responsible for variations in baking performance (Dobraszczyk, 2004a).

The rheological characterization of wheat flour dough is necessary for the successful manufacturing of bakery products because of its influence on mechanical handling and quality characteristics of the finished products (Agyare et al., 2005). The suitability of wheat flour for the production of different baked products like breads, cakes, biscuits and chapattis depends primarily on particular rheological properties of dough such as water absorption, dough stability, strength, extensibility, elasticity etc. (Karaoğlu, 2011). During breadmaking, rheological properties of dough change at every stage of breadmaking process. When the dough is mixed in a high speed mixer, it is converted into an elastic and coherent mass due to high stress conditions prevailing at this speed (Stojceska et al., 2007). Rheological behaviour is associated directly with textural qualities such as mouth feel, taste and shelf stability (Herh et al., 2000).

**Conclusion**

It can be concluded from the available literature that the dynamic rheological technique of frequency sweep under small deformations is highly promising for elucidating the structure of wheat proteins and the processibility of wheat flour dough. These studies demonstrate that the component interactions are fairly important for determining the rheological behaviours of gluten and flour doughs. It would appear that for HMW polymers such as gluten, large deformation extensional rheological properties are more sensitive to changes in polymer entanglements and branching than small deformation dynamic shear properties, based on sound polymer physics principles and experimental data. Insoluble HMW glutenins have been shown to be best related to variations in baking quality, and to the presence of long relaxation times, indicating entanglements of the HMW polymers. Strain hardening, which has been shown to be a sensitive indicator of entanglements and long-chain branching in HMW polymers, is seen in large extensional deformation of doughs and gluts, and is well related to bubble wall stability, long relaxation times and to variations in baking performance amongst different wheat varieties.

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