Contributions of the Main Flour Constituents to Dough Rheology, and Implications for Dough Quality and its Assessment

M. Meerts*, R. Cardinaels**, F. Oosterlinck***, C. M. Courtin* and P. Moldenaers*

* KU Leuven, Leuven, Belgium, mathieu.meerts@cit.kuleuven.be
** TU Eindhoven, Eindhoven, The Netherlands, r.m.cardinaels@tue.nl
*** DSM Ahead B.V., Geleen, The Netherlands, filip.oosterlinck@dsm.com

ABSTRACT

Despite extensive research, there is still no consensus in the literature about the roles of starch and gluten in both the linear and non-linear rheology of wheat flour dough. To elucidate the contributions of gluten and starch to the dough behavior, the rheological properties of dough and mixtures of different gluten-starch ratios were studied in shear (small amplitude oscillatory shear tests) and uniaxial extension. The breadmaking quality of a given wheat flour is mostly linked to the gluten network. In the linear region, starch has the potential to obscure differences between different gluten systems. Hence, only non-linear rheological tests are able to distinguish strong from weak flour dough. Changes in water content mostly affect the gluten-starch and starch-starch interactions, whereas the mixing time has a strong impact on the gluten network itself.

Keywords: dough rheology, gluten-starch mixtures, strain hardening, water content, mixing time

MATERIALS & METHODS

Two wheat flour types were used in this study: a strong flour (Bilux) and a weak flour (Bison). Both flours were obtained from Dossche Mills (Deinze, Belgium). The Bilux and Bison flour differed significantly in protein content (15.1% vs. 12.4% on a dry matter basis, AOACI method 990.03 [1]), which was also reflected in their breadmaking performance. Native wheat starch and wheat gluten were provided by Tereos Syral (Aalst, Belgium). Dough was prepared with the following formula (AACCI method 10-10.03 [2]): 10.0 g flour (on 14% moisture base), 1.5% (w/w) sodium chloride, 6% (w/w) sucrose and 58.0% resp. 54.4% (v/w) water for Bilux and Bison flour. The optimal water amount and mixing time were determined with the Farinograph (Brabender, Duisburg, Germany) and Mixograph (National Manufacturing, Lincoln, NE, USA) in line with the AACCI methods 54-40.02 and 54-21.02, respectively [2]. For the gluten, starch and gluten-starch mixtures, the amount of water required to obtain a cohesive and well-developed sample had to be determined by trial-and-error, and increased with gluten content. Except for the pure gluten and pure starch, all samples were prepared by mixing the ingredients in a 10 g pin bowl mixer (National Manufacturing) for 3 min 30 s. The pure gluten samples only required 3 min of mixing, whereas the pure starch samples had to be prepared by hand.

The oscillatory shear tests were performed on a stress-controlled MCR501 rheometer (Anton Paar, Graz, Austria), equipped with 40 mm parallel plates covered with sandpaper. The storage modulus G' and loss modulus G'' [Pa] at 25 °C were obtained as a function of strain amplitude γ_0 at fixed angular frequency ($\omega = 1$ rad/s).

Dough behavior in uniaxial extension was studied by means of an extensional viscosity fixture (EVF) installed on an ARES-G2 rotational rheometer (TA Instruments, New Castle, DE). The EVF fixture consists of two drums to which the dough strand is attached by means of clips. With this setup, extension at a constant rate is obtained as one drum remains stationary and the other moves in a circular orbit around it whilst also rotating on its own axis. The resistance against stretching was quantified in terms of the extensional viscosity $\eta_e(\epsilon)$.

1 CONTRIBUTIONS OF GLUTEN AND STARCH

1.1 Linear Behavior

The complex dough matrix mainly consists of a hydrated gluten network that is filled with starch granules. These starch particles play a pivotal role in the linear viscoelastic dough behavior, as is evident from Fig. 1. This figure provides the dynamic moduli G' and G'' for different gluten-starch mixtures as a function of strain amplitude. With increasing starch concentration, the linearity limit of the gluten-starch mixtures decreases substantially. Although the effect is partially masked by the differences in water content, the presence of starch also seems to lead to an increase in G' [3]. As far as its linear behavior is concerned, dough can be regarded as a concentrated dispersion of starch particles in a gluten protein matrix. The 10% gluten - 90% starch mixture, which closely resembles the composition of dough, indeed clearly exhibits this suspension-like behavior in the strain sweep, as the $G''(\gamma_0)$ curve shows a shallow maximum close to the linearity limit, reflecting the breakup of the particle network (Fig. 1). This local maximum in

$G''(\gamma_0)$ is also often observed in dough systems [4], but not for the dough types studied here.

In linear oscillatory mode the strong Bilux dough and the weak Bison dough both yield very similar values for G' and G'' (Fig. 1). Often the dynamic moduli are even slightly higher for weaker doughs than for stronger doughs [5], as strong doughs typically require more water to build up the gluten network, and this difference in water content can already be sufficient to mask the intrinsic differences in the gluten network between the different flour types. Linear oscillatory tests are thus unable to distinguish between strong and weak flour doughs.

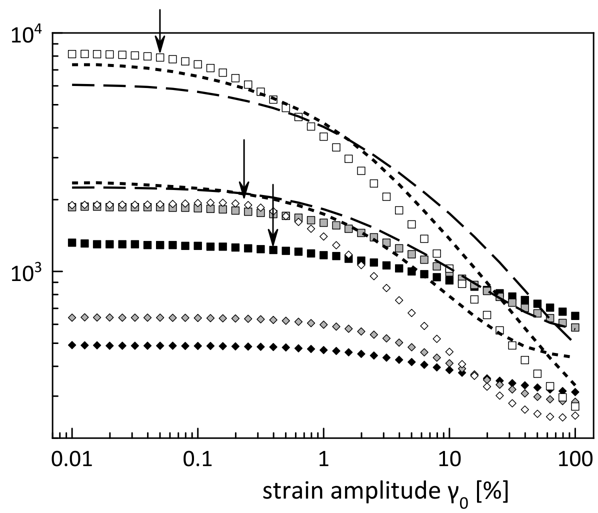

Figure 1: Dynamic moduli G' and G'' versus strain amplitude γ_0 at $\omega = 1$ rad/s for gluten-starch mixtures of ratio 75% - 25% (*black*), 50% - 50% (*grey*) and 10% - 90% (*white*). The dashed and dotted lines indicate the strain-dependency of the dynamic moduli for strong Bilux dough and weak Bison dough, resp. Arrows indicate the linearity limits.

1.2 Non-linear Behavior

The linear oscillatory tests discussed above indicated that at very small strains, the dough response is determined by the starch-starch and gluten-starch interactions (i.e. the short-range interactions). Under these conditions the gluten-gluten interactions only seem to be of minor importance [5]. The practical relevance of the linear oscillatory tests is however limited as the applied deformation does not correspond to the type of deformations dough encounters in the breadmaking process. During mixing, fermentation and oven rise, dough will mostly experience large-strain, extensional deformations, rather than small-strain, shear flows. It is therefore imperative to also study dough behavior under extension. The results of the uniaxial extensional tests on strong Bilux dough, weak Bison dough and gluten are shown in Fig. 2. It is clear from this figure that under large extensional deformation dough behaves similarly to the gluten proteins [6]. Indeed, upon increasing the strain the short-range gluten-starch and starch-starch interactions in dough will start to break down, to such an extent that eventually only the longer-range gluten-gluten interactions remain to provide structural integrity to the material [5]. At sufficiently large strains, both dough and gluten exhibit strain-hardening, i.e. the more these samples are stretched, the higher the resistance they will provide against further stretching. We quantified the degree of strain-hardening by means of a strain-hardening index (SHI) that takes the ratio of the maximum viscosity $\eta_e^{\max}$ (at $\epsilon = 2.7$) to the extrapolation of the linear viscosity η_e^{ref} at smaller strains (Fig. 2). The breadmaking qualities of wheat flour are

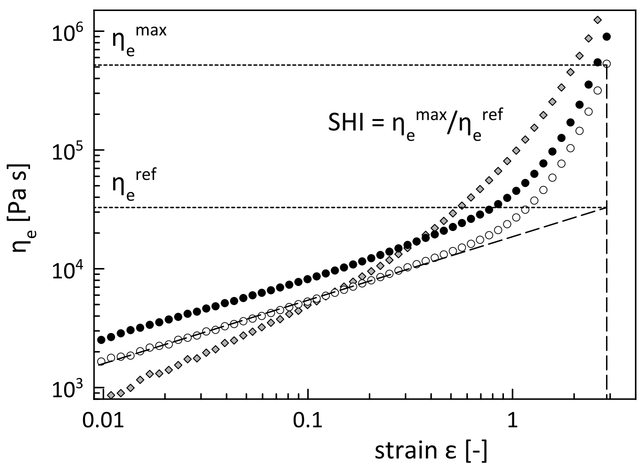

Figure 2: Extensional behavior of strong Bilux dough (*black*) and weak Bison dough (*white*), compared to that of gluten (*grey*) for $\dot{\epsilon} = 0.1$ s^{-1}.

	0.01 s^{-1}	0.1 s^{-1}	1 s^{-1}
Bilux	7.3	10.1	8.8
Bison	5.4	7.5	7.0

Table 1: Values of the strain-hardening index for the strong Bilux dough and the weak Bison dough in uniaxial extension for different extension rates.

known to be intrinsically linked to the gluten network. As only rheological tests that involve large deformations can be expected to probe adequately the response of the gluten network, only these non-linear tests will be able to assess the breadmaking potential of a given wheat flour. It is clear from Fig. 2 that extensional tests can

TechConnect Briefs 2016, TechConnect.org, ISBN 978-0-9975-1172-7

indeed be used to distinguish strong from weak flour dough. At first sight, the two dough systems seem to behave rather similarly, but their absolute viscosities are in fact quite different ($\eta_e^{max} = 9.9 \times 10^5$ and 5.3×10^5 Pa s, respectively). The difference between the two flour types is also clearly reflected in the strain-hardening index (Table 1): the SHI values for the strong dough are systematically higher than those for the weak dough. The SHI has already been acknowledged as a promising tool to predict the breadmaking performance of a given wheat flour [7].

2 IMPACT OF PROCESS PARAMETERS

2.1 Water Content

The water content and mixing time are both important process parameters in dough making. Small changes in water content and mixing time are known to significantly alter the appearance, feeling, and breadmaking potential of dough.

Fig. 3 illustrates the impact of changes in water content on the extensional behavior of strong Bilux dough. The addition of water mainly results in a parallel, downward shift of the extensional viscosity curves at small strains. As the dough response at small strains is primarily determined by the starch granules, this indicates that water mostly affects the gluten-starch and starch-starch interactions. By contrast, at large strains the viscosity curves are much less affected. Clearly, the starch component is more sensitive to changes in water content than the gluten network [8]. This finding also explains the enhanced sensitivity of weak Bison dough (which has a lower amount of proteins) to water content in comparison to the strong Bilux dough (results not shown). For both flour types the SHI values tend to become larger as the water content is increased (cf. Table 2, results for Bilux dough). Since the addition of water typically results in a better loaf quality [9], the SHI again seems to provide a reliable measure of the breadmaking performance.

The water content also has a strong impact on the values of the dynamic moduli for dough. Small additions of water already lead to a substantial and parallel decrease in the dynamic moduli [10]. Hibberd [11] suggested that the water dependency of the dynamic moduli can be captured by a simple scaling law:

$$G'(\omega, W) = G'(\omega, W_0) \cdot Q(W - W_0) \quad (1)$$

$$G''(\omega, W) = G''(\omega, W_0) \cdot Q(W - W_0) \quad (2)$$

We established that exactly the same scaling law can be used to capture the water dependency of the extensional viscosity at small strains (see also the inset in Fig. 3):

$$\eta_e(\epsilon, W) = \eta_e(\epsilon, W_0) \cdot Q_e(W - W_0) \quad (3)$$

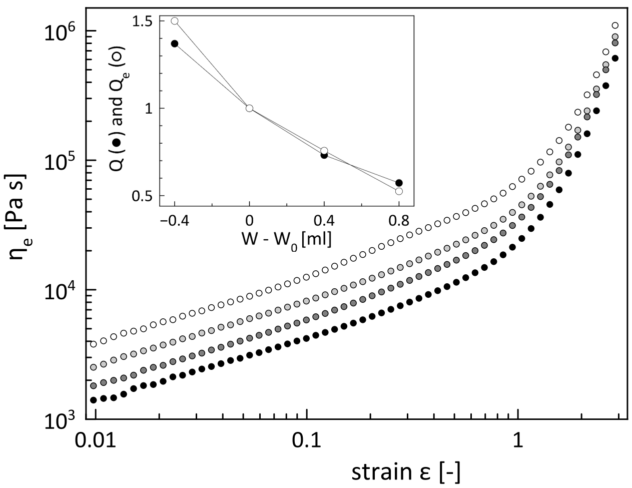

Figure 3: Impact of water content on the extensional behavior of strong Bilux dough at $\dot{\epsilon} = 0.1$ s^{-1}. The following water levels have been used: 5.4 ml (*white*), 5.8 ml (optimal level W_0, *light grey*), 6.2 ml (*dark grey*) and 6.6 ml (*black*).

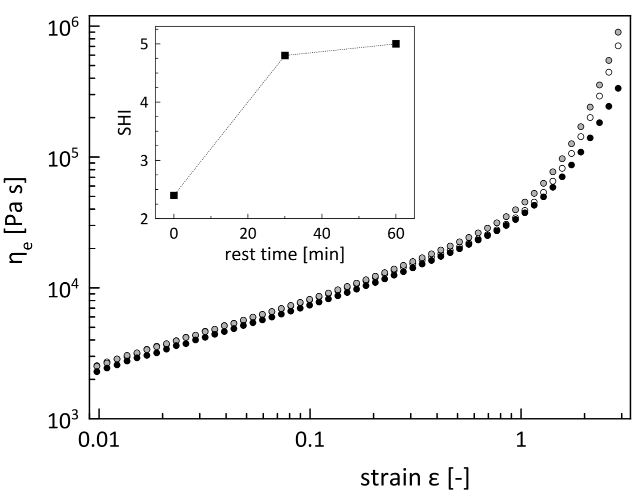

Figure 4: Impact of mixing time on the extensional behavior of strong Bilux dough at $\dot{\epsilon} = 0.1$ s^{-1}. Dough samples were mixed for 1 min (*white*), 3.5 min (optimal mixing time, *grey*) and 15 min (*black*). Inset shows the time evolution in the SHI after 15 min of mixing.

2.2 Mixing Time

In the mixing step, wheat flour dough is developed into a three-dimensional viscoelastic structure with gas-retaining properties. Fig. 4 depicts the extensional behavior of strong Bilux dough prepared with three different mixing times. It is obvious that the mixing time affects the dough structure in a different way than the water content, as the baseline does not change position significantly. Instead, the effect of mixing time is seen most clearly in the final part of the viscosity curves. Since the dough behavior at large strains is determined primarily by the gluten network, this observation indicates that the gluten network is much more affected by the mixing than the starch granules. This can also explain why we found the effect of mixing time on the G' and G'' curves to be surprisingly limited: the values of the dynamic moduli only decreased very slightly with increasing mixing time (results not shown). Under- and overmixing are both known to be detrimental to loaf quality [12], and this trend is also clearly reflected in the strain-hardening index (Table 2). The SHI values indeed show a maximum at or at least nearby the so-called optimal mixing time that was determined with the Mixograph. For shorter mixing times, the gluten network has not yet been formed completely, while for longer mixing times the gluten proteins experience partial disaggregation/depolymerization, which results in an attenuation of the strain-hardening phenomenon.

Yet this loss of network strength appears to be, to some extent at least, reversible. During the resting period after mixing, Weegels and coworkers [13] noted a steady increase in the amount of glutenin macropolymer, but even after 1.5 - 2 hours, this recovery was still far from complete. This self-healing ability of dough is also evident when we compare the SHI values obtained after 15 min of mixing but with different rest times (cf. inset in Fig. 4). Immediately after 15 min of mixing, the SHI value is only 2.4, but this value increases again if the dough is allowed to recover for some time. After 30 min the SHI value seems to have reached a plateau (4.8 - 5.0), that is, however, still well below the maximum SHI value (10.1) corresponding to a mixing time of 3.5 min. With extensional tests it is thus possible to track the recovery of the gluten network, but in line with the compositional data [13], we also observe that in the end this recovery cannot undo all the damage caused by overmixing.

	1 min	3.5 min	15 min
5.4 ml		8.9	
5.8 ml	7.9	10.1	4.8
6.2 ml		12.4	
6.6 ml		14.6	

Table 2: Values of the strain-hardening index for strong Bilux dough prepared with different water contents and mixing times. Extension rate $\dot{\epsilon} = 0.1$ s^{-1}.

CONCLUSION

It has already been established a long time ago that the behavior of dough closely resembles that of the gluten network. However, for small deformations, the starch granules also play a pivotal role in the dough response, to such an extent that the presence of starch may even mask differences in gluten content and quality. Consequently, in order to assert the breadmaking performance of a given flour, it is imperative to study dough behavior under large deformations by means of non-linear rheological tests. Uniaxial extensional tests are able to distinguish clearly between strong and weak flour doughs, and the strain-hardening index turned out to be a reliable predictor of flour quality.

The viscoelastic properties of dough are very sensitive to changes in water content and mixing time. Water mainly acts as a lubricant, affecting mostly the gluten-starch and starch-starch interactions. By contrast, the mixing time has a direct impact on the gluten network itself. Overmixing may lead to a disaggregation or depolymerization of the gluten proteins. This loss of network integrity was found to be reversible, but typically the recovery is rather slow and only partial. The strain-hardening index reaches a maximum value for mixing times close to the so-called optimal mixing time that is typically determined with the Mixograph.

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