The pattern of the linear viscoelastic behaviour of wheat flour dough as delineated from the effects of water content and high molecular weight glutenin subunits composition

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Abstract

Dynamic measurements and retardation tests were combined to characterise the linear viscoelastic behaviour of wheat flour dough in the 10^{-5}–10^2 rad/s frequency range. Analysis of the data provided the Newtonian steady-state viscosity, the steady-state compliance, the terminal relaxation time, the viscoelastic plateau compliance and a measure of the upper frequency limit of the viscoelastic plateau. The influence of dough water content and composition of high molecular weight glutenin subunits on dough viscoelasticity was studied. Both factors affected dough viscoelasticity in a similar and remarkable way. In particular, the same inverse relationship between steady-state viscosity and compliance, and the same power law relationship between steady-state and plateau compliances, was found to hold whether the variability was due to high molecular weight glutenin subunits or to dough water content.
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1. Introduction

Mixing is a key step in baking technology; it is common experience that the behaviour of dough during mixing and its final mechanical properties determine, to a large extent, the quality of the end product. Recording small-scale mixers are used to evaluate flour mixing characteristics and dough consistency; much effort has been devoted to the analysis of dough development curves and to correlation of the parameters extracted from these curves with flour composition and dough formulation, on one hand, and to the behaviour of dough during processing and to the quality of the final product, on the other. It is generally accepted that mixing characteristics—recorded as the torque versus time curves by small-scale mixers—are strongly related to dough rheological properties (Dobraszczyk and Morgenstern, 2003). However, many aspects of this relationship remain unclear because the rheological behaviour of dough, and how it is affected by extrinsic and intrinsic factors, are far from understood. In particular, water absorption, protein content, and protein 'quality' have a very strong influence on dough mixing properties and on its final consistency; but the available information about the rheological bases of these effects, which would help understanding the under-lying structural mechanisms, remains fragmented and, sometimes, conflicting.

It is often and rightly stressed that dough mixing involves large deformations, far beyond the linearity limit, and consequently that dough mixing characteristics or product quality descriptors should be correlated with non-linear rheological parameters rather than with linear rheological properties (see for example: Dobraszczyk

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Abbreviations: db, on dry basis; G_N^o, viscoelastic plateau modulus (Pa); HMW-GS, high molecular weight glutenin subunits; $J(t)$, compliance function (m^2/N); $J_r(t)$, recoverable compliance function (m^2/N); $J'(\omega)$, storage compliance function (m^2/N); $J''(\omega)$, loss compliance function (m^2/N); $J_r''(\omega)$, recoverable loss compliance function (m^2/N); J_e^o, steady-state linear compliance (m^2/N); J_N^o, viscoelastic plateau compliance (m^2/N); n_1, Cole–Cole exponent relative to the "fast" retardation loss peak; η_o, Newtonian steady flow viscosity (Pa s); $(\tau_m)_o$, terminal relaxation time (s); ω, angular frequency (rad/s); ω_1, central frequency of the high-frequency loss compliance peak (rad/s)

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et al., 2003; Safar-Ardi and Phan-Thien, 1998; Sliwinski et al., 2004). However, the non-linear viscoelastic behaviour of dough in shear is very poorly documented. Stress relaxation, retardation, or stress growth studies in the non-linear domain are quite limited, and are also usually performed at one value of shear strain, shear stress or shear rate, often arbitrarily chosen, whereas characterisation of non-linear viscoelasticity requires a scan of a large range of values of the control variables. In fact, most of the literature on the non-linear rheological properties of dough concerns extensional deformations, but again at single values of the control variables. Emphasis on extensional deformations is justified since during mixing, as well as in later stages of processing, dough is not only subjected to large shear deformations, but uni- and biaxial extensional deformations clearly also play an important role (see for example: Dobraszczyk and Morgenstern, 2003; Janssen et al., 1996; Kokelaar et al., 1996; Sliwinski et al., 2004; Wikström and Bohlin, 1999; Zheng et al., 2000). Nevertheless, characterising non-linear viscoelastic behaviour is still more difficult in extensional deformations than in shear, even with materials which lend themselves more readily than dough to this type of experimentation.

Most of the information available about the effect of water content on dough viscoelastic behaviour in shear is based on dynamic testing, and consequently it essentially reflects the linear viscoelastic response. As expected, the storage and loss moduli, G' and G'', respectively, decrease as dough water content increases. Various studies show that the magnitude of the effect is indeed large (Mani et al., 1992; Navickis et al., 1982; Smith et al., 1970; Zheng et al., 2000) and seems to depend somewhat on flour composition. Smith et al. (1970) observed that the sensitivity of G' and G'' to water content decreased as flour protein content increased, and that it also depended on other factors. Navickis et al. (1982) came to the same conclusions. Hibberd (1970) studied the influence of water content (43–47%) on the linear viscoelastic behaviour of doughs from different wheat varieties in the 0.2–20 rad/s frequency range; he observed that the effect of hydration on G' and G'' is identical, and that the effects of frequency, water content, and variety can be separated. However, more recent results seem to indicate that dough linear behaviour does not comply strictly with this 'principle'. On the one hand, the amplitude of the effect of moisture content on G' was found to be different at $\omega < \sim 5$ rad/s from that observed at higher frequencies, where the 'principle' was verified (Masi et al., 1998). On the other hand, Georgo-poulos et al. (2004) observed that a master curve could be obtained by shifting G' data, recorded in the 0.63–63 rad/s frequency range for different dough water contents, on the frequency axis, but that superposition did not work well for G'' data, whereas the 'principle' implies that it should, and that the shift factors should be the same for both components of the complex modulus (Hibberd, 1970). The results of both studies indicate that dough hydration does not affect slow and fast relaxation mechanisms to the

same extent or in the same way. However, for practical and instrumental reasons the experimentally accessible frequency window of dynamic measurements in shear is in the 10^{-2}–100 rad/s range, i.e. not exceeding four logarithmic decades. 'Mechanical spectra' of dough show that this frequency window of dynamic measurements (corresponding to a $0.01 < t = 1/\omega < 100$ s time scale) encompasses only a section of the viscoelastic plateau. Therefore, the effect of hydration, as well as other factors, on slow relaxation mechanisms in dough cannot be assessed by dynamic measurements, so that transient tests (creep and recovery, stress relaxation), which extend the observation window to very long times, must be employed. In the linear domain, dynamic measurements and transient tests contain, in principle, the same information, but they are actually complementary, since the short-time behaviour is in practice inaccessible to transient tests and the long-time behaviour to dynamic measurements. Phan-Thien and Safar-Ardi (1998) have used stress relaxation experiments and dynamic measurements, in parallel, to study the effect of water content on dough linear viscoelasticity. However, the time scale of relaxation measurements was limited to 1000 s, extending the window of dynamic measurements by only one decade, so that little additional information was actually gained. The effects of water content in the 36.5–42.5% range on the relaxation spectra were quite small, especially above 38.5% water content; nevertheless, differences in the shape of the relaxation spectra were observed in the 10–1000 s time range, showing that relaxation increased with hydration. This appears to be in agreement with the observations of Masi et al. (1998).

Linear viscoelasticity measurements in shear have been concurrently performed to compare doughs prepared from commercial flours or wheat cultivars (or experimental lines) with different 'strengths', protein contents and compositions. As a rule, the 'mechanical spectra' show very similar shapes and the moduli values only small differences (see for example: Keentok et al., 2002; Larsson et al., 2000; Pedersen et al., 2004; Safar-Ardi and Phan-Thien, 1998), although for some varieties these differences have been reported to be larger (Rao et al., 2000, 2001). Linear stress relaxation behaviours in the 0.1–1000 s time window also appear to be very close (Safar-Ardi and Phan-Thien, 1998). The only comparative study performed in the linear range over a time scale long enough for the steady-state to be reached, using the retardation test (creep and recovery) (Edwards et al., 2001), showed that the ranges of variation of the steady-state Newtonian viscosity and of the linear steady-state compliance of doughs of different strengths were in fact limited. In most studies different doughs are compared at the same Farinograph consistency but not at the same water content, and this could result in restricting their rheological variability to some extent; nevertheless, the impression is, for dough, in contrast to gluten, that varietal or 'strength' effects on linear viscoelasticity are not large. Although they are less important than those of hydration, there is certainly a complex interplay between