Review Article

Rheometric Measurement of Dough Rheological Characteristics and Factors Affecting It

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ABSTRACT

Bread is one of the most important foods consumed all over the world. This review focuses on the use of rheometer for the measurement of dough rheological properties and factors affecting them. Rheological properties of dough are very important in bread baking quality. Knowledge of the rheological behavior of bread dough is very important to understand mechanical properties of the dough and control finished products. Small amplitude oscillatory shear (SAOS) measurements afford the measurement of dynamic rheological functions, without altering the internal network structure of materials tested and are far more reliable than steady shear measurement. Viscoelasticity of dough is related to many factors such as nature of flour, dough ingredient, temperature, water uptake, air incorporation and type of mixing. There are many models to predicate dough rheology. In this work some of these models such as power low, linear Maxwell model, Lethersich's model, Peleg's model and etc., were presented. The instruments such as faringograph, mixograph, Rheomixer, Extensigraph, Alveograph, Amylograph, Maturograph, Oven Rise Recorder, Fermentometer, Dynamic oscillatory, Concentric cylinders, Parallel plates, which are used for the measurement of dough rheological properties (due to viscoelastic behavior of dough) were also described.

Key Word: Bread; Dough; Rheology; Flour; Rheology models

INTRODUCTION

Rheology is now well established as the science of the deformation and flow of matter. It is the study of the manner in which materials respond to applied stress or strain. All materials have rheological properties. These properties are described by rheometers. Many rheometers are used for the measurement of the dough rheological properties such as penetrometer, consistometer, amylograph, faringograph, mixograph, extensigraph and alveograph described later.

Bread dough is a viscoelastic and shear thinning material combined of Hookean solid and non-Newtonian viscous liquid. Dough has non-linear rheological behavior, but in very low strains has linear behavior. The amount of low strain in which dough has linear behavior, depends on the type of dough, mixing and testing method.

Storage modulus (G') and loss modulus (G") can describe materials rheological properties described as follow:

$$G' = \frac{\tau_0 \cos\theta}{\gamma_0} \qquad G'' = \frac{\tau_0 \sin\theta}{\gamma_0}$$

$$tg\,\delta = \frac{G''}{G'}$$

The storage modulus can be used as a measure of the elastic component of the sample and similarly, the loss modulus- the viscous component of the sample.

When strain is below 0.1%, G' is greater than G", but when greater strain is used, this ratio becomes reversed due to viscoelastic solid conversion to elastoviscous liquid (Rasper, 1993). Addition of some ingredient such as yeast and salt to water-flour mix causes thixotropic behavior. Viscoelastic behavior of dough is attributed to gluten protein (Shiau & Yeh, 2001). Greater amounts of protein in water-starch-gluten system causes greater G' and lower G" (Rouillé *et al.*, 2005). Dough having a high protein quality has a greater G' and lower tg δ than a weak one (Khatkar *et al.*, 1995; Toufeili *et al.*, 1999). Gluten has viscoelastic behavior in which gliadin fraction represents viscous behavior and glutenin fraction represents elastic behavior due to difference in molecular size of these fractions (Tsiami *et al.*, 1997; Spies, 1997; Edwards *et al.*, 2001). Hydrophobic reactions have key role in elastic behavior of dough (Launay, 1990). Glutenin has a major role in the difference between baking processes (Toufeili *et al.*, 1999). When gliadin to glutenin ratio increases elasticity decreases considerable as G' decreased due to gliadin plasticising effect and interference of gliadin with glutenin-glutenin interactions and tg δ increased (Khatkar *et al.*, 1995).

Increase of protein in dough causes larger consistency. Increasing intermolecular cross-linkage causes higher G' and lower loss tangent in dough. The interactions (including physical & chemical forces) among protein molecules play key roles on the rheological properties (Shiau & Yeh, 2001). With increasing gliadin/glutenin ratio

dough extension stability decreases and extensibility increases (Angioloni & Rosa, 2005). G' and G" decrease by increasing molecular weight and number of high molecular weight glutenin fractions, but increasing molecular weight causes increasing relaxation time. Thus, dough relaxation properties depend on the distribution of molecular weight in dough and particularly to glutenin subfraction. Strong flour dough has higher relaxation modules and relaxation intensity over the whole relaxation time than those from weak flour. In gluten protein fractions, gliadin and soluble glutenin has one relaxation process, indicating no network structure (Li *et al.,* 2003). To produce bread with good volume quality, two factors should be considered: (a) Dough should have a high viscosity to prevent gas cells rising and (b) dough should remain extensible at high level to prevent sudden breakage in gas cell membranes (Sliwinski *et al.,* 2004).

Effect of energy input on dough rheological properties. Dough is divided into two groups: developed and un-developed. Un-developed dough is defined to be wheat flour that has become fully hydrated without being deformed (i.e., subjected to no mechanical action) and developed dough to be the transformation of un-developed dough, through some appropriate deformational energy input, to form the protein matrix associated with developed dough. The undeveloped dough is less resistant to deformation than the developed dough, showing that the energy input via deformation is responsible for modifications of the molecular structure in the un-developed dough. Hydration plays major role in modification of protein structure in dough (Gras *et al.,* 2000). Complex module (G*) is a factor representing strength of dough. A dough without any deformation has the lowest G*. A dough subjected to only shear deformation has the second lowest G*, a dough subjected to only extensional deformation has third lowest G* and a dough with a combination of shear and extensional deformations has the highest G*; greater the value of G*, greater the strength. Thus developed dough has the greatest rigidity. This suggests that the protein network inside the undeveloped dough is formed mainly with non-covalent cross-links and intrachain disulfide bonds, which may be broken by shear and extensional deformations during the mixing process. In developed dough the protein molecules are more unfolded and can form new cross-links at new positions, including interchain disulfide bonds. In this way, a much bigger protein network may be produced, giving the developed dough the most elasticity.

Mixed gluten in the mixing time, lower than optimum, has lower G* than dough mixing in optimum mixing time. There is a relationship between rheological properties and micro structural properties of dough. Undeveloped dough has the least protein matrix and developed dough has the most protein matrix. The energy addition and the type of deformation result in the formation of protein matrix in dough. Addition of energy increases the amount of protein matrix formation from undeveloped dough to developed one. Extensional deformation creates more protein matrix than the shear deformation (Lee *et al.,* 2001).

Researchers deduced that G' and G" dependent to mixing time and type of wheat variety affect order of this dependency. Increasing of mixing time decreases G' (Faubion & Hoseney, 1997). Mixing rapidly hydrates the flour particles, develops the gluten matrix and incorporates air into the system. A high shear rate in a dough mixer aids hydration by removing the outer layer of flour particles as they become hydrated and expose a new surface for hydration. As protein is hydrated, it forms fibrils aligned in a matrix by the shearing action of the mixer and the resistance of the system to extension increases. G' and elasticity decreases and tg δ increases by mixing. The rate in which dough becomes softer depends on the type of the mixer. When the dough is rested tg δ decrease and dough become more elastic. Elasticity affects capacity of gas maintaining. The optimum mixing time can be predicted by G' and tg δ that are dependent on the type of flour, bread and mixing (Mani *et al.,* 1992). Researchers found a strong correlation between the storage modulus and the optimum mixing time indicated by farinograms, while the optimum mixing times indicated by mixograph curves are one minute longer than the rheologically established optimum ones (Rasper, 1993). Other researchers indicated that un-mixed dough is less elastic than that mixed to optimum consistency due to increase in protein interactions.

During mechanical development, dough is subjected to both shear and extensional deformations. Dough elastic properties decrease after peak dough development. Apparent viscosity of dough increases by mixing to peak dough development and after this peak, addition of energy causes lower apparent viscosity (Zheng *et al.,* 2000). In another study, this opposition is modified and shows G' decreases by increasing of mixing time in commercial bread flour and increases in spring and winter flour dough (Kim & Cornillon, 2001). Remixing causes resistance increase in rested dough that produces more solid-like behavior (Kieffer & Stein, 1999). Also G' and G" increase by an increase in mixing time and in the optimum mixing time meet the maximum amount and then, by addition of mixing time, decrease (Ross *et al.,* 2004).

Effect of fermentation on dough rheology. *Saccharomyces cerevisiae* is major yeast in dough fermentation and has an important effect on dough rheological properties. Some researches showed that the effect of this yeast on rheological properties is similar to the effect of H_2O_2. This fact indicates that the effect of yeast on rheological properties is mainly due to the production of H_2O_2 by yeasts. Yeast caused dough to be more elastic. Addition of catalase and H_2O_2 together prevent changes in rheological properties but addition of catalase before didn't cause this reversal. Apparently, catalase is inhibited by lipid peroxides formed in the lipid fraction of flour (Liao *et al.,* 1998). Also CO_2 produced in fermentation dissolved in water and decrease its ph. Therefore CO_2 affects rheological

properties of fermented dough (Spies, 1997).

Effect of Ingredient on Dough Rheological Properties

Effect of water content. Water content has a negative effect on G' and G". Therefore, with increase in water content, G' and G" decrease inconsistently (Rasper, 1993; Faubion & Hosseney, 1997). If there is insufficient water to meet the hydration needs of the entire dough ingredient, the gluten does not become fully hydrated and the elastic nature of the dough does not become fully developed. Conversely, an excessive level of free water in the dough results in the domination of the viscous component of dough, with a decreased resistance to extension, increased extensibility and the development of sticky dough (Spies, 1997).

Effect of air. Air incorporation is a major function of the mixing step. The oxygen present in the air plays an important role in determining the rheology of dough. Dough mixed in the presence of oxygen is more elastic and offer more resistance to the extension than those mixed in the absence of oxygen (Spies, 1997).

Effect of salt. Several other minor ingredients such as salt also affect the rheology of dough. These effects occur primarily through the action of minor ingredients on, or interaction with, major constituents of the dough. Salt changes water interactions between components and it alters the configuration of gluten proteins, because of its composition for water. The combination of these actions results in increased mixing time for the dough (Spies, 1997).

Effect of surfactant. Sucrose fatty acid ester is added to dough as a surfactant. This esters decrease resistance to deformation and increases extensibility in dough. The esters increase quality of flat bread (Addo *et al.*, 1995). Moreover, addition of surfactants such as mono- and di-glyceride and lecithin to flat bread improves bread rheological and baking qualities (Azizi *et al.*, 2003).

Effect of ethyl galactoside. Ethyl galactoside decreases viscoelastic properties of dough. Adding this component results in decrease in elasticity module and viscosity (Shimizu *et al.*, 2003).

Effect of water soluble fractions. If there is not any water soluble fractions in dough, it has less tg δ and more elastic properties (greater G') than standard dough (Faubion & Hoseney, 1997; Rouillé *et al.,* 2005).

Effect of oxidants. The oxidants increase elastic/viscous ratio in dough. Type of this action is dependent on type of oxidant (Spies, 1997). Instant oxidants such as KIO3 increase G' but do not change tg δ sensibly (Faubion & Hoseney, 1997).

Effect of sodium caseinate and whey protein. Dairy ingredients are added to bakery products to increase nutritional and functional properties. Addition of 4% sodium caseinate decreases resistance to extension ($R_{5\ cm}$ measured with the extensigraph), while adding 4% whey protein concentrate increases extensibility. Whey protein concentrate also decreases G' and G", while heat treatment of whey protein concentrate increases G' and G". Confocal laser scanning microscopy showed that milk proteins cause

increasing in gluten network compared with the control, while un-treated whey protein concentrate appears to interfere with the gluten network (Kenny *et al.*, 2001).

Effect of acid and alkali. Alkali salts increase maximum resistance in extensigraph, water absorption in farinograph and viscosity and decrease extensibility and mixing demand. They delay thickening in dough and make it shorter and harder. Also alkali induces the interchange of sulphhydryl group and disulphide bond, which caused the increase in G' and apparent viscosity of dough. Alkali decreases tg δ in dough and an increase in pH results in the decrease in flow behavior index of dough with more shear thinning. Heating causes the gelatinization of starch and reduces the difference in G' in dough. Consequently adding alkali to dough makes it more solid-like. Adding acid to dough has the opposite effect and results in a dough with less shear thinning and decrease apparent viscosity in dough. Consistency index (K) in power low equation decreases by adding acid to dough (Shiau & Yeh, 2001).

Influence of hydrocolloids. Xanthan and alginate make dough more strong. K-carrageenan or hydroxypropyl-methylcellulose reduces the firmness of bread crumb. Addition of these component leads to bread with better specific volume and softer crumb (Rosell *et al.*, 2001).

Effect of hydrocolloid-enzyme-surfactant mixture. Adding mixture of hydrocolloid (hydroxypropylmethylcellulose & high ester pectin) and enzyme (α-amylase & transglutaminase) and surfactant (diacetyl tartaric acid ester of mono-diglycerides) to dough causes high quality bread, optimum resistance to uni- and bi-axial extension, high strain hardening in bi-axial extension and greater relaxation time (Bollain & Collar, 2004).

Effect of pentosan and systeine. Addition of pentosan to dough causes less G' and greater tg δ (Baltsavias *et al.*, 1997). Cysteine has SH group that can be used as a reducing agent and free radical scavenger in processing of cereal-based foods. Protein-protein interactions via formation of disulphide covalent linkage can be destroyed by cysteine theoretically. In 40°C primary G' decreases in cysteine added samples. It is suggested that even during mixing, viscoelastic behavior of dough is affected by depolymerization caused by cysteine and primary G' decreases. Consequently, increase of cysteine concentration destroys cross-link and decreases maximum G' and increases tg δ value. By breaking this linkage, molecular weight between cross-links increases and the number of cross-links decreases (Rasper, 1993; Spies, 1997; Faubion & Hoseney, 1997; Lambert & Kokini, 2001).

Effect of barely components. Barely ingredients such as β-glucans or arabinoxylans increase peak resistance, mixing stability and G' in dough. Arabinoxylans have more influence than β-glucans (Lzydorczyk *et al.,* 2001).

Effect of fiber and added fat. A good correlation exists between fiber and the reduction of coronary heart-related diseases and diabetes incidence. Adding fiber to dough increases P in alveograph (dough resistance to deformation

or tenacity). This is likely due to interactions between the fiber structure and the wheat proteins. Additionally, parameter in alveograph (stands for the height of the bubble that was achieved, measured from where the slop of the bubble started to the top of the bubble and shows how flexible the dough was) decreases by adding most of the dough (Wang *et al.,* 2002). Likewise, added fats have plasticizing effect on G' and G" in elastic region. Addition of fat delays viscous flow (Mulvaney & Cohen, 1997).

Effect of added enzymes. Wheat dough contains some enzymes such as α and β-amylase, protease, lipase, phosphatase and oxidase. These enzymes become inactive when wheat grain doesn't germinate. Effect of enzymes on rheological properties of dough is dependent on temperature. The elastic modules (G') increases slowly with time at room temperature, whereas during the same time (2 h) at 40°C, a maximum value flowed by a continuous decrease in G' was observed. The phase angle, δ, increases slightly with time at 40°C. The presence of α-amylase causes a decrease in G' after a shorter period of time and lower G' values are obtained (Lindahl & Eliasson, 1992). The use of enzymes such as peroxidases or glucose oxidase instead of chemical oxidants is a very interesting option for improving bread making performance of dough. Peroxidase increases only the number or life span of transient bonds, whereas glucose oxidase additionally produces cross-links that are permanent on time scales up to three hours. Peroxidase probably introduces a second, more transient structure (arabinoxylan network) through the gluten network, whereas glucose oxidase may also have strengthened the gluten network. Addition of only glucose oxidase causes increasing in G' by order 1.2 and decreases tg δ partly. In biaxial and uni-axial extension tests addition of peroxides only increases stress levels (Dunnewind *et al.,* 2002). Protein disulphide isomerase causes dough more elastic and increases relaxation time. Traditionally, methods such as extensometer are useful in the detection of these changes (Watanabe *et al.,* 1998).

Varietal differences in wheat for dough rheological properties. There are many wheat varieties with different properties in the world. Some of these varieties are useful for bread making. The ingredient in each variety is different from another one that causes different rheological properties. Some of these varieties are compared together such as Obelisk vt. and Katepwa vt. First variety is winter wheat and the second one is spring red wheat. Obelisk has 10.5% and Katepwa has 12.4% protein. Dynamic methods such as oscillatory showed that Katepwa dough had more resistance to deformation and is more elastic than Obelisk dough (Janssen *et al.,* 1995). In another study, two varieties (extra strong & moderate to strong) are compared together. Extra strong has greater G' and G", less tg δ and more slow relaxation rate than moderate to strong vt. Extra strong needs greater time to receive peak resistance in mixing than moderate to strong vt. Addition of cysteine to extra strong vt. causes decreasing in mixing time (Rao *et al.,* 2000).

Effect of temperature on dough rheology. In Fig. 1, the effect of temperature on storage and loss modules is showed. G' and G" decrease by increasing temperature before 87°C. Decrease in G' is caused by complexity of the polymer flow behavior and increasing molecular mobility and when temperature increases to 90°C, G' increases gradually. This phenomenon can be attributed to cross-linking interactions inducing in gluten during formation of network structure. Protein-protein interactions through thiol-disulfide interchange reactions would begin to provide an increasingly highly cross-linked structure resulting in higher G' and generally lower G" values. Another study showed that during temperature scans of flour-water dough at 25-90°C, G' values decreased slowly as the dough temperature increased from 25 to 50°C. At ≈55°C, G' begins to increase rapidly reaching a peak at ≈75°C. Starch gelatinisation, gluten cross-linking, or both, are advanced as possible explanations for the thermally induced rheological changes occurring between 55 and 75°C. Sodium hydroxide (NaOH) is effective in deferment of gelatinisation (Lambert & Kokini, 2001; Angioloni & Rosa, 2005). Starch gelatinisation causes a rapid increase in G'. Substitution of starch by pregelatinized starch causes little or no increase in G'. Probably gelatinisation induces more hydrogen band between starch and gluten. Complex module increases during gelatinisation and all of them are caused by increasing temperature (Kim & Cornillon, 2001). The glutenin fraction of gluten has been found to be more sensitive to heat than the gliadin fraction; on heating up to 75°C glutenin protein unfolds and disulphide/sulphhydryl interchange reactions are promoted (Angioloni & Rosa, 2005). Another study showed that the effect of temperature on dough rheological properties is mainly due to the effect of temperature on gluten rheological properties and resistance to mixing increases in heated gluten (Gélinas & Mckinnon, 2004).

Frozen dough has a great usage in all of the world. Compared to fresh, relaxation module and relaxation time reduce in frozen dough. Relaxation half time reduces in frozen dough due to weakening of gluten network. Also G' and complex module decrease and tg δ increases in frozen dough compared to fresh dough, due to reduction of cross-linking in polymer by water crystallization (Autio & Sinda, 1992; Ribotta *et al.,* 2004).

Effect of aging time on dough rheology. Aging increases storage module and does not change the loss module sensibly (Baltsavias *et al.*, 1997).

Models used in dough rheology. Flour dough follows power low equation:

$$\tau = k.D^n$$

Where τ is tangentic stress, k is viscosity coefficient, n is flow index and D is shear rate. This equation can be linear as follows:

$$Log\ \tau = Logk + nLogD$$
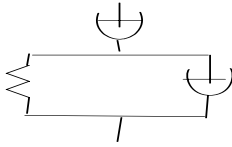
k and n are affected by water content in dough (Weipert, 1990).

By power low equation η can be accounted by:

$$\eta = \frac{\sigma}{\overset{\circ}{\gamma}} = k^{1/\alpha}\sigma^{1-1/\alpha}$$

Where α = 0.3±0.1.

k decreases by increasing γ in power low equation. Due to non-linear behavior of dough, it is not consistent to fit the relaxation curves with one or several linear Maxwell models. Studies showed that the simplest model that may qualitatively describe stress relaxation and partial elastic recovery in dough is Lethersich's model. This model has following characteristic:

With this model stress relaxation is complete and its rate depends on ($\eta + \eta_k$), but steady flow properties are solely defined by η.

The equation corresponding to this model is:

$$\sigma = G\gamma_{el} + \eta_k \overset{\circ}{\gamma}_{el} = \eta \overset{\circ}{\gamma}_V$$

With γ_{el}, elastic deformation and γ_V viscous (irrecoverable) deformation.

For non-linear viscous properties, η_k and η are functions of the absolute values of $\overset{\circ}{\gamma}_{el}$ and $\overset{\circ}{\gamma}_V$, respectively. During the relaxation process

$$\overset{\circ}{\gamma} = \overset{\circ}{\gamma}_{el} + \overset{\circ}{\gamma}_V = 0 \ , \text{i.e.,} \ \left|\overset{\circ}{\gamma}_{el}\right| = \left|\overset{\circ}{\gamma}_V\right|$$

and therefore, η_k and η are functions of the same shear rate values.

Studies showed that G is constant during relaxation process and does not depend on σ.

From equation showed above:

$$\overset{\circ}{\gamma} = \overset{\circ}{\gamma}_{el} + \overset{\circ}{\gamma}_V = \frac{\overset{\circ}{\sigma}}{G} + \frac{\sigma}{\eta} = 0$$

And by replacing η by its value as a function of σ:

$$\overset{\circ}{\sigma}/G + k^{-1/\alpha}\sigma^{1/\alpha} = 0$$

By integration, putting $\sigma_0 = \sigma$ and t = 0 when stress relaxation starts, one can obtain:

$$\left(\sigma_\circ/\sigma\right)^{n-1} = 1 + pt$$

Where $n = \dfrac{1}{\alpha}$ and $p = (n-1)G\sigma_\circ^{n-1}k^{-n}$

The value of the half-relaxation time ($\sigma/\sigma_\circ = 0.5$) is easily deduced from equation shown above:

$$t_\frac{1}{2} = \left[(2^{n-1}-1)/(n-1)\right]\times\left(k^n/G\sigma_\circ^{n-1}\right)$$

The half-relaxation time decreases when σ_0 increases.

There are other viscoelastic models. A very simple empirical equation was proposed by Peleg:

$$\sigma_\circ/(\sigma_\circ - \sigma) = a + (kt)^{-1}$$

Where k is a rate constant of the relaxation process. For a viscoelastic liquid a = 1 and for a viscoelastic solid a > 1. Studies showed that the experimental point fitted with this equation might be better than the other one.

Bohlin and Carlson (2004) offered another model for dough as:

$$\overset{\circ}{\sigma} = -\sigma\left(\sigma/\sigma_\circ + \varepsilon\right)^{z/T}$$

Which T is a relaxation time and Z is the coordination number of flow units and ε is a measure of the strength of the cooperation.

Integration of equation showed that the above leads to following equation, where z = n+1:

$$T = k^n G^{-1}\sigma_\circ^{1-n} = (n-1)/p = \left.(n-1)t_\frac{1}{2}\right/\left(2^{n-1}-1\right)$$

According to studies elastic modulus (G) can be calculated as (Launay, 1990):

$$G = (\sigma - \sigma_k)/\gamma_{el} \cong \sigma/\gamma_{el}$$

According to Bird-Carreau model apparent viscosity in high shear rate in dough can be calculated as:

$$\eta = \frac{\pi\eta_\circ}{\xi(\alpha_1)-1}\frac{\left(2^{\alpha_1}\lambda_1\overset{\circ}{\gamma}\right)^{(1-\alpha_1)/\alpha_1}}{2\alpha_1\sin\left(\dfrac{1-\alpha_1}{\alpha_1}\pi\right)}$$

Which $\lambda_{1p} = \lambda_1\left(\dfrac{1+n_1}{p+n_1}\right)^{\alpha_1}$

And for $n_1 = 1$, $\eta_p = \eta_\circ\left(\dfrac{\lambda_{1p}}{\sum\limits_{n=1}^{\infty}\lambda_{1p}}\right)$

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And ξ is Riemann's zeta function (Kokini *et al.*, 1995).

Recently, Mackey et al (1990) modified the model of Morgan et al for use in determining the viscosity of starch-based products.

$$\eta = \left[\left(\frac{\delta_\circ}{\overset{\circ}{\gamma}}\right)^{n1} + \mu_\infty \overset{\circ}{\gamma}^{n2-n1}\right]^{1/n1} \left\{\exp\left[(\Delta E_v / R)(T^{-1} - T_r^{-1}) + b(MC - MC_r)\right]\right\}$$

$$\{1 + A'[1 - \exp(-K_a\psi)]^\alpha\}\{1 - \beta[1 - \exp(-d\varphi)]\}$$

This model can be modified and the effect of dough ingredients such as protein and fat on its viscosity can be studied (Mackey & Ofoli, 1990).

Measurement of rheological properties of dough. There are many techniques for studying the rheological properties of dough. In about 1930, one of the first special instruments was designed for physical testing of wheat flour dough, the so-called Brabender Farinograph (Janssen *et al.*, 1995). Many instruments were used for the measurement of the dough rheological properties such as penetrometer, consistometer, retetexturom, amylograph, faringraph, mixograph, extensigraph, maturograph, oven rise recorder and alveograph (Table I).

Empirical tests are purely 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. Many of these tests are used as single point tests. 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 discrepancy between such single point type tests and actual performance in the plant. Irreversible changes in samples are another disadvantage in some empirical tests (Dobraszczyk & Morgenstern, 2003).
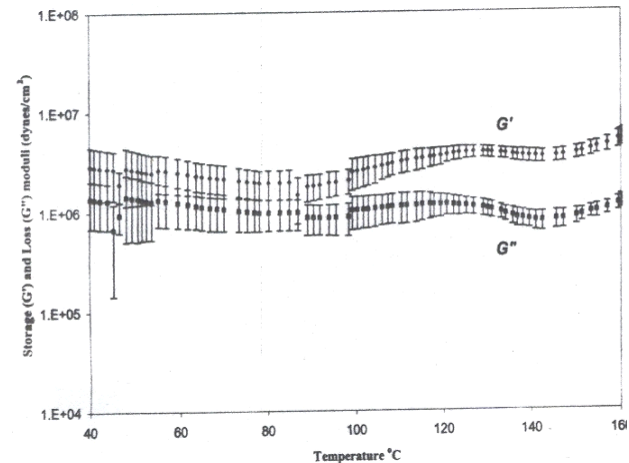
Rheological changes caused by dough ingredients make sample presentation difficult and cause the complication of the use of fundamental rheological equations (Spies, 1997). Used instruments in dough rheology measurements must be capable of measuring both viscous and elastic properties of dough due to its viscoelastic behavior. One of the useful tests is dynamic oscillatory shear measurement (DOSM) . DOSM is designed to be small strain set, generally involving strains in the order of 0.1% to 5%, while the strains experienced by dough in the bread-making process can range from 100% during sheeting, to 1000% during fermentation and oven rise and up to 500000% during mixing. Perhaps the two most successful instruments in terms of attempting to match kinematic conditions during bread-making are the extensigraph and alveograph. Their mode of deformation is similar to the extension that takes place during fermentation and oven rise. But the rates of deformation they apply on dough are higher than those found in practice.

One of the most useful methods is that in which a dough sample is loaded between the two plates and enough

Table I. Instruments used in measuring dough rheological characteristics and their properties

Method	Property measured
Empirical methods	
Mixers: faringraph, mixograph	Mixing time/torque
reomixer	Apparent viscosity
Extensigraph	Extensibility
Alveograph	Biaxial extensibility
Amylograph	Apparent viscosity, Gelatinisation temperature
Maturograph	Volume change of complete Dough (final proving time, Proving stability, elasticity, Dough level)
Oven Rise Recorder	Buoyancy of the dough (dough volume, baking Volume, oven rise, final rise, Peaks (when gas escapes)
Fermentometer	Height, Volume
Fundamental methods:	
Dynamic oscillatory	Dynamic shear module
Concentric cylinders, Parallel plates	Dynamic viscosity

Fig. 1. Effect of temperature on G' and G'' in dough with 25% moisture and without adding any thing to flour in 0.75 rad/sec and 0.7% strain and heating rate 5˚C/min

time is given for normal stress to relax. In this instrument:

$$\text{Velocity field} = V_\theta = \frac{rzw}{h}$$

$$\text{Shear rate at R} = \gamma_R = \frac{Rw}{h}$$

$$\text{Shear stress at R} = \tau = \frac{2M}{\pi R^3}$$

In Which
W = angular velocity
M = torque.

After 15 min for rest, the lower plate is rotated at a constant angular velocity, which in turn gives rise to a constant shear rate at the plate edge. Since this is constant shear rate experiment, the total shear strain applied on the dough sample can be obtained by multiplying the shear rate

by the elapsed time. By this action stress-strain diagram can be obtained as shown in Fig. 2. In this diagram shear rate is 5.0×10^{-2} s^{-1}. This diagram has two advantages: (a) the stress-strain diagram can be obtained easily and expressed in fundamental units and (b) the deformation history of dough during the experiment is well defined. Therefore, fundamental rheological properties should, in turn, be relatable to extensigraph or alveograph data.

Extensigram is shown in Fig. 3. In this diagram maximum resistance (R_{max}) is similar to failure stress in prior diagram and extensibility (E) is similar to the failure strain in prior diagram. Oscillatory rheometer can measure elastic and viscous properties and complex viscosity in dough (Menjivar, 1997). In small amplitude dynamic rheometry, when a material is deformed sinusoidally at a frequency ω (rad/sec), the shear strain can be expressed as:

$$\gamma(t) = \gamma_\circ \sin(\omega t)$$

Where γ is the strain amplitude, ω is the angular frequency and t is the time. The stress function can be written in these rheometers as:

$$\sigma(t) = \gamma_\circ [G' \sin(\omega t) + G'' \cos(\omega t)]$$
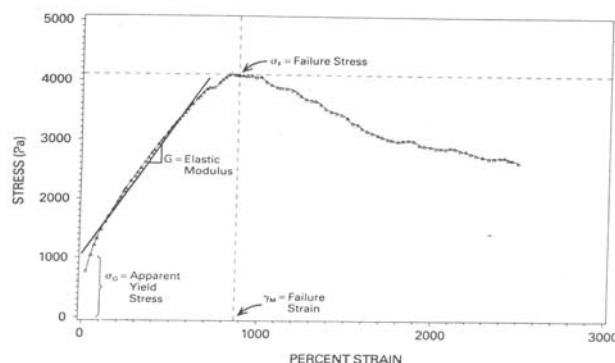
In which:

$$G = \sigma_\circ / \gamma_\circ \cos\delta, G'' = \sigma_\circ / \gamma_\circ \sin\delta$$

There are two components in sinusoidal tests; in-phase and out-of-phase. The in-phase component represents the elastic character of the material (the storage modulus). It is a measure of the energy stored in the material on sinusoidal deformation and recovered per cycle. The out-of-phase component represents the viscous character of the material (the loss modulus). It is a measure of the energy dissipated or lost as heat per cycle of deformation. Another parameter useful in characterizing the physical state of viscoelastic material is the loss tangent or tan δ. This dimensionless parameter is the ratio of energy lost to energy stored for each cycle of deformation. This parameter is more sensitive than G' and G'' in probing changes in the viscoelastic character of a polymer network (Lambert & Kokini, 2001).
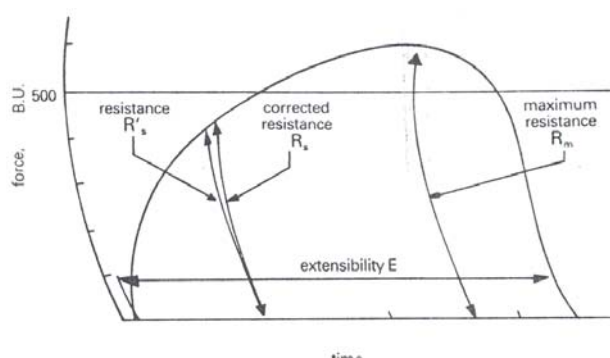
Dough hardening. Gluten quality, especially its ability to aggregate and starch and water content are the three main parameters that account for the degree of dough-hardening, where chemical reactions with oxygen, like cross-linking of glutenin polymers by disulfide bonds, can't explain the effect of dough-hardening. The observed dough-hardening in rheological tests involving large uniaxial deformations must be due to the dilatant behavior of the starch aggregates. It increases when water content is reduced or when starch content is increased either by addition of starch or when the protein content of the flour is low (Kieffer & Stein, 1999).

Relationship between bread quality and rheological properties. Water and flour type has a significant effect on storage modulus (G') or phase angle measured by an oscillatory test both in the linear viscoelastic region and as a

Fig. 2. Stress strain diagram when a dough sample is loaded between the two plates

Fig. 3. Extensigram

function of stress, and on compressional force measured as a function of time, good correlation of rheological measurements of dough and baking performance. Although water content of dough are correlated with the rheological measurements, the correlation of G' measured in the linear viscoelastic region or maximum force from stress-time curve during compression was poor for bread loaf volumes. No correlation was observed with the maximum force of compression or G' of dough measured in the linear viscoelastic region and baking performance. Good correlation of rheological measurements of dough and baking performance was obtained when all the data points from force-time curve and whole stress sweep (G' as a function of stress) were evaluated with multivariate partial least squares regression (Autio *et al.*, 2001). There are good correlation between extensional tests and baking performance. R_{max} and extensibility both characterize gas bubble expansion indirectly, which is showing bread loaf volume quality (Anderssen *et al.*, 2004).

CONCLUSION

Dough rheological properties have an important effect on baking characteristics. It is revealed that parameters such as the addition of salt, temperature, time and etc., affect these properties. To predict final products quality, having a good knowledge about these properties and their related parameters is necessary. So choosing instruments and models, which can provide us this knowledge, is a very important step in the prediction of product quality.

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