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A Review on Rheological Properties and Measurements of Dough and Gluten

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Abstract: The field of rheology has seen a wider application in the food industry recently although, it is a complex concept and that most food systems possess non-ideal characteristics. Nevertheless, the rheological behavior of foods are able to be determined using various techniques and equipment. Studies on rheological properties related to dough and gluten are often challenging due to its variance in nature and high dependence on many factors. This study attempts to give a review on the various types of experimental techniques and set-up used in quantifying rheological properties of dough and gluten. The rheological properties are defined and the behaviors are described by inducing stress and strains in small and large deformation studies.

Key words: Dough, gluten, food rheology, deformation, rheological measurement

INTRODUCTION

Rheology is defined as a study of the deformation and flow of matter (Bourne, 2002). The applications of rheology have expanded into food processing, food acceptability and handling. Many researches have been conducted to understand the rheology of various types of food such as food powder (Weert *et al*., 2001; Grabowski *et al*., 2008), liquid food (Sabato, 2004; Park, 2007), gels (Michon *et al*., 2004; Foegeding, 2007), emulsions (Robins *et al*., 2002; Corredig and Alexander, 2008) and pastes (Abu-Jdayil *et al*., 2002; Lim and Narsimhan, 2006). Vast food materials show a rheological behavior that classifies them in between the liquid and solid states; meaning that their characteristic varies in both viscous and elastic behaviors. This behavior, known as viscoelasticity, is caused by the entanglement of the long chain molecules with other molecules. Figure 1 shows the creep and recovery test on the ideal elastic, ideal viscous and viscoelastic materials. The ideal elastic materials have the ability to recover to its original shape upon the removal of stress while the stress acted on the ideal viscous materials caused them to deform and it is non-recoverable. By combining both the ideal elastic and viscous behaviors, the viscoelastic materials exhibit behavior in recovering some of its original shape by storing the energy. They show a permanent deformation less than the total deformation applied to the material.

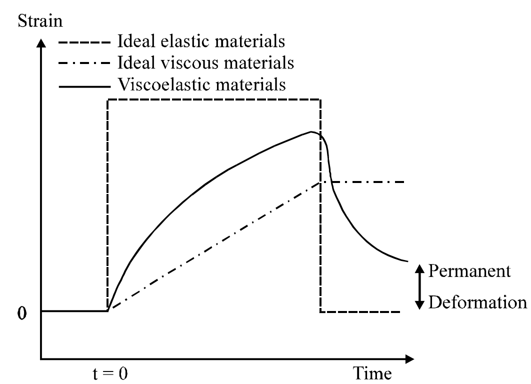

Fig. 1: Creep and recovery curves for ideal elastic, ideal viscous and viscoelastic materials (Steffe, 1996)

Dough and gluten consist of complex structures of protein and carbohydrate cross links and due to this many studies had been reported on their rheological properties. The focus of this study is to provide a description of rheological properties of dough and gluten, to highlight the various types of experimental techniques and set-up used in quantifying their rheological properties from past and current studies initiated.

Rheological behavior and development of dough and gluten: Rheological behavior of dough and gluten can be determined by two distinct measurements that are

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fundamental and empirical. Studies on the fundamental rheology of dough and gluten are usually carried out using small deformation while the empirical measurements are measured using large deformation. Nonetheless, fundamental dough and gluten rheological testings using large deformation are growing popularity with the presence of newer techniques and equipment. Ferry (1970) described that the rheological behavior of gluten is related to the rheological properties of synthetic polymer where the fundamental rheological properties of polymers reflect the degree and type of cross-linking of the polymers. Thus, the rheological behavior of dough was predicted using molecular models of gluten development during mixing by Belton (1999) and Letang *et al.* (1999) as shown in Fig. 2 and 3. In these models, gluten development mainly involves glutenin proteins interactions with each other in the loop by disulphide bonds. At the early stage of mixing, the gluten fibrils are in contact with the mixer blade, the sides of the bowl and other flour particles. The hydrated gluten fibrils and starch granules are continuously dispersed throughout. Glutenins, which are the long polymeric proteins, are folded and the chains are in random orientation. As mixing proceeds, more protein

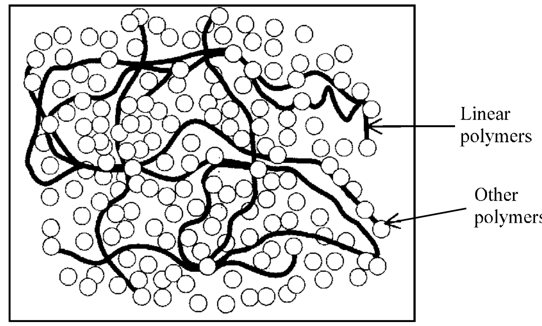

Fig. 2: A model for the molecular structure of gluten. HMW subunits are approximately by linear polymers, interchain disulphide links are not shown. Other polymers are approximated by spheres (Belton, 1999)

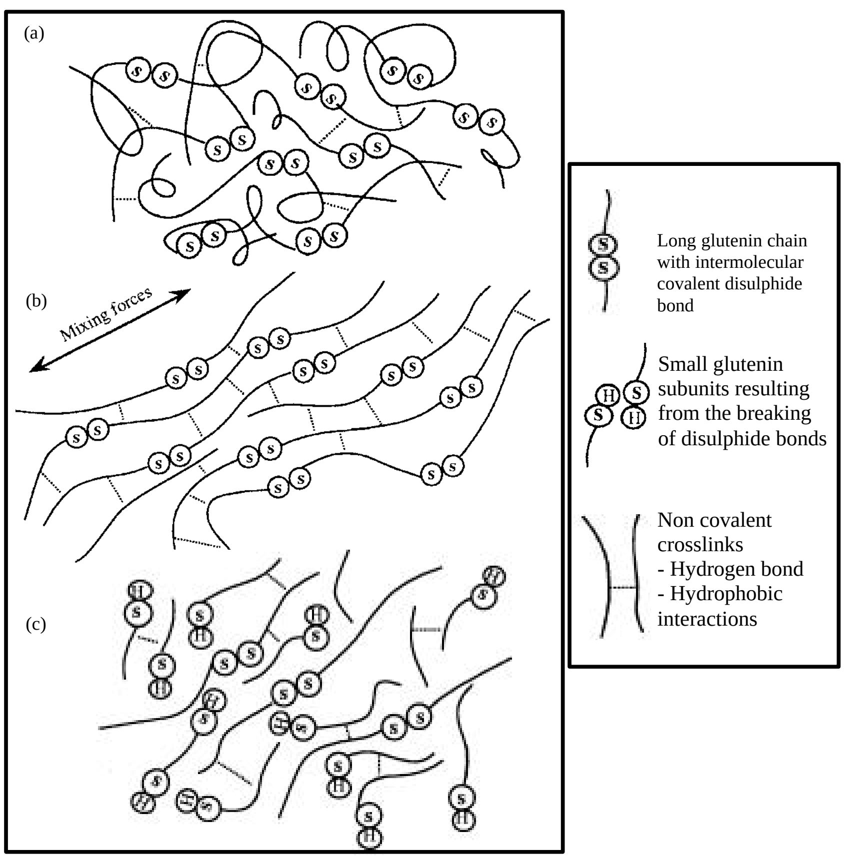

Fig. 3: Molecular interpretation of gluten development (a) beginning of mixing, (b) optimum development and (c) overmixing (Letang *et al.*, 1999)

becomes hydrated and the glutenins tend to align because of the shear and stretching forces imposed. At this stage, gluten networks are more developed by the cross-linking of protein with disulphide bonds. At optimum dough development, the interactions between the polymers cross-links are becoming stronger which leads to an increase in dough strength, maximum resistance to extension and restoring force after deformation. When the dough is mixed longer past its optimum development, the cross-links begin to break due to the breaking of disulphide bonds. The glutenins become depolymerised and the dough is overmixed. The presence of smaller chains in the dough makes the dough stickier. The monomeric proteins, gliadins form a matrix within the long polymer networks and contribute to resistance to extension by forming viscous behavior. Increasing the interactions between protein polymers increases gluten viscous resistance and resistance to extension. It was said that gliadins acted like a plasticiser, promoting viscous behavior and extensibility of gluten (Kuktaite, 2004).

Many works have been attempted on determining the rheological properties of dough (Khatkar *et al*., 2002; Uthayakumaran *et al*., 2002; Sliwinski *et al*., 2004a; Chin and Campbell, 2005; Chi *et al*., 2005; Indrani and Rao, 2007; Skendi *et al*., 2010) and gluten (Amemiya and Menjivar, 1992; Janssen *et al*., 1996a; Kieffer *et al*., 1998; Khatkar *et al*., 2002; Tronsmo *et al*., 2003; Song and Zheng, 2008). In application studies, the rheological properties are related to the end-product quality such as bread loaf volume (Janssen *et al*., 1996a; Kokelaar *et al*., 1996; Kieffer *et al*., 1998; Tronsmo *et al*., 2003; Sliwinski *et al*., 2004b; Dobraszczyk and Salmanowicz, 2008), texture (Uthayakumaran *et al*., 2002; Vetrimani *et al*., 2005; Jacob and Leelavathi, 2007; Sudha *et al*., 2007) and sensory attributes (Bhattacharya *et al*., 2006; Lazaridou *et al*., 2007).

Factors affecting dough and gluten rheological properties: Rheological properties of dough and gluten during mixing are affected greatly by the flour composition (low or high protein content), processing parameters (mixing time, energy, temperature) and ingredients (water, salt, yeast, fats and emulsifiers). Studies were conducted to investigate the effect of protein content on the gluten quality and rheological properties (Janssen *et al*., 1996a; Tronsmo *et al*., 2003; Sliwinski *et al*., 2004c), on bread making quality (Janssen *et al*., 1996a; Sliwinski *et al*., 2004b) and also on volume expansion resulted from frying (Chiang *et al*., 2006). These works, conclusively suggested that the strong flour produces a better gluten and dough quality than the weak flour in terms of giving a higher response in extensibility, bread loaf volume and height and also volume expansion.

Mixing is an important step in producing gluten with desired strength as to produce a good quality end-product. Processing factors during flour-water mixing include the mixing time, work input, mixer type and temperature. In order to achieve optimum dough development, the mixing time and work input must be above the minimum critical level (Angioloni and Dalla Rosa, 2005). Different wheat flour has different optimum mixing time (Hoseney, 1985). A longer mixing time is expected for mixing dough from strong flour. It is probably due to the dense particles of strong flour and slower water penetration (Hoseney, 1985). Sliwinski *et al.* (2004c) reported that a positive correlation was observed between dough mixing time and the percentage of glutenin protein in flour. Dobraszczyk and Morgenstern (2003) related optimum mixing time of dough with the development of the glutens networks and monomers. Increasing mixing time and work input above the optimum level during mixing induces the changes in mechanical properties of dough (Cuq *et al*., 2002). Whilst mixing speed influenced the development of gluten during dough mixing through the intensity of mixing imparted on dough, insufficient mixing intensity would result in weak gluten networks which bring failures in baking performance (MacRitchie, 1985).

Water is responsible in hydrating the protein fibrils and start the interactions between the proteins cross links with the disulphide bonds during dough mixing. Too much water addition to the flour will result in slurry and too little water results in slightly cohesive powder (Faubion and Hoseney, 1989). Hence, an optimum water level is required to develop cohesive, viscoelastic dough with optimum gluten strength. While the optimum water level differs from flour to flour, the strong flours require higher water level than weak flours largely due to the higher protein content and dense particles in the strong flours. Protein content is known to be an important factor in determining the water uptake of flour (Sliwinski *et al*., 2004c). Mani *et al.* (1992) and Janssen *et al.* (1996a) reported that the G' and G" decreased as the water content of dough increased. Ablett *et al.* (1985) explained the effect of water content on gluten networks in terms of a rubber network such that its elongation reduced as water content increased as if in rubber network. However, for dough, the elongation increased as water content increased. It was suggested that the soft continuous phase of dough will swell in direct proportion of free-water which is responsible in the increase of the elongation (Ablett *et al*., 1985).

Sodium chloride or commonly known as salt is said to have a strengthening or tightening effect on the gluten during mixing of dough (Niman, 1981). Salt must be added early in the dough-mixing to give maximum dissolution time and accelerate gluten formation, tighten the dough and increase the mixing time. Salt is used to overcome the low pH of dough since the effect of pH will alter the mixing time; a low pH gives a shorter time and a high pH gives a longer time (Hoseney, 1985). Roach *et al.* (1992) suggested that the influences of salt on the protein solubility affect the dough properties. Salt decreases the solubility of protein in the wheat flour dough as its concentration increases. Salvador *et al.* (2006) found that the elastic modulus (G') falls slightly in the presence of salt. This reduction is probably due to the decrease in inter-protein hydrophobic interactions which reduce the tendency of the proteins to aggregate and thus reduce the elasticity. The amount of salt added into the dough mixing can be varied from 1.8-2.1% on flour basis (Farahnaky and Hill, 2007). However, due to increase concern in health related issues by consumers in food intake, addition of lower amount of salt has become one of the main focus in recent studies (Farahnaky and Hill, 2007; Lynch *et al.*, 2009). Omission of salt entirely leads to a significant reduction in dough and bread quality and also the sensory attributes of bread, where the bread was described as sour/acidic and having yeasty flavour (Lynch *et al.*, 2009).

RHEOLOGICAL MEASUREMENTS OF DOUGH AND GLUTEN

The rheological measurements used are dependent on foods types although in general, the small deformations are more meticulous than the large deformation testing. In small deformation testing, the rheological properties of foods are well-defined by exerting very small strain on the food. Large deformation testings on food material are easier to perform, the equipments are inexpensive comparatively and they are more commonly used in the food industry. Table 1 shows the various types of rheological testing methods available for obtaining different rheological parameters using different equipment.

Small deformation measurement: In small deformation measurement, the tested material is assumed continuous, has regular shape and is exerted by small strain (1-3% maximum) (Bourne, 2002). Tests performed by various researchers to determine the rheological properties of dough and gluten include the dynamic oscillation (Amemiya and Menjivar, 1992; Khatkar *et al.*, 1995; Janssen *et al.*, 1996a, b; Uthayakumaran *et al.*, 2002; Tronsmo *et al.*, 2003; Sivaramakrishnan *et al.*, 2004), creep recovery (Janssen *et al.*, 1996a; Tronsmo *et al.*, 2003; Sivaramakrishnan *et al.*, 2004; Onyango *et al.*, 2009) and stress relaxation tests (Rao *et al.*, 2000; Li *et al.*, 2003; Song and Zheng, 2008; Bhattacharya, 2010).

Table 1: Rheological measurement for dough and gluten

	Authors		Measured rheological parameter	Equipment used
	Test on dough	Test on gluten		
Dynamic oscillation	Janssen *et al.* (1996b), Khatkar *et al.* (2002), Uthayakumaran *et al.* (2002), Sivaramakrishnan *et al.* (2004),	Amemiya and Menjivar (1992), Khatkar *et al.* (1995) Janssen *et al.* (1996a), Tronsmo *et al.* (2003)	Elastic modulus, viscous modulus, tan δ	Rheometer
Creep recovery	Sivaramakrishnan *et al.* (2004), Onyango *et al.* (2009), Skendi *et al.* (2010)	Janssen *et al.*, (1996a), Tronsmo *et al.* (2003)	Shear stress, shear strain, apparent viscosity	Rheometer
Stress relaxation	Rao *et al.* (2000), Li *et al.* (2003) Bhattacharya (2010)	Song and Zheng (2008)	Stress, relaxation modulus, relaxation spectrum	Rheometer
Uniaxial extension and compression	Muller *et al.* (1961), Janssen *et al.* (1996b), Kokelaar *et al.*, (1996), Gujral and Pathak (2002), Uthayakumaran *et al.* (2002), Dunnewind *et al.* (2004), Sliwinski *et al.* (2004a), Dobraszczyk and Salmanowicz (2008)	Kieffer *et al.*, (1998), Tronsmo *et al.* (2003), Abang Zaidel *et al.* (2008), Song and Zheng (2008), Abang Zaidel *et al.* (2009a)	Extensibility, stress, strain, force, strain hardening, maximum resistance to extension	Brabender extensograph, texture analyser, instron UTM, SER
Biaxial extension	Janssen *et al.* (1996b), Kokelaar *et al.* (1996), Sliwinski *et al.* (2004a), Chin and Campbell (2005), Indrani and Rao (2007), Indrani *et al.* (2007), Stojceska *et al.* (2007), Dobraszczyk and Salmanowicz (2008), Tanner *et al.* (2008)	Janssen *et al.* (1996a), Song and Zheng (2008)	Biaxial stress, biaxial strain, biaxial viscosity, strain hardening	Alveograph, DIS on texture analyser, Instron UTM, overload dynamics material testing instrument

Dynamic oscillation: The dynamic oscillation test is most suitable in testing the rheological properties of viscoelastic material. The test material is applied with sinusoidal oscillating stress or strain with time in a dynamic oscillation shear measurement. When subjected to a sinusoidal strain ($\gamma = \gamma_0 \sin \omega t$), the viscoelastic material responds with a sinusoidal stress ($\sigma = \sigma_0 \sin \omega t$) which depends on the properties of the material. The elastic component is accounted as the storage modulus (G') and the viscous component is measured as the loss modulus (G"). The ratio of the viscous to elastic modulus (G"/G') is equal to the tangent of the phase angle (tan δ). A material having higher degree cross-linking is expected to have a low tan δ. In the study of Tronsmo *et al*. (2003), wet gluten was tested with a small strain of 2% and frequency between 0.005-10 Hz. They reported that the elastic modulus (G') was higher than the viscous modulus (G"). This result agrees with studies by Amemiyar and Menjivar (1992) who found that the storage modulus (G') for all tested doughs are higher than the loss modulus (G"). They further described that the gluten network behaves like a cross-linked polymer at the tested frequency. Uthayakumaran *et al.* (2002) who conducted a study on rheological behavior of wheat gluten using dynamic oscillation testing found that both the elastic and viscous modulus of flour doughs were significantly higher than gluten doughs. This indicates that starch content in the flour dough influence the viscoelasticity of the flour dough. Other work which utilised this testing method on dough include studies on effect of different protein content (Amemiya and Menjivar, 1992; Janssen *et al*., 1996a; Tronsmo *et al*., 2003), water level (Uthayakumaran *et al*., 2002) and mixing time (Amemiya and Menjivar, 1992; Janssen *et al*., 1996a) on the rheological properties of dough and gluten. Tronsmo *et al*. (2003) found that dough with higher protein content gave lower G' and G" but higher tan δ. Janssen *et al.* (1996a) found that the resistance to small deformation was higher and more elastic for gluten with higher protein content and as the angular frequency (ω) increased, G" increased more than G', indicating a viscous behavior of gluten due to more bonds are involved in the response of stress or strain. Generally, it can be concluded that gluten from poor quality wheats are rheologically characterised as less elastic and more viscous than glutens from good quality wheats (Khatkar *et al*., 1995; Janssen *et al*., 1996a; Tronsmo *et al*., 2003).

Creep recovery: Creep recovery is performed by subjecting the material to a constant shear stress and the shear strain is monitored as a function of time.

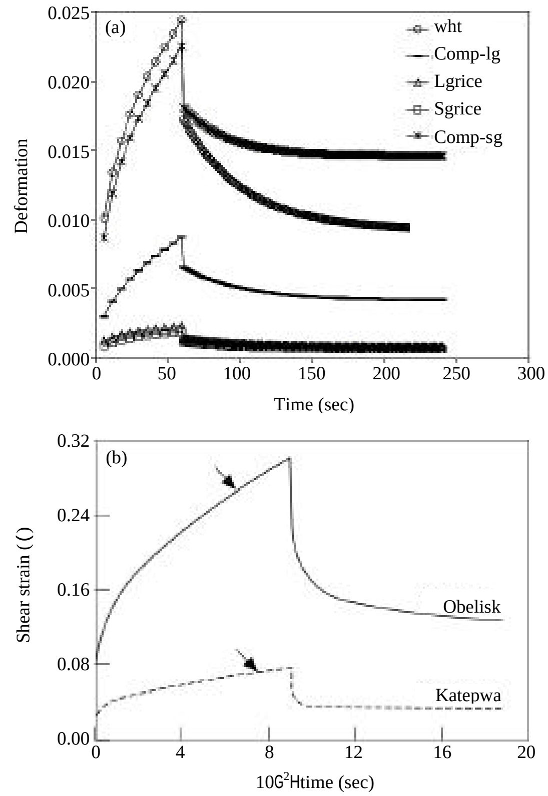

Fig. 4: Creep analysis curves for (a) pure wheat (O), pure rice (lgrice, sgrice) and composite flour (comp-lg, comp-sg) (Sivaramakrishnan *et al*., 2004) and (b) gluten with different protein content (from two types of wheat, i.e., Obelisk and Katepwa) (Janssen *et al*., 1996a)

Sivaramakrishnan *et al.* (2004) performed creep recovery test on pure wheat flour and combinations with long/short grain rice flour found that the pure wheat flour dough showed high recovery of elastic strain after removal of load (Fig. 4a) while the creep behavior of the two composite flours with long and short grain rice flour showed considerable variation with the pure rice flours. Janssen *et al.* (1996a) conducted creep recovery test on two different wheat flours, weak (Obelisk) and strong flour (Katepwa) found that Obelisk showed a higher recovery of elastic strain after removal of load compared to Katepwa (Fig. 4b). Janssen *et al.* (1996a) suggested that the apparent viscosity (η_{app}) can be estimated from the slope of the creep curve (as indicated by the arrow in Fig. 4b and from their observation there was no clear strain hardening in creep tests since the slope of the curve was nearly independent of time and strain at the end of the load phase.

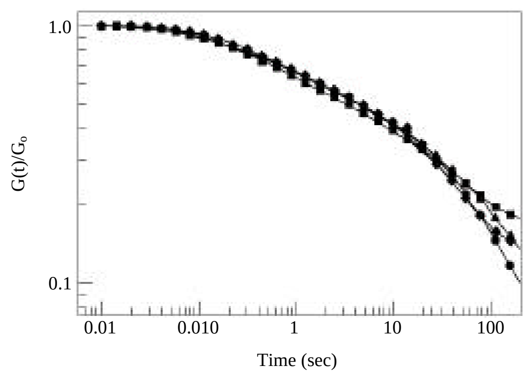

Fig. 5: Normalised stress relaxation of the different cultivars of high protein flour-water doughs at applied shear strain of 0.05% and strain rise time of 0.2 sec (Glenlea at 12.8% protein, Wildcat at 14.0% protein, ES12 at 12.8% protein and ES20 at 12.4% protein) (Rao *et al.*, 2000)

Stress relaxation: In stress a relaxation test, the material is given an instantaneous constant strain and the stress required to maintain the deformation is observed as a function of time. This test is a convenient means to characterise the linear viscoelastic properties of polymers which contain the information on molecular weight. Rao *et al.* (2000) conducted a test with 0.05% strain on dough for 200 sec at 25°C and relaxation spectrum was calculated to characterise the rheological behavior. Figure 5 shows the stress relaxation curve for doughs plotted as $G(t)/G_0$ versus time where G(t) is the relaxation modulus at any time and G_0 is the initial relaxation modulus. The longest relaxation times are associated with largest molecules. Dough and gluten obtained from strong flour (higher protein content) had higher relaxation modulus (G(t)) and spectrum ($H(\tau)$) over the whole relaxation time than those from weak flour (lower protein content) (Li *et al.*, 2003). It indicates that strong flour dough and gluten has stronger network structure due to entanglements, physical cross-links or combination of both.

Large deformation measurement: A material is applied to a large deformation when the stress exceeds the yield value. Some of the common tests used in measuring large deformation of dough and gluten are uniaxial extension and compression (Janssen *et al.*, 1996b; Kieffer *et al.*, 1998; Uthayakumaran *et al.*, 2002; Tronsmo *et al.*, 2003; Dunnewind *et al.*, 2004; Sliwinski *et al.*, 2004a; Song and Zheng, 2008) and biaxial extension (Janssen *et al.*, 1996a, b; Kokelaar *et al.*, 1996; Dobraszczyk, 2004; Chin and Campbell, 2005; Chi *et al.*, 2005; Stojceska *et al.*, 2007; Tanner *et al.*, 2008). For the test of gluten quality used as food product, large deformation is more suitable since it gives good correlations with breadmaking quality (Dobraszczyk and Morgenstern, 2003; Tronsmo *et al.*, 2003) and can be related to its eating quality.

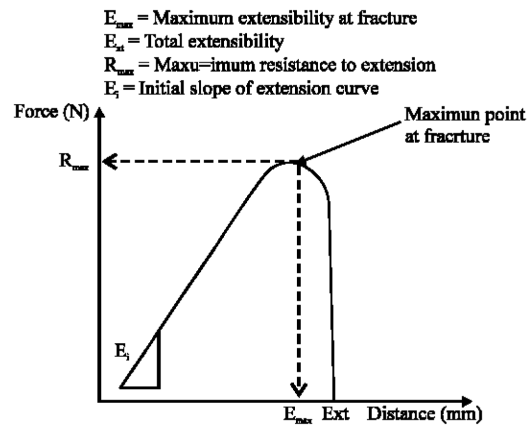

Fig. 6: Typical load-extension of gluten extension test from Kieffer dough and gluten extensibility rig (Tronsmo *et al.*, 2003)

Uniaxial extension: The most commonly adapted large deformation test of dough and gluten is the extension test where a material is clamped at two ends and being pulled or extended by a hook at the centre of the sample at a constant strain rate. During stretching, the material undergoes deformation and break after the stress is beyond its limit or known as the tensile failure. The main problem encountered in tensile test is to hold the material such a way that it breaks within the material and not at the jaws holding the material. Cutting the material in dumbbell-shaped and clamping the wide ends is often done to solve the problem. Clamping the material in vertical plane is usually performed for strong solid materials while for weak materials that cannot support its own weight, such as dough, the test is usually performed on a horizontal plane (Bourne, 2002). A typical curve of load-extension obtained from the test is shown in Fig. 6. Figure 7, the stress-strain curves obtained shows that stress increases with increasing strain and reaches a maximum at sample fracture point. The gradient of the curve is related to the modulus of gluten and the curves displayed a curvature up to fracture indicating that the modulus increased with extension. This behavior is known as strain hardening in which the force that extend the material increases in order for additional strain to occur. The phenomena of strain hardening occur when the stress increases more than proportional with the strain. Sliwinski *et al.* (2004a) reported that strong flour

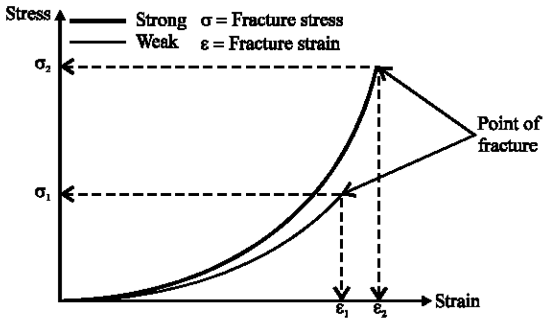

Fig. 7: Typical stress-strain curve obtained from a large deformation measurement of dough and gluten

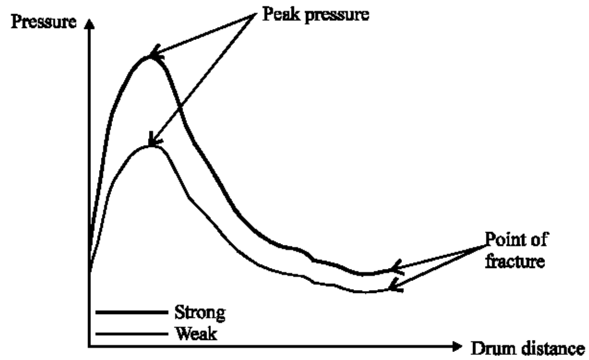

Fig. 8: Typical pressure-drum distance of inflating dough bubbles from DIS

dough possesses higher strain hardening than weak flour dough (Fig. 7) and thus prevents premature fracture of dough and gluten. Uthayakumaran *et al.* (2002) performed the uniaxial extension of gluten dough by first compressing the dough sample in between two parallel plates before pulling the dough apart by the moving upper plates at a constant strain rate. Their results showed the strain hardening properties exhibited during elongation was related to the baking performance. They also suggested that gluten dough possessed larger elongational viscosities than flour dough.

Biaxial extension: As oppose to uniaxial extension, a biaxial extension is where a material is stretched at equal rates in two perpendicular directions in one plane (Dobraszczyk and Morgenstern, 2003). Results from this test are plotted as pressure versus drum distance trace of an inflating bubble from dough sample. Chin and Campbell (2005) studied the relationship of aeration and rheology of dough using biaxial extension and found that dough from strong flour had higher peak pressure and further drum distance before bubble rupture (Fig. 8). This suggests that strong flour dough has stronger gluten network and needed higher pressure to break them. The stress-strain curve obtained (Fig. 7) shows considerable increase in stress with strain indicating increased shear modulus and a clear strain hardening effect within the walls of the inflating dough bubble. The advantage of this test is that it resembles practical conditions experienced by the cell walls within the dough during proof and oven rise (Dobraszczyk and Morgenstern, 2003). Sliwinski *et al.* (2004a) studied the effect of water content, mixing time and resting time on the dough rheology in biaxial extension. They reported that increasing the water content led to a decrease of biaxial stress which supported the findings of Kokelaar *et al.* (1996) while strain hardening was not significantly affected by the water content. The biaxial stress and strain hardening are least affected by the resting time but for mixing time, they both increased. The decrease of the fracture strain with increasing mixing time was reported. In recent work, Song and Zheng (2008) studied the influence of rest time on the structural development of gluten/glycerol mixtures for biodegradable packaging material by equibiaxial deformations on a universal testing machine.

EQUIPMENT FOR RHEOLOGICAL MEASUREMENTS OF DOUGH AND GLUTEN

A wide range of equipment is available to determine rheological properties of dough and gluten. This section discusses the working principles of common instruments and their attachments used for measuring rheological properties of dough and gluten which include the rheometer for small deformation testing and the alveograph, extensograph, Kieffer rig and dough inflation system from the texture analyser and the universal testing machine for large deformation testing.

Rheometer: The rheometer is frequently used in determining the viscoelastic properties of dough and gluten (Amemiya and Menjivar, 1992; Uthayakumaran *et al.*, 2002; Tronsmo *et al.*, 2003; Skendi *et al.*, 2010). The parallel plate configuration has the material loaded is between and while one plate is rotating in a sinusoidal motion, the other plate is stationary. Surplus materials between parallel plates are trimmed and coated with suitable fluid like silicon oil to prevent it from drying. The common rheological parameters obtained using the dynamic oscillatory, creep recovery and stress relaxation often related to the behavior of dough and gluten at molecular level. Recent study on the effect of water and β-glucan from two types of barley on the viscoelasticity of wheat dough was performed on a rheometer equipped with a Paar Physica circulating bath and a controlled peltier system (TEZ 150 P/MCR) that was maintained at 25±0.1°C throughout the experiment (Skendi *et al*., 2010). Oscillatory and creep recovery tests were measured using a 25 mm plate-plate geometry.

Extensograph and alveograph: The extensograph and alveograph are probably the earliest instruments used for empirical dough testing. The extensograph is essentially an extensional test where a cylindrical dough sample is clamped horizontally in a cradle and stretched by a hook which is placed in the middle of the sample and moves downwards until rupture after 45 min resting (Kokelaar *et al*., 1996). Muller *et al.* (1961) derived the equations of stress and strain from the extension test of dough in Brabender extensograph and also reported that the maximum extensibility at fracture is a better index of elasticity than the total extensibility.

The alveograph has been used to measure and evaluate wheat flours of breadmaking (Khattak *et al*., 1974; Chen and D'Appolonia, 1985; Janssen *et al*., 1996b) and cookie making quality (Rasper *et al*., 1986; Bettge *et al*., 1989). The alveograph uses air pressure to inflate a thin sheet of dough, simulating the bubbles that are present in bread dough, that cause dough to stretch when rising. This instrument measures the resistance to expansion and the extensibility of a dough by providing the measurement for maximum over pressure, average abscissa at rupture, index of swelling and deformation energy of dough (Indrani *et al*., 2007).

Texture analyser: The texture analyser has a robust measuring system due to the various attachments possible for a wide range of food types in different forms and giving reports on a long list of textural properties, such as hardness, brittleness, elasticity, cohesiveness, stickiness, gumminess, springiness, consistency, fracturability, etc. In the context of dough and gluten, most researchers have used the Kieffer dough and gluten extensibility rig and the dough inflation system.

Kieffer dough and gluten extensibility rig: The Kieffer dough and gluten extensibility rig was developed with similar concept with the extensograph except that the sample is pulled upwards. Figure 9 shows the extension test of the gluten on Kieffer dough and gluten extensibility rig. A small amount of sample in this system (Kieffer *et al*., 1998; Tronsmo *et al*., 2003; Dunnewind *et al*., 2004; Sliwinski *et al*., 2004a, b). Kieffer *et al.* (1998), who investigated the extension of wet gluten, used 10 g of flour in obtaining dough during wet gluten preparation. Dunnewind *et al.* (2004) used a 0.4 g sample with 5 cm length in their investigation of extension of strong and weak flour dough using the Kieffer rig. The samples were clamped at a distance of 18 mm apart and the hooks used were with 1.20 and 4.55 mm diameter. They concluded that the speed of the hook had no influence on sample fracture and a thicker hook (4.55 mm) resulted in fracture of dough occurring more often at the clamp. Dunnewind *et al.* (2004) presented the formulas for calculating fundamental rheological parameters namely the actual and measured force acting on gluten, length of gluten at fracture, stress and strain from the Kieffer rig results. In comparing rheological properties of dough and gluten, Tronsmo *et al.* (2003), who performed a uniaxial extension on dough and gluten using the Kieffer rig found that gluten showed higher maximum resistance to extension (R_{max}) and total extensibility (Ext) than dough.

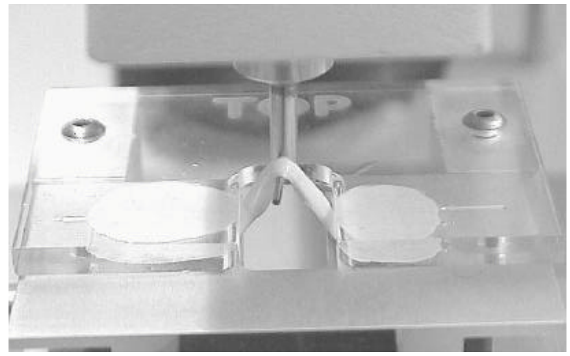

Fig. 9: The extension test of a strip of gluten on a Kieffer dough and gluten extensibility rig fitted to a texture analyser (Wang, 2003)

Dough inflation system: The Dough Inflation System (DIS) was introduced in the early 90's and was developed based on the concept of Alveograph to provide fundamental rheological measurements. Traditionally, the DIS is used for comparing flour quality (Dobraszczyk and Roberts, 1994; Dobraszczyk, 1999; Dobraszczyk *et al*., 2003) and measures the stress and strain relationships based on the inflation of a sheet of dough through a biaxial extension test. It was designed to operate at constant volumetric air flow rates which vary from 10 and 2000 mL min^{-1}, corresponding to maximum strain rates of 0.001 to 0.2 sec^{-1}, unlike the Alveograph which operates at strain rates in the range of 0.1 to 1 sec^{-1}, which are at least 100 fold higher than those occurring in actual baking processes (Huang and Kokini, 1999; Chin and Campbell, 2005). The deformations involved in biaxial extension tests are preferred as they are more relevant to the type of deformation of the dough around an expanding gas

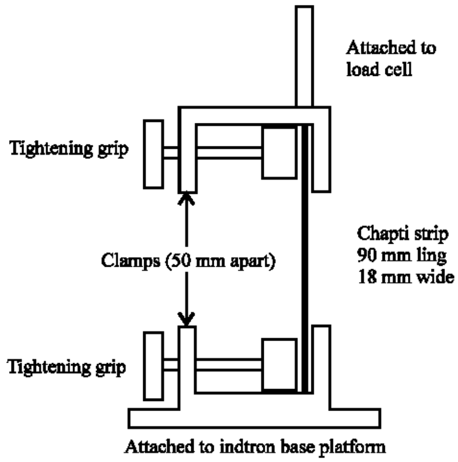

Fig. 10: Attachment for measuring chapati extensibility on Instron (Gujral and Pathak, 2002)

bubble during proving and baking. Chin and Campbell (2005) and Chin *et al*. (2005) used this instrument to measure and analyse rheological properties of aerated doughs. In principle, the sheeted dough sample is cut into circular sample of 55 mm diameter and 8 mm thickness, coated with paraffin oil to prevent moisture loss and drying and placed securely in the sample holder before inflation into dough bubble until a break or rupture was detected. Examples of graphs of pressure versus drum distance and corresponding stress-strain produced from the measurement using DIS are given in Fig. 7 and 8.

Universal testing machine: The Universal Testing Machine (UTM) is another alternative equipment for rheological properties measurement of dough and gluten; namely to measure tensile and compressive stress. Gujral and Pathak (2002) studied the extensibility of chapatti dough by performing tensile test using an attachment on an Instron UTM as shown in Fig. 10. They clamped the dough strip 50 mm apart and tighten the sample at the two ends. The texture of the chapatti dough was reported in terms of its extensibility, peak force to rupture, modulus of deformation and energy to rupture. Anderssen *et al.* (2004) used a micro-extension tester with 19 mm gap and 6 mm hook diameter operating at 1 cm sec^{-1} to study the extension of dough. Stojceska *et al.* (2007) conducted a biaxial extensional measurement of dough on Instron UTM with cylindrical test pieces of diameter 50 mm and thickness 12 mm and subjected it to biaxial compression to a final height of 2 mm at constant displacement speed of the upper plate. They found that at the given biaxial strain rate, the apparent biaxial viscosity of dough was higher when compressed at lower cross-head speed and

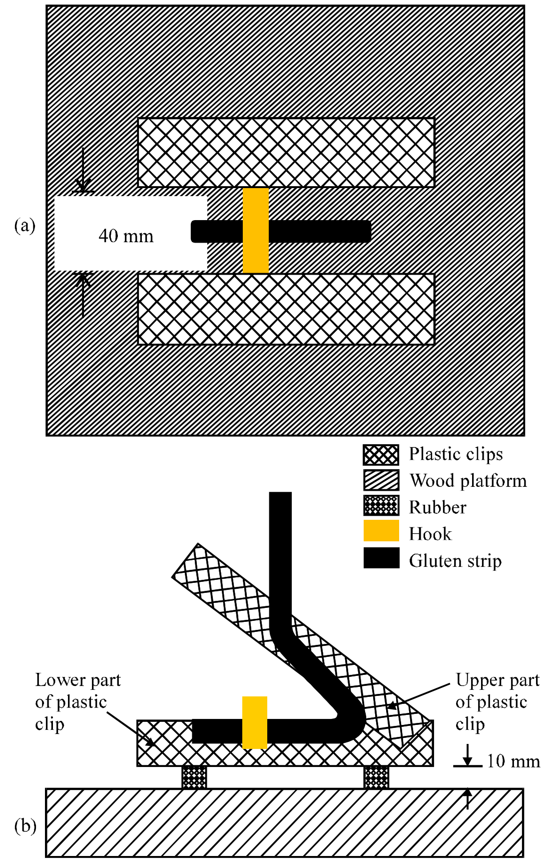

Fig. 11: Tensile test set-up for gluten extensibility using two plastic clips set at 40 mm distance and a hook attached to the Instron. Diagram from (a) top and (b) side view (Abang Zaidel *et al.*, 2008)

a weak negative correlation was obtained between protein content and biaxial extensional viscosity.

Improvisation in dough and gluten rheological measurement: Improvised attachments are developed from time to time for convenient measurements of dough and gluten properties due to the inconsistency in shapes and sizes of samples. Trevor *et al.* (2006) determined the extensibility of a rectangular wheat flour dough sample mounted onto two cylindrical drums by stretching it until a fracture occurs. They used the Sentmanat Extensional Rheometer (SER) for measurement of rheological parameters including strain, stress, strain rate and relaxation modulus. Abang Zaidel *et al.* (2008) developed an attachment on Instron for gluten extensibility studies (Abang Zaidel *et al.*, 2009a, b) (Fig. 11a, b). The set-up was built based on the working principle of the Kieffer dough and gluten extensibility rig with a dimension of 10×10×70 mm gluten strip. Rested gluten strip was clamped at two ends using plastic clips placed at a distance of 40 mm, nailed to a wood platform held tightly to the Instron platform. The tensile test set-up consists of a hook bent into a V-shaped using metal rod of 3.2 mm diameter. The developed tensile test attachment was successful in performing extensibility measurements where the gluten does not fracture at the clamping areas. The extensibility parameters obtained provided results which implied that the strong flour experienced greater strain hardening effect and the extensibility of gluten from both strong and weak flour dough increased as dough mixing time increased up to a peak point. This demonstrated that the gluten development is at its optimum at the peak and further mixing of dough passed this optimum time results in reduction in extensibility of gluten.

CONCLUSIONS

Glutens and doughs are most unique from the point of material science as they have complex behaviors. Rheological studies are conducted to determine these properties using various suitable testing methods and equipments. These properties measured to accuracy, be it fundamental or empirical, are important as information and references for product development both in research and the industry. The correlation studies on rheological properties of dough and gluten with the baking performance of the end product is an example of such appliance. As such, the development and improvisation of new instruments and attachments for measuring dough and gluten rheology is evolving along the expanding knowledge of their unique behavior.

NOMENCLATURE

Roman:

E_i = Initial slope of extension curve
E_{max} = Maximum extensibility at fracture
Ext = Total extensibility
G' = Elastic (storage) modulus
G" = Viscous (loss) modulus
G_0 = Initial relaxation modulus
G(t) = Relaxation modulus at any time
H(τ) = Relaxation spectrum
l = Final length after elongation
R_{max} = Maximum resistance to extension

Greek:

ϵ = Elongational strain
σ = Stress
η_{app} = Apparent viscosity
γ = Strain
ω = Angular frequency

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