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Viscoelastic properties of bread dough kneaded with a kitchen machine

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ABSTRACT

Linear viscoelastic range (LVR) of bread dough with various compositions was determined with oscillatory amplitude tests, while frequency tests (performed in LVR) enabled determination of viscoelastic behaviour at small deformation. In order to determine flow characteristics of the dough and to evaluate the torque, which was generated during the kneading on the impeller shaft, rotational flow tests were performed. As the dough is highly viscoelastic material, normal forces stimulate the dough to climb up the impeller shaft. Thus, shear stress dependence of 1st normal stress coefficient and 1st normal stress difference was determined for all compositions of the dough.

INTRODUCTION

Rheological properties of bread dough play an important role during kneading in a kitchen machine and significantly influence also the quality of baked bread. As the bread dough is highly viscoelastic material with explicit nonlinear behaviour, the proper determination of the rheological properties and their effect on kneading process is extremely important.[1,2] Each of the ingredients (flour, salt, water, yeast, preservatives …) that are combined in a cohesive viscoelastic substance (dough) can considerably change the rheological properties of the dough during kneading, and makes the final structure rheologically complex. In fact, the combination of the ingredients produces a three dimensional network called gluten which has a crucial role in complex viscoelastic behaviour of wheat flour dough[3].

Among other components, water is prerequisite for making dough, therefore 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.[4]

In order to improve the quality of baked bread, the development of relevant kitchen machines depends strongly on a comprehensive knowledge of dough rheology. It is therefore essential to gain a deep knowledge of dough rheological behaviour, which is possible only if we ensure the accuracy of the measured rheological data. In the past, many specific instruments and methods have been developed for the characterization of bread dough, however due to complexity of the dough there are still many questions not solved yet. Therefore, the main goal of the presented research was to determine the influence of bread dough's viscoelastic properties on kneading process during its preparation in kitchen machine.

In the present study, the rheological measurements were performed with a rotational controlled rate rheometer (Physica MCR302, Anton Paar). Various rheological tests were performed on three types of dough, prepared by home professional kitchen appliance Bosch MUM5. The compositions of the dough differed in the amount of water, while the basic ingredients remained the same. However, in order to mimic the behaviour of the dough during the process of kneading and to observe the effect of viscoelastic properties on the torque, tests were performed in the wide range of shear with several sensor system. Among them 4 blade vane geometry enabled optimal measurements since it prevented slippage and mimicked the kneading process the best. The following results are therefore presented only for measurements with this sensor system.

EXPERIMENTAL

Preparation of bread dough

For the investigation of rheological properties, three types of bread doughs were prepared by following the same recipe. The compositions differed in the amount of water, while the basic ingredients remained the same: 500 g white flour, 14 g sugar, 14 g oil, 7 g salt and water: 250 ml, 285 ml and 300 ml.

The ingredients were mixed for 5 minutes at stage 3 with Home Professional Kitchen Machine Bosch MUM5 (supplied by BSH, Home appliances, Nazarje).

Rheological characterization

The rheological measurements were performed with a rotational controlled rate rheometer (Physica MCR302, Anton Paar), equipped with a 4 blade vane geometry cylindrical sensor system. In order to determine the viscoelastic properties of the dough and to simulate the behaviour of the mixing process inside Bosch MUM5 various rheological tests were performed. As the doughs are highly time-dependent materials, the filling of the sensor system and the order of measurements was extremely important. Hence, each measurement was performed with fresh sample and following the same filling procedure.

Linear viscoelastic range (LVR) of the doughs was determined with oscillatory stress sweep tests at constant frequency of oscillation 1 Hz. These tests were performed by increasing the strain deformation from 0.01 % to 100 %. During kneading high destructive conditions are formed inside the mixing vessel. Thus, in order to determine the flow characteristics of the dough during kneading, destructive shear flow tests were performed. Standard rotational flow tests were performed with a triangular method by changing the shear stress in the range of 1 – 6000 – 1 Pa. The higher value of the applied shear stress depended on the composition of the dough (the amount of added water). Furthermore, frequency tests were performed at constant small deformation in LVR by decreasing the frequency from 100 Hz – 0.01 Hz at constant strain deformation 0.1 %.

RESULTS

For some materials with solid-like behaviour, like bread dough, viscosity measurements with plate-plate or cone-plate geometry makes no sense, since the shear stress just keeps increasing with time until the sample breaks or flows out of the test cell. The results of measurements therefore don't reveal the properties of the material, but are an indication of the friction between the sample and the sensor system. In the present study parallel plate sensor system was used for some measurements; however, as mentioned above, the results were not accurate and due to high slippage of the samples the conditions of high shear were not possible to achieve. Consequently, the results, obtained with parallel plate sensor system are not presented.

In order to avoid the above problems a sensor system, more similar to the impeller in the dough-making vessel was used for the measurements. For further measurements, 4 blade vane geometry provided similar conditions as are developed during kneading and to some extent eliminated the slippage of the sample. Following results were obtained with this sensor system.

Oscillatory strain sweep tests

Strain sweep tests were performed by keeping the frequency of oscillation constant at 1 Hz.

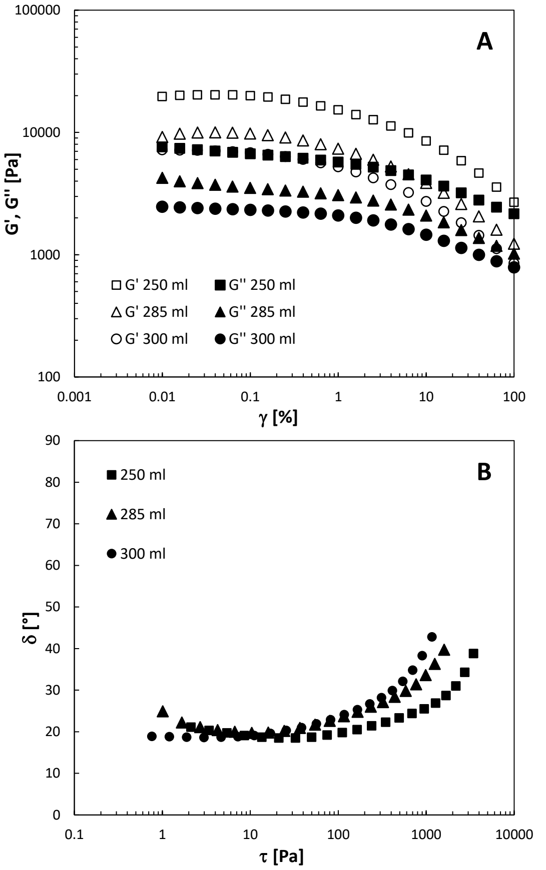

Figure 1: Stress sweep tests at constant frequency of oscillation A) dynamic moduli; B) phase angle.

The results showed that all compositions exhibited linear viscoelastic behaviour below 0.1 % of strain (Fig. 1A).

All samples possessed higher G' values compared to G'', indicating that all compositions of the dough exhibited a firm, elastic-like behaviour. Fig. 1B presents the dependence of phase shift angle δ as a function of the applied shear stress. The tan δ value is calculated as the quotient of the lost (G'') and stored (G') deformation energy. It reveals the ratio of viscous and elastic contribution to viscoelastic behaviour. In general, the ideal-elastic behaviour, where G' completely dominates G'', is specified in terms of δ = 0°, while ideal-viscous behaviour is expressed as δ = 90° since G'' completely dominates G'. δ equals 45° for materials (i.e. gels) where viscous and elastic contributions exactly balance (i.e. G' = G''). The results show that for all compositions of the dough the δ values were below 45° in the whole frequency range examined. Therefore we can conclude that all samples exhibited highly viscoelastic solid-like structure.

Oscillatory frequency tests

In order to investigate the viscoelastic behaviour of the dough during small deformation, frequency tests were performed in linear viscoelastic range (0.1 % of strain).

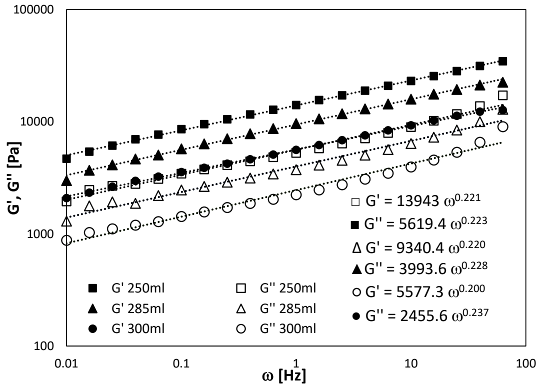

Figure 2: Frequency tests at constant strain deformation.

Fig.2 represents frequency dependency of dynamic moduli (G', G''). Both moduli decreased with increasing amount of water indicating that the structure of the dough became more liquid – like when higher amount of water was added. All three compositions exhibited similar frequency dependence of dynamic moduli, where, over the entire frequency range, the elastic moduli G' prevailed over the viscous one G''. Moreover, as angular frequency increased up to 100 Hz, storage G' and loss modulus G'' increased as a function of frequency. The flow properties of flour-water dough obey the power law as a function of frequency. The power law constants were calculated using the following equation[5]:

$$G(\omega) = A\cdot\omega^{1/n} \quad (1)$$

where, G represents the modulus, A is flow coefficient, 1/n the slope of linear portion of log G vs. log ω and ω is the frequency of oscillation. The constants were obtained from the linear regression analysis after a logarithmic transformation of the raw data. The results of the calculated parameters, presented in Fig. 2, are in agreement with many other reports in the literature, for example, Berland and Launay[6], Phan-Thien et al.[7], Tanner et al.[8] and Uthayakumaran et al.[9] In all above studies, the exponent n was in the range 0.15 – 0.28 [10]. The magnitude of the slope of log G' vs. log ω provides useful information about the structure of the polymer.[11] According to Ferry[12], when the slope of log G' vs. log ω, i.e. (n), has a value approaching 0, the material behaves like a rubbery material, while a liquid flowing material has a slope (n) approaching 2. When a 3D network is present, we expect the slope to be near zero[13]. In the present work, G' was higher than G'' for all the compositions of dough. Linear regression of log G' vs. log ω data showed that the resulting values of n for all studied water contents were low (< 0.3), indicating the existence of a 3D network. The values of 1/n varied from 0.20 to 0.24. Increasing values of n are considered to indicate an increasing fraction of uncross linked material[14].

Moreover, it was found that with increasing water content, G' and G'' decreased. The trend of a decreasing G' and G'', as the water content of dough increased, is also in agreement with earlier studies.[9, 10, 15-19] Decreased values of moduli indicate that there is reduction in dough firmness and elasticity. Added water softens the dough, decreases the hydration time and the energy required for mixing.[20]

The measured values of dynamic moduli, obtained by frequency tests, enabled the determination of the relaxation spectrum for each of the dough. A relaxation spectra is vital not only for constitutive models but also for the insight into the properties of a viscoelastic material. Particularly, the generalized Maxwell model was used to fit the experimental data in the present work. In this model, the values of the overall G′ and G″ at any frequency are given by the sum of N contributions from N Maxwell elements in parallel. Each element is defined by the elastic response of the spring (G_i) and the relaxation time which is the ratio between the viscosity of the dashpot and the rigidity of the spring ($\lambda_i = \eta_i/G_i$). The following equations were fitted to the experimental data of the storage G' and loss G'' moduli:

$$G'(\omega) = \sum_{i=1}^{N} G_i \frac{(\omega\lambda_i)^2}{1+(\omega\lambda_i)^2} \quad (2)$$

$$G''(\omega) = \sum_{i=1}^{N} G_i \frac{(\omega\lambda_i)}{1+(\omega\lambda_i)^2} \quad (3)$$

An iterative process using simultaneously the above Eqs. was employed to minimize the sum of the square differences. The computed G_i and λ_i values were used to predict the storage and loss moduli.

The relaxation spectrum for all compositions of the dough, examined in the present study, is presented in Fig. 3. According to the literature, relaxation spectrum should pass through a minimum in the region where the storage modulus or relaxation modulus is flat, separating the two sets of relaxation times that correspond to motions within entanglement strands and motions across entanglement loci.[12] In practice, the minimum is often blurred, probably in part because of distributions of entanglement-spacings and some inhomogeneity of molecular weight even in relatively sharp polymer fractions. For the doughs studied in the present work, the addition of water shifted the relaxation spectrum towards shorter times, which means that the water acts in the way of speeding up the processes and acting as lubricant.

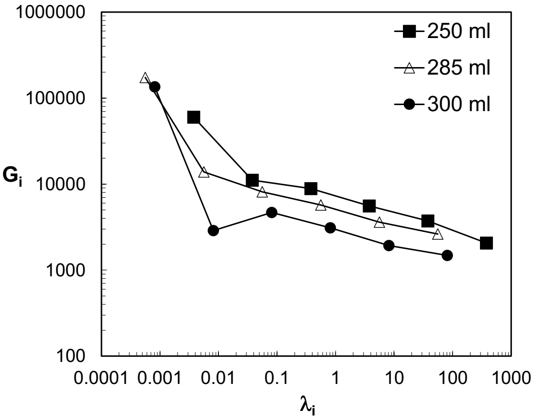

Figure 3: Relaxation spectra for various bread doughs.

Flow tests under destructive shear conditions

In order to determine flow characteristics of the dough at conditions, similar to the conditions during kneading inside kitchen machine, flow tests under destructive shear conditions were performed. During kneading, the dough is exposed to high shear, which influences the viscosity and viscoelastic behaviour of the dough. Flow tests were performed in two steps: 1) increasing the shear stress from low to the highest achievable value and 2) decreasing the shear stress from the highest value back to the initial one. Time interval was the same in both steps, i.e. 180 s. The highest values of the shear stress which were possible to achieve depended on the composition of the dough and varied from 3000 Pa to 6000 Pa (Fig. 4), which corresponded to shear rates 1 s^{-1} to 10 s^{-1}. For each composition of the dough two consecutive identical tests were performed. The results showed that, as expected, the viscosity decreased with increasing amount of water. For all compositions of the dough the viscosity decreased with increasing shear conditions up to the highest value of the applied shear stress. As the shear stress started to decrease in the 2nd step of the experiment, the viscosity increased further, indicating that the internal stress inside the dough remained to some extend even after the applied shear stress was removed.

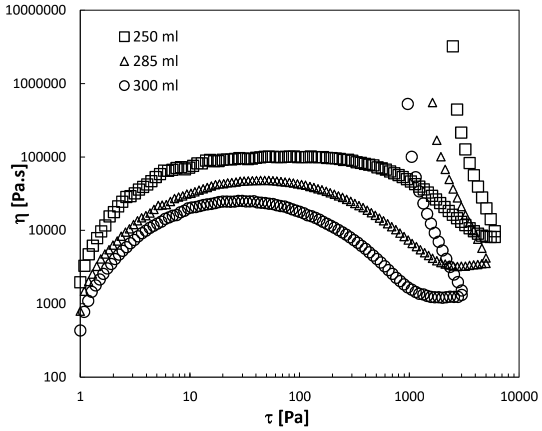

Figure 4: Flow curves for various compositions of bread dough; the dependence of viscosity on shear stress.

Dough is highly viscoelastic material, therefore, when a rod is rotating during the kneading, the dough starts climbing the rod rather than depressing the free surface near the rod. This effect is called Weissenberg effect of rod-climbing, which is a consequence of the ability of fluid element to support a tension along a streamline (first normal stress difference) and therefore forces the fluid to move up the rod.

Normal stress differences are differences between unequal normal stresses in shear flow of viscoelastic fluids. For a Newtonian fluid the normal stresses in shear flow are always equal.

The first normal stress difference is an even function of shear strain and shear rate:

$$N_1(\gamma)=G\gamma^2 + B_1\gamma^4 + \cdots \qquad (4)$$

The first term comes from the Lodge-Meissner Relation:

$$N_1 = \sigma \cdot \gamma \qquad (5)$$

$$N_1(\dot{\gamma})=\Psi_1^0 \cdot \dot{\gamma}^2 + B_2 \cdot \dot{\gamma}^4 + \cdots \qquad (6)$$

First Normal Stress Coefficient is thus an even function of shear rate.

$$\Psi_1 \equiv N_1(\dot{\gamma})/\dot{\gamma}^2 = \Psi_1^0 + B_2 \cdot \dot{\gamma}^2 + \cdots \qquad (7)$$

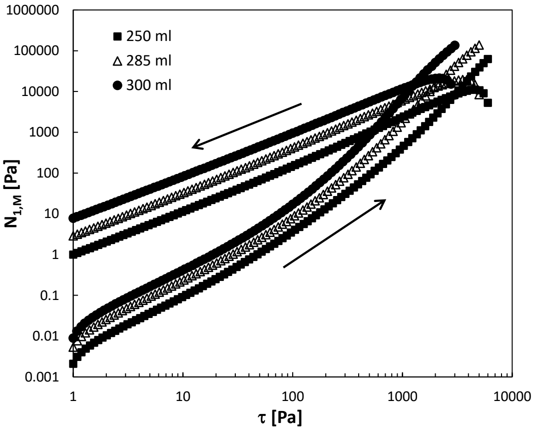

Figure 5: 1st Normal Stress Difference according to Lodge-Meissner for various compositions of bread dough.

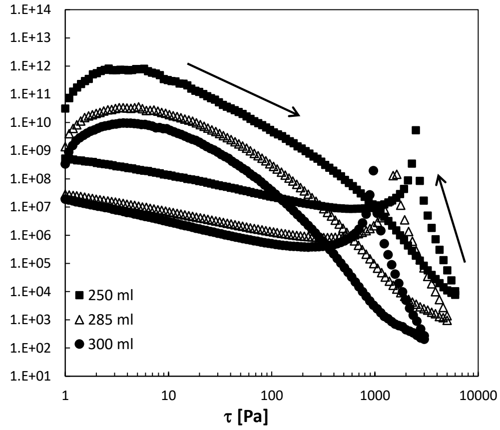

Figure 6: 1st Normal Stress Coefficient for various compositions of bread dough.

First normal stress coefficient from the Lodge-Meissner relation was obtained from the flow tests and their dependence on shear stress is presented in Fig. 5, while the dependence of 1st Normal Stress Coefficient on shear stress is presented in Fig. 6.

In general higher normal forces indicate higher elasticity of a material, which could be also seen from the results. Lower amount of water resulted in more elastic and solid-like structure with higher values of normal forces.

CONCLUSIONS

The results showed that the structure of the dough considerably changes with the addition of water. Higher amounts of water decreased the consistency (dynamic moduli, viscosity) and normal forces of the dough indicating the reduction of dough's firmness and elasticity leading to lower energy required for successful kneading in the kitchen machine. However, the study showed that choosing the proper rheological instrument and method for measurements of rheological properties is essential in order to predict the behaviour of the dough inside kitchen machine.

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REFERENCES

1. Mirsaeedghazi, H., Emam-Djomeh Z., Ali Mousavi S.M. (2008), "Rheometric measurement of dough rheological characteristics and factors affecting it", *Int. J. Agri. Biol.*, **10**, 112-119.
2. Amjid M.R., Shehzad A., Hussain S., Shabbir M.A., Khan M.R., Shoaib M. (2013), "A comprehensive review on wheat flour dough rheology", *Pakistan J. Food Sci.*, **23**, 105-123.
3. Hosseinalipour S.M., Tohidi A., Shokrpour M. (2012), "a review of dough rheological models used in numerical applications", *JCARME*, **1**, 129-147.
4. Belton, P.S. (2003), "The molecular basis of dough rheology", in: Breadmaking improving quality, Woodhead Publishing, Cambridge, UK. pp. 273-287.
5. Bohlin, L. (1980), "A theory of flow as a cooperative phenomenon", *J. Colloid Interface Sci.*, **74**, 423-434.
6. Berland, S. and Launay, B. (1995), "Rheological properties of wheat flour

doughs in steady and dynamic shear: effect of water content and some additives", *Cereal Chem.*, **72**, 48–52.

7. Phan-Thien, N., Newberry, M., Tanner, R.I. (2000), "Non-linear oscillatory flow of a soft solid-like viscoelastic material", *J. Non-Newtonian Fluid Mech.*, **92**, 67–80.

8. Tanner, R.I., Qi, F., Dai, S. (2008), "Bread dough rheology and recoil. I. Rheology", *J. Non-Newtonian Fluid Mech.*, **148**, 33–40.

9. Uthayakumaran, S., Newberry, M., Phan-Thien, N., Tanner, R. (2002), "Small and large strain rheology of wheat gluten", *Rheol. Acta*, **41**, 162–172.

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

11. Ross-Murphy, S.B. (1995), "Structure–properties relationships in food biopolymer gels and solutions", *J. Rheol.*, **39**, 1451–1463.

12. Ferry, J.D. (1980), "Viscoelastic Properties of Polymer", 3rd ed. Wiley, New York.

13. Gabriele, D., de Bruno, C., D'Antona, P. (2001), "A weak gel model for foods", *Rheol. Acta*, **40**, 120–127.

14. Kokini, J.L., Cocero, A.M., Madeka, H., de Graaf, E. (1994), "The development of state diagrams for cereal proteins", *Trends in Food Sci. Tech.*, **5**, 281–288.

15. Autio, K., Flander, L., Kinnunen, A., Heinonen, R. (2001), "Bread quality relationship with rheological measurements of wheat flour dough", *Cereal Chem.*, **78**, 654–657.

16. Dreese, P.C., Faubion, J.M., Hoseney, R.C. (1988), "The effect of different heating and washing procedures on the dynamic rheological properties of wheat gluten", *Cereal Food World*, **33**, 225–228.

17. Hibberd, G.E. (1970), "Dynamic viscoelastic behaviour of wheat flour dough. Part II: Effect of water content in linear region", *Rheol. Acta*, **9**, 497–500.

18. Lètang, C., Piau, M., Verdier, C. (1999), "Characterization of wheat flour-water doughs. Part I: Rheometry and microstructure", *J. Food Eng.*, **41**, 121–132.

19. Mani, Z., Trägårdh, E., Lindahl, Z. (1992), "Water content, water soluble fraction, and mixing affect fundamental rheological properties of wheat flour doughs", *J. Food Sci.*, **57**, 1198–1200.

20. Farahnaky, A. and Hill, S.E. (2007), "The effect of salt, water and temperature on wheat dough rheology", *J. Texture Studies*, **38**, 499–510.