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Another word on the rheology of silicone putty: Bingham

JOHN M. DIXON and JOHN M. SUMMERS

Experimental Tectonics Laboratory, Department of Geological Sciences, Queen's University, Kingston, Ontario K7L 3N6, Canada

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Abstract—Silicone putty, a material commonly used as a rock-analog in tectonic scale-model studies, exhibits rheological behavior that is similar to the Bingham rheological model over a wide range of strain rate. Nevertheless, at low strain rates a power law is a useful approximation. Similarly, at high strain rates a linear viscous model can be applied. Thus, the choice of rheologic expression can be based on knowledge of the range of stress levels that are achieved in a given model. Conversely, models can be designed to develop appropriate stress levels so that the rheological formulation appropriate to the relevant prototype material will be applicable.

INTRODUCTION

SILICONE putty is commonly used as a rock-analog material in experimental model studies. In a recent paper (Dixon & Summers 1985) we reported the results of a preliminary series of rheological tests on the particular grade of silicone putty (Dow Corning Dilatant Compound 3179) that we have been using in our centrifuge model studies of various tectonic phenomena (Dixon & Summers 1983, 1985, Dixon 1984). This material exhibits complex flow behavior which we described as varying from approximately power-law flow with a high stress exponent at low strain rates to approximately linear (Newtonian viscous) at high strain rates, and an effective yield strength of a few hundred Pascals (Pa). In our original analysis of the test data (Dixon & Summers 1985, Appendix 2) we did not recognize that the flow behavior of the silicone putty can be characterized as approximating that of a Bingham substance, as we will demonstrate in this note.

TEST DATA

We performed constant-load creep tests on our silicone putty at 18, 22 and 26°C, using a cylindrical, annular test rig. The results of these tests are illustrated graphically in Fig. 1, which shows, in logarithmic form, the relationship between shear stress (τ) and shear strain rate ($\dot{\gamma}$) measured at 20% shear strain. See Dixon & Summers (1985) for a complete description of the test rig and the method of data analysis.

On such a plot, Newtonian viscous behavior,

$$\dot{\gamma} = \tau/\mu_N \tag{1}$$

or

$$\log \dot{\gamma} = \log \tau - \log \mu_N \tag{2}$$

where μ_N = coefficient of Newtonian viscosity, would be represented by a line with unit slope, whereas power-law (pseudoplastic) behavior, with stress exponent n,

$$\dot{\gamma} = A\ \tau^n \tag{3}$$

or

$$\log \dot{\gamma} = n \log \tau + \log A, \tag{4}$$

where A is a constant of proportionality, would be represented by a straight line with slope $1/n$.

The rheologic behavior of the silicone putty (Fig. 1) can be approximated as power-law flow with n equal to 7 ± 2 at strain rates between 10^{-4} and 10^{-2} s^{-1}, and as approaching linear behavior, corresponding to a viscosity of about 1.8 × 10^{-4} Pa s at 18°C, at strain rates above 10^0 s^{-1}. We have discussed elsewhere (Dixon & Summers 1985) the extrapolations beyond the range of strain rates covered by the tests. We will repeat these arguments very briefly here. The linear behavior at high strain rates is interpolated between our measured data and our observation that the silicone putty exhibits the same ductility as Plasticine at a strain rate, admittedly difficult to estimate, of 10^0–10^1 s^{-1}, under which conditions a laminate of Plasticine and our silicone putty can be rolled without boudinage of either component. (This crude interpolation has been confirmed by Weijermars (in press), who determined log stress vs log strain rate

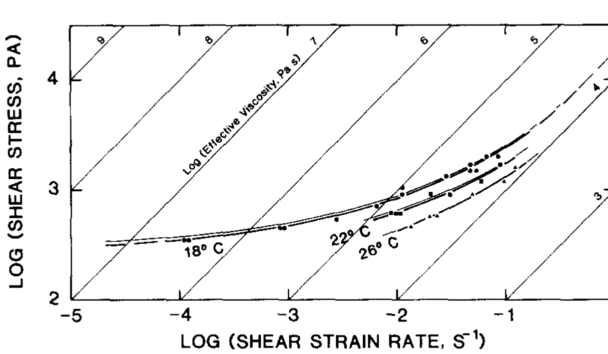

Fig. 1. Rheologic test results for silicone putty (Dow-Corning Dilatant Compound 3179) obtained at 18 ± 1°C (circles), 22 ± 1°C (squares) and 26 ± 1°C (triangles). Heavy curves were fitted by eye to the data at each temperature. Light curves are adjusted to take account of radial stress gradient in the test apparatus, and represent the variation of local shear strain rate with shear stress at the radial mid-point of the test annulus. From Dixon & Summers (1985).

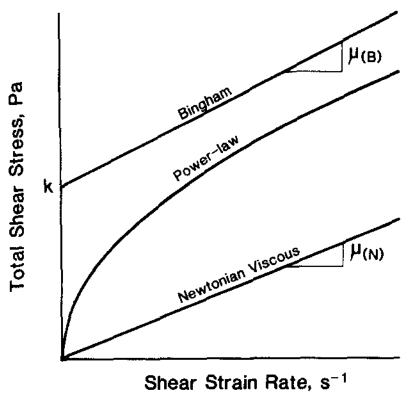

Fig. 2. Relations between shear strain rate and shear stress for Newtonian viscous (eqn 1), power-law (eqn 3) and Bingham (eqn 5) flow laws. k, shear strength; μ_N, Newtonian viscosity; μ_B, Bingham viscosity. After Johnson & Pollard (1973).

curves for a wide range of silicone putties, using four types of extrusion viscometer, and found that all exhibit linear behavior at strain rates above about 10^0 s^{-1}.) The 18° curve (Fig. 1) appears to decrease in slope towards lower strain rates (corresponding to an increase in stress exponent, n), and we found that a shear stress of 300 Pa produced no detectable strain, even over a period of weeks (corresponding to a strain rate lower than 10^{-7} s^{-1}). On this basis we suggested that the material has an effective yield strength of approximately 300 Pa at 18°C.

Clearly, neither the linear nor the power-law relationship matches the behavior of our silicone putty over the whole range of strain rate. However, the form of the curves can be represented by another relatively simple rheological model, the Bingham material.

THE BINGHAM MODEL

Johnson & Pollard (1973) have discussed the properties of the linear viscous (Newtonian), power-law (pseudoplastic) and Bingham rheological models, with reference to the rheological behavior of various types of magma. A Bingham material exhibits a yield strength as well as a viscous resistance to flow at stresses exceeding the yield strength. Thus

$$\tau = k + \mu_B \dot{\gamma} \quad \text{for } \tau > k, \tag{5}$$

where k is the yield strength and μ_B is the Bingham coefficient of viscosity. An ideal Bingham substance does not deform unless the applied shear stress exceeds its shear strength. As shear stress is increased above the shear strength, the shear strain rate increases in direct proportion to the excess of the shear stress over the shear strength. The stress-strain rate relations (eqns 1, 3 and 5) of these ideal fluids are represented graphically in Fig. 2. The Bingham flow law is generally represented in this linear space rather than in the log–log space of Fig. 1.

Equation (5) can be rearranged for plotting in log–log space

$$\log(\tau - k) = \log \dot{\gamma} + \log \mu_B. \tag{6}$$

This equation defines a straight line of unit slope in

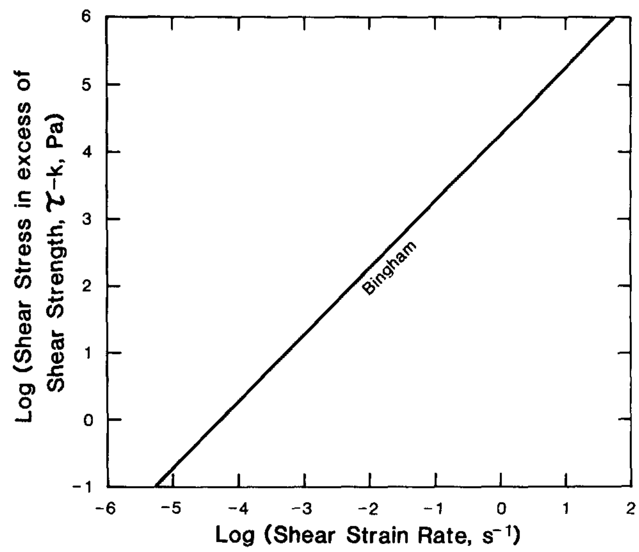

Fig. 3. The Bingham flow law (eqn 6) plotted in $\log(\tau - k)$ vs $\log \dot{\gamma}$ space, assuming shear strength k = 325 Pa and Bingham viscosity $\mu_B = 1.82 \times 10^4$ Pa s^{-1} (see text and Table 1, columns 1 and 5).

$\log(\tau - k)$ vs $\log \dot{\gamma}$ space (Fig. 3). We can rearrange it so that it can be plotted in the $\log \tau$ vs $\log \dot{\gamma}$ space of Fig. 1, if we can estimate values for k and μ_B. The data for silicone putty tend towards linear behavior, corresponding to a viscosity of 1.82×10^4 Pa s, at the high-strain-rate end of the data set, and suggest an effective yield strength of 325 Pa at the low-strain-rate end (Fig. 1). We can use these values to derive ordered pairs (τ, $\dot{\gamma}$) and hence ordered pairs ($\log \tau$, $\log \dot{\gamma}$), as listed in Table 1. The corresponding Bingham curve, plotted as a solid curve in Fig. 4, is very similar to the experimentally determined silicone putty curve in Fig. 1 (dashed curve in Fig. 4). Thus we suggest that the Bingham model is a suitable description of the rheology of our silicone putty, over a wide range of stress-strain rate conditions. This is consistent with Ramberg's (1981, pp. 240–241) apparently contradictory observations that most silicone putties behave almost as Newtonian substances, yet some exhibit finite strength.

The reader may ask why we have gone to the trouble of replotting the Bingham model on the log vs log plot of Fig. 4, instead of plotting the silicone putty data on a linear plot of total shear stress vs shear strain rate (like Fig. 2). The reason is that the silicone putty data (and extrapolations) extend over five orders of magnitude of strain rate; the subtleties of the low end of this range would be lost on a linear plot.

Table 1. Calculation of $\log \tau$ and $\log \dot{\gamma}$ for Bingham flow law, assuming k = 325 Pa and $\mu_B = 1.82 \times 10^4$ Pa s ($\log \mu_B$ = 4.26)

$\log(\tau - k)$	$(\tau - k)$ Pa	τ Pa	$\log \tau$	$\dot{\gamma}$
−1.000	0.10	325.1	2.512	−5.26
0.000	1.0	326.0	2.513	−4.26
1.000	10	335.0	2.525	−3.26
2.000	100	425.0	2.628	−2.26
3.000	1000	1325	3.122	−1.26
4.000	10000	10325	4.014	−0.26
5.000	100000	100325	5.001	0.74
6.000	1000000	1000325	6.000	1.74

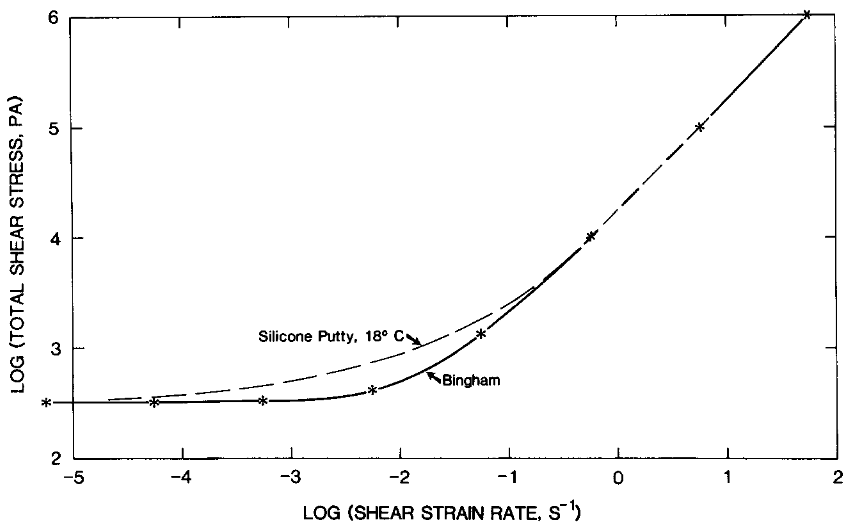

Fig. 4. Comparison of the experimental data for silicone putty at 18°C (light dashed line, taken from Fig. 1) and the theoretical Bingham curve (heavy line) calculated assuming a shear strength of 325 Pa and a Bingham viscosity of 1.82×10^4 Pa s (stars represent calculated points from Table 1, columns 4 and 5; see text).

DISCUSSION

The Bingham and experimental curves in Fig. 4 do not match exactly. The silicone putty is stronger than a true Bingham substance (that is, it exhibits slightly 'nonlinear viscous' behavior) just above the yield strength. Over this range of strain rate (that is, below about 10^{-2} s^{-1}), the power-law or pseudoplastic rheologic model, with stress exponent n equal to about 7, is still a useful approximation. Similarly, at relatively high strain rates (above 10^0 s^{-1}), the linear viscous model can be applied. Thus, the choice of rheologic expression can be tempered by knowledge of the range of stress levels that are achieved in a given model. Conversely, models can be designed so that the appropriate rheologic formulation will be applicable. If the silicone putty is being used to simulate a rock material that is thought to exhibit power-law flow in the prototype, then care can be taken to ensure that the appropriate range of stress levels is produced in the model. On the other hand, the silicone putty can also be used as an analog for magma which exhibits Bingham behavior, provided that higher stress levels are produced in the models. Dixon & Simpson (in press) have simulated the intrusion of laccoliths, using silicone putty as the analog for magma which probably exhibited Bingham behavior during its intrusion (Johnson & Pollard, 1973).

As Johnson (1970, pp. 517–518) pointed out, it is always possible to select a more complex rheological model that would better describe a set of empirical data. We are of the opinion, given the uncertainty in data reduction due to the design of our test rig (Dixon & Summers 1985), and the other uncertainties involved in using analog materials to simulate rock deformation, that it is not particularly fruitful to search for a mathematically more complex rheological model. The simple and elegant Bingham and power-law expressions are adequate for our purposes.

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