Rheological properties of wheat flour doughs

IV. Creep and creep recovery in simple tension

By T. L. Smith and N. W. Tschoegl

With 6 figures and 1 table

Introduction

Tschoegl et al. (1) recently reported the results from a study of the large deformation and rupture properties of wheat flour doughs in simple tension. The doughs were mixed from a medium strength Kansas flour and a weak Lemhi flour. Oval-shaped dough rings were stretched at constant extension rates, immersed in a liquid of matching density to prevent the rings from sagging under their own weight. In these experiments, the true stress (the force per unit deformed area) always increased progressively until rupture occurred; hence, a state of steady flow did not develop. At each test temperature, the time dependence of the constant strain rate modulus, $F(t)$, could be expressed by:

$$F(t) = F(t^*) (t/t^*)^n$$  \[1\]

when $t$ and $t^*$ are the variable and fixed (isochronal) time, and $n$ is a characteristic exponent, not dependent on either temperature or water content, over the ranges of experimental conditions employed. For the Kansas and Lemhi doughs, $n = -0.29$ and $-0.40$, respectively. Also, data obtained on a reconstituted wet gluten (2) gave $n = -0.17$. (A zero exponent would signify that the response is purely elastic; and an exponent of $-1$ that the response is steady-state viscous flow.) From these findings, it was concluded that, over the time period covered by the tests, the response shown by the doughs from both flours, and even more so by the gluten, was predominantly delayed elastic. However, the data did not preclude the simultaneous occurrence of viscous flow.

The experimental results reported previously (1) did not show unambiguously whether dough has an equilibrium modulus and, hence, whether dough can be regarded as a crosslinked material. If a three-dimensional network exists, resulting from chemical crosslinks among polymeric chains, then the steady-state viscosity is infinite and the terminal compliance is the equilibrium (elastic) compliance. In certain crosslinked materials, however, the chemical linkages are labile; creep and creep recovery result from the breaking, or breaking and reforming, of chemical bonds. The observed creep behavior may be similar phenomenologically to that shown by materials in which the chemical bonds are stable. In general, however, creep and creep recovery data cannot be interrelated quantitatively as is possible for data obtained on chemically stable polymeric materials in the range of linear viscoelastic behavior. The study of creep and creep recovery described in this paper was made to obtain additional information on dough structure. Similar experimental studies have been made in the past by Schofield and Scott-Blair (3), Glucklich and Shelef (4), and Bloksma (5). Their data, however, do not provide answers to certain key questions.

Specific purposes of this study were (1) to determine the steady-state viscosity and steady-state compliance from both creep and recovery data; and (2) to ascertain whether dough behaves like a linear viscoelastic material at relatively large tensile strains, e. g. up to 10–20%.

Discussion of creep and creep recovery

Creep and creep recovery data provide considerable information about material properties, especially if the deformations during a test remain sufficiently small so that the behavior is linear viscoelastic. Such data normally show clearly whether the material is uncrosslinked and thus whether viscous
flow occurs under stress. If a creep test on an uncrosslinked material is continued until the strain increases linearly with time, the data provide not only the creep compliance but also the steady-state viscosity and the so-called steady-state compliance, a measure of the elastic energy stored under steady flow conditions. From such information, the recovery which follows removal of the stress can be derived. If the derived data agree with those found experimentally, it can be assumed that the material, under the particular conditions of the test, shows linear viscoelastic behavior. Equivalently, recovery data obtained following the establishment of steady-state creep give the steady-state compliance and the steady-state viscosity, in addition to the creep compliance.

For a crosslinked material, steady-state flow (reflecting the progressive development of a permanent deformation) is not observed; following removal of the stress, complete recovery is obtained. Creep data on such a material give the equilibrium compliance, in addition to the creep compliance. The parameters that represent creep and recovery data are independent of the stress if the behavior is linear viscoelastic; hence, tests should be made using several values of the stress to determine whether or not the response is linear.

To provide the necessary background for the subsequent discussion, the behavior of a linear viscoelastic material in creep and in creep recovery will be reviewed.

Consider that a tensile stress \( \sigma \), which is sufficiently small so that the response is linear viscoelastic, is applied at zero time to an uncrosslinked polymer and that thereafter the stress remains constant. The resulting deformation (fig. 1) consists of a delayed elastic strain \( \varepsilon_d(t) \) and a nonrecoverable "strain" \( \varepsilon_v(t) \), both strains being functions of the time \( t \). The total strain \( \varepsilon_T(t) \) is given by:

\[
\varepsilon_T(t) = \varepsilon_d(t) + \varepsilon_v(t) = \varepsilon_d(t) + \frac{\sigma}{\eta},
\]

[2]

where \( \varepsilon_v(t) = \frac{\sigma}{\eta} \), \( \eta \) being the (steady-state) Newtonian viscosity in tension. If both sides of eq. [2] are divided by \( \sigma \), we obtain:

\[
D(t) = D_d(t) + \frac{t}{\eta},
\]

[3]

where \( D(t) \) is the tensile creep compliance and \( D_d(t) \) is the delayed compliance. After a sufficiently long time, \( \varepsilon_d(t) \) becomes constant; its constant value is here designated by \( \varepsilon_{ds} \). Likewise, \( D_d(t) \) attains a constant value, called the steady-state compliance \( D_s \).

Now consider that the stress is removed at time \( t_1 \) when the total strain is \( \varepsilon_T(t_1) = \varepsilon_m \). Following removal of the stress, elastic recovery occurs and the following relation applies:

\[
\varepsilon_m - \varepsilon_T(t) = \varepsilon_d(t - t_1) \quad \text{for} \quad t > t_1.
\]

[4]

That is, if a material shows linear viscoelastic response, a plot of \( \varepsilon_d(t) \) vs. \( t \), from creep data, will give the same curve as a plot of \( \varepsilon_m - \varepsilon_T(t) \) vs. \( t - t_1 \), from recovery data. Also, the time required for complete elastic recovery equals that required to establish steady-state flow. The total elastic recovery \( \varepsilon_r \) is given by \( \varepsilon_r = \varepsilon_m - \varepsilon_T(\infty) \), where \( \varepsilon_T(\infty) \) is the total deformation (permanent "strain") after the recovery has stopped. Although \( \varepsilon_r \) theoretically equals \( \varepsilon_{ds} \), the two symbols will be used to indicate whether the elastic recoverable strain was obtained from creep or from recovery data.

The viscosity can be obtained from the slope of the linear portion of a plot of \( \varepsilon_T \) vs. \( t \), given by the creep data. It can also be obtained from the permanent deformation following elastic recovery. The applicable equations are given in fig. 1.

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1) Strictly speaking, the term strain refers to a recoverable elastic deformation. In certain instances, however, it is convenient to speak of a nonrecoverable strain \( \varepsilon_v(t) \), which represents the permanent deformation resulting from flow, and also of the total strain \( \varepsilon_T(t) \), which represents the total deformation. In many discussions of creep, a third term to represent the so-called instantaneous elastic response is included on the right side of eq. [2]. However, such a term is needed only when the creep of rigid materials is being considered. For dough, the instantaneous response is completely overshadowed by the delayed elastic and viscous flow terms.