

Are polymers suitable rock analogs?

Saskia M. ten Grotenhuis^{a,*}, Sandra Piazzolo^{a,1}, T. Pakula^b,
Cees W. Passchier^a, Paul D. Bons^a

^a*Institute for Geosciences, Tectonophysics, Johannes Gutenberg University, Becherweg 21, D-55099 Mainz, Germany*

^b*Max-Planck Institute for Polymer Research Mainz, P.O. Box 3148, D-55021 Mainz, Germany*

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Abstract

To evaluate if a polymer is suitable for analog modeling, it is essential to know the rheological properties of the material. Polymers used in analog modeling exhibit a complex rheological behavior; only part of which has been taken into account in most modeling studies. The mechanical behavior is strongly dependent on strain rate and temperature, and is characterized by specific dependencies of the storage and loss moduli, related to the elasticity and viscosity, on the deformation rate (frequency). We have measured the storage and loss moduli at a broad range of strain rates and strains, using an oscillatory parallel-disk rheometer. Investigated materials are polydimethylsiloxane (PDMS), mixtures of PDMS and BaSO₄ (filler), Rhodorsil Gomme and mixtures of Rhodorsil Gomme and plastilina, all commonly used in analog experiments. Our measurements show that the rheological properties of mixtures of plastilina and Rhodorsil Gomme depend on its deformation history. Therefore, these mixtures are problematic for analog modeling. For mixtures of PDMS and BaSO₄, the significance of the elastic component increases with increasing filler content, and accordingly, these mixtures have a limited application for modeling of viscous deformation. Pure PDMS and Rhodorsil Gomme exhibit Newtonian flow behavior at strain rates commonly used in analog modeling. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Polymers (e.g. polydimethylsiloxane (PDMS)) and polymers with fillers (e.g. bouncing or silicone put-

ties) in combination with other materials (e.g. sand) have been extensively used for analog modeling in geosciences for decades. Polymers have been applied in experiments modeling the development of small-scale structures in ductile shear zones (e.g. Ghosh and Sengupta, 1973; Fernandez et al., 1983; Ildefonse et al., 1992a,b; Passchier and Sokoutis, 1993), medium-scale structures such as boudinage or mullions (e.g. Ramberg, 1955; Ghosh and Ramberg, 1976; Sokoutis, 1987; Koberger and Zulauf, 1995) and strain variation in layers of different rheology (e.g. Treagus and Sokoutis, 1992), and large-scale fold and fault structures (e.g. Dixon and Summers, 1985; Brun et al.,

* Corresponding author. Present address: HPT-laboratory, Faculty of Earth Sciences, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, The Netherlands. Tel.: +31-30-2531177; fax: +31-30-2537725.

E-mail address: saskiatg@geo.uu.nl (S.M. ten Grotenhuis).

¹ Present address: Department of Geological Mapping, Geological Survey of Denmark and Greenland, Thoravej 8, 2400 Copenhagen NV, Denmark.

1994). In large-scale experiments, polymers are commonly used to represent the ductile lower crust and upper mantle (Davy and Cobbold, 1991; Faccenna et al., 1999; Bonini et al., 2000; Koyi and Skelton, 2001). Polymers are also used to model salt flow and diapirism (e.g. Nalpas and Brun, 1993; Koyi, 2001) and rising plumes, convection, magmatic fabric development, and emplacement of igneous bodies (e.g. Whitehead and Luther, 1975; Nataf et al., 1984; Roman-Berdiel et al., 1995; Anma, 1997; Anma and Sokoutis, 1997; Donnadieu and Merle, 1998).

Several papers have been published in the geological literature, which specifically or in parts investigate the physical properties of polymeric liquids and related materials (e.g. McClay, 1976; Dixon and Summers, 1985, 1986; Weijermars, 1986; Sokoutis, 1987; Treagus and Sokoutis, 1992; Kobberger and Zulauf, 1995). McClay (1976) and Kobberger and Zulauf (1995) performed constant strain rate, plane strain compression tests and concluded that the mechanical behavior of different types of plasticine is complex, but that after a certain amount of strain, it is linear viscoelastic. Dixon and Summers (1985, 1986) used an annular shear rig to obtain rheological properties of a silicone putty. They have shown that the mechanical behavior of the silicone putty and the plasticine cannot be fully described by flow laws, which are used to describe rock deformation (power-law flow, Newtonian flow, Bingham flow behavior). Sokoutis (1987) and Treagus and Sokoutis (1992) used a capillary (extrusion) viscometer and a concentric cylinder (Couette) viscometer. Weijermars (1986) performed additional measurements with a Stokes (falling-ball) viscometer and a Weissenberg cone and plate rheometer, for the investigation of the viscosity of polymeric analog materials (plasticine, Rhodorsil Gomme, polymers and mixtures). They reported changes in viscosity with strain rate. In all these studies, no other rheological properties than effective viscosity were measured.

Geologists performing analog modeling need comprehensive information about the rheological character of a material to evaluate its suitability as a rock analog. However, the knowledge of the rheological properties of polymeric materials in the geological literature is strongly restricted to analyses of effective viscosity without specification of any other rheolog-

ical quantities. Quantities such as the loss and storage moduli, especially when determined in a broad range of deformation rates, express more comprehensively the rheological character of a material (Nelson and Dealy, 1993).

We performed a series of rheological measurements on several commonly used polymers. Our results show that the mechanical behavior is complex and that some commonly used polymers are in fact problematic as analog materials for rocks.

2. Structure and deformation of polymeric liquids

2.1. Structure and mechanical behavior of polymeric liquids

Polymeric materials used for analog modeling belong to the so-called thermoplastics. These are characterized by flexible linear chainlike macromolecules, which are formed by chemical binding of a number of small molecules (monomers). The polymer chains, when sufficiently long, are entangled and assume complex three-dimensional structures. The mean form of the three-dimensional structure can be characterized as a soft ellipsoid, the size of which is chain length-dependent. In an undeformed system, the chains assume an equilibrium state with random orientation of their long axes (Winter et al., 1993). During deformation, chains can reorient with their long axes preferentially directed towards the drawing direction, they can straighten and finally they can glide past each other (Fig. 1). When deformation ceases, chains tend to “relax” to their equilibrium state both by a form retraction and by a randomization of orientation. Therefore, polymers behave like an elastic material when a high stress is applied for a short time (less than the chain relaxation time), but like a viscous material when a low stress is applied for a long time (longer than the chain relaxation time). For a constant imposed strain, the initial elastic response is gradually converted into permanent viscous deformation and the associated stress decays with time (Maxwell model). Such behavior is termed *viscoelastic* as it is characterized by a combination of elastic deformation and viscous flow. An important feature of viscoelastic materials is the time dependence of rheological properties (Askeland, 1990). At a

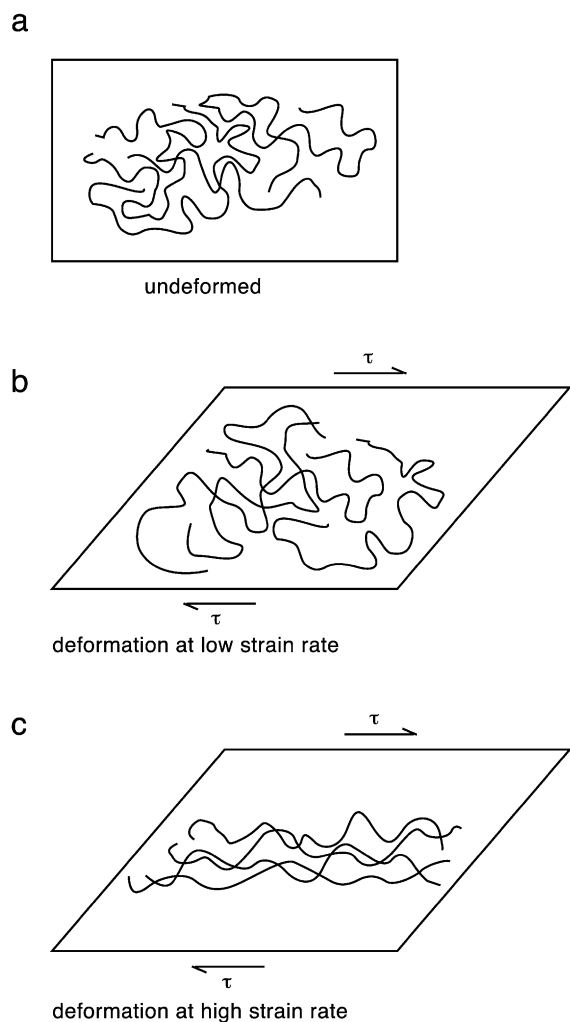


Fig. 1. Sketch of chains of a polymeric liquid in (a) undeformed equilibrium state, (b) deformed state at low deformation rate relative to relaxation time of polymer chains, and (c) deformed state at high deformation rate relative to relaxation time of polymer chains.

certain range of deformation rates, time-independent rheological properties may be observed for a given material but there exists a range where the material will show time-dependent properties. Besides this time-dependence, properties of viscoelastic materials can be strain-independent, “linear”, or strain-dependent, “nonlinear”. The term *linear viscoelastic* is used when, during testing, the material remains in steady state and the rheological properties are not influenced by the conditions of testing, hence rheological proper-

ties are strain-independent. The term *nonlinear viscoelastic* is used when the material structure is altered under observed conditions and consequently rheological properties are strain-dependent. (Fig. 1).

2.2. Viscoelastic properties of polymers

2.2.1. Linear viscoelastic behavior

The properties of linear viscoelastic materials are usually described by the storage (G') and loss (G'') moduli, which represent the elastic and viscous components, respectively (Nelson and Dealy, 1993).

These material properties are usually determined by applying sinusoidal shear strain of amplitude γ_0 and frequency ω to a sample. The shear strain as a function of time is

$$\gamma(t) = \gamma_0 \sin(\omega t) \quad (1)$$

and the corresponding shear strain rate

$$\dot{\gamma}(t) = \gamma_0 \omega \cos(\omega t). \quad (2)$$

If the response is linear, the resulting shear stress will also be sinusoidal but can be shifted in phase as follows

$$\sigma(t) = \sigma_0 \sin(\omega t + \delta) \quad (3)$$

where δ is the phase shift angle and σ_0 is the stress amplitude (Nelson and Dealy, 1993; Jeffrey Giacomin and Dealy, 1993). The phase angle δ can be regarded as characterizing the distribution of the deformation energy into the two fractions: (1) the energy stored in the system as an elastic deformation and (2) the energy lost irreversibly. For purely elastic behavior δ is zero, and the ratio between shear stress and strain is constant in time. For viscous behavior $\delta = \pi/2$ and the ratio between shear stress and strain rate is constant (Fig. 2).

The shear stress is usually written as a trigonometric identity as follows

$$\sigma(t) = \gamma_0 [G' \sin(\omega t) + G'' \cos(\omega t)] \quad (4)$$

and δ as

$$\tan \delta = \frac{G''}{G'} \quad (5)$$

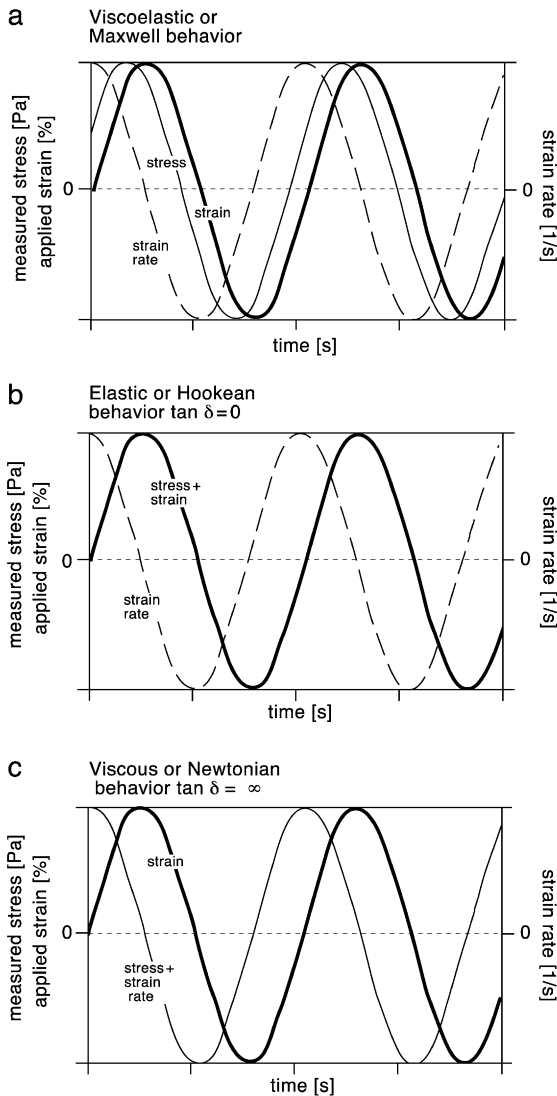


Fig. 2. Graph to illustrate the applied sinusoidal strain and strain rate and resulting stress. (a) Viscoelastic or Maxwell behavior; resulting stress is not in phase with the applied strain or strain rate. (b) Elastic or Hookean behavior; resulting stress is in phase with the applied strain. (c) Viscous or Newtonian behavior; resulting stress is in phase with the strain rate.

where $G'(\omega)$ is the storage modulus and $G''(\omega)$ is the loss modulus. In a simple viscoelastic system, both moduli are functions of frequency with a characteristic behavior, which is linked to the relaxation time of the structural units, e.g. the polymer chains. An example

of such behavior is illustrated schematically in Fig. 3. In such a diagram, a plateau of G' and a high G'/G'' ratio ($G' \gg G''$) are both characteristic of elastic behavior

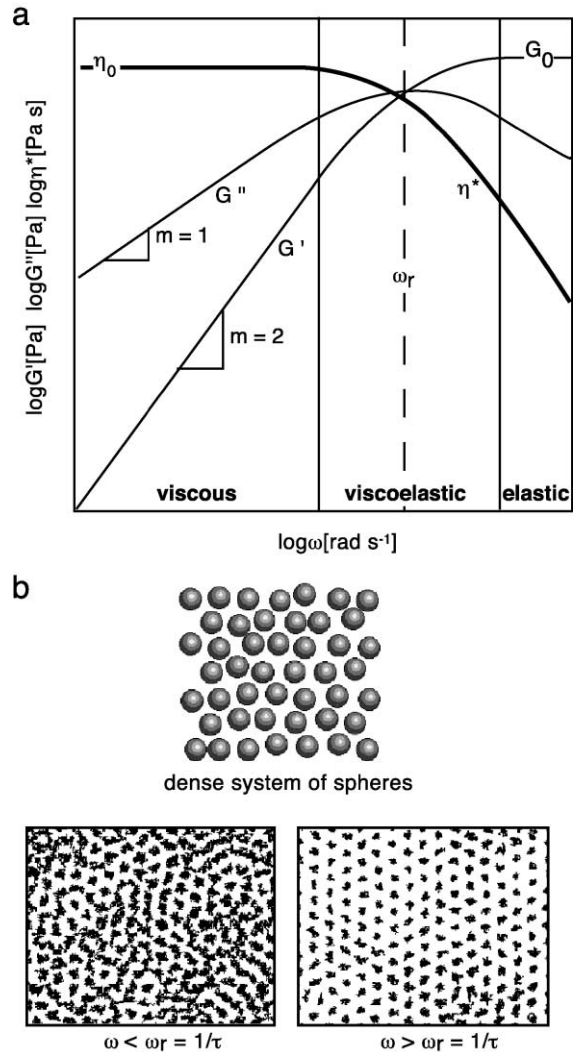


Fig. 3. Representation of typical rheological properties of linear viscoelastic material; (a) plot of log frequency (ω), against log storage modulus (G') or loss modulus (G''); different fields signify different mechanical behavior, determined by the relation between G' and G'' . Viscous behavior is characterised by $G'' \gg G'$ and slopes of G'' and G' of 1 and 2, respectively. Elastic behavior is characterised by $G' \gg G''$ and by a constant value for G' . Viscoelastic field is between the elastic and viscous field. $\eta^* [\text{Pa s}]$ is the complex viscosity; (b) representation of center paths of particles in a simple model (dense system of spheres) corresponding to low ($\omega < 1/\tau$) and high ($\omega > 1/\tau$) deformation rate.

ior (Hookean). The elastic shear modulus describing the material properties in this range is given by

$$G_0 = \lim_{\omega \rightarrow \infty} G'(\omega). \quad (6)$$

In the frequency range where $G'' \gg G'$ and where G' and G'' obey the characteristic proportionalities to ω^2 and ω , respectively, flow behavior is viscous (Newtonian). Here the system can be characterized by the complex viscosity $\eta^*(\omega)$ given by

$$\eta^*(\omega) = \frac{\sqrt{G'^2 + G''^2}}{\omega} \quad (7)$$

(Winter et al., 1993). The complex viscosity $\eta^*(\omega)$ is equal to the kinematic viscosity η only if $G'' \gg G'$. Only in this range is the viscosity a meaningful material property and the complex viscosity can then approach the value of the zero shear viscosity

$$\eta_0 = \lim_{\omega \rightarrow 0} G''(\omega)/\omega. \quad (8)$$

The intermediate crossover region between the two limiting types of behavior (elastic and viscous) can be regarded as typically viscoelastic (Maxwell). The point at which G' and G'' cross each other determines the place (ω_r) on the frequency scale, which is related to the relaxation time τ of the structural units constituting the system, ($\tau=1/\omega_r$). Assuming a simple Maxwell model, the maximum of G'' and intersection of the functions of $\log(G')$ and $\log(G'')$ vs. $\log(\omega)$ always occur at the same frequency.

Fig. 3b gives an example of a possible structural interpretation of the mechanically observed relaxation, which can be considered for molecular or colloidal systems. For a dense system of spheres which can be regarded as representing molecules or particles, there is a solidlike state at higher frequencies and a liquidlike state at low frequencies. In the high frequency regime, they indicate only vibrational motions and quasi-localized positions of particles between the neighbors, whereas at low frequencies, displacements exceeding particle sizes make the system viscous; changing neighbors becomes possible. According to such a model, the relaxation is related to the position correlation of particles and the mechanical response can be considered as a Fourier transform of the position autocorrelation function with the character-

istic relaxation time necessary for particles to escape from the surroundings of the initial neighbors.

2.2.2. Nonlinear viscoelastic behavior

In nonlinear viscoelastic materials, increasing deformation amplitude (i.e. finite strain at a constant frequency) leads to structural changes, such as changes in chain orientation and extension, which influence the material properties. In such cases, the stress–response becomes nonsinusoidal. Therefore, the property definitions for G' , G'' and δ are not meaningful for such a response (Jeffrey Giacomin and Dealy, 1993). Methods of analysis other than those discussed here are required in order to characterize such nonlinear viscoelastic behavior.

2.3. Relation of G' and G'' to shear modulus and coefficient of viscosity

In geological literature it is common to describe the viscous and elastic behavior of rocks in terms of the coefficient of viscosity (η), which relates the shear strain rate to shear stress, and the shear modulus (G), which relates elastic shear strain to shear stress:

$$\eta = \frac{\sigma(t)}{\dot{\gamma}} \quad (9)$$

$$G = \frac{\sigma(t)}{\gamma(t)}. \quad (10)$$

Using Eqs. (1)–(7), the coefficient of viscosity η and the shear modulus G can be rewritten in terms of G' and G''

$$\eta = \frac{G''}{\omega} \quad (11)$$

$$G = G'. \quad (12)$$

The coefficient of viscosity η may only be used in ranges where the material exhibits viscous behavior ($\tan\delta \rightarrow \infty$). The shear modulus G can only be used for elastic behavior ($\tan\delta \rightarrow 0$). Therefore, to describe the rheological behavior of rocks, either the viscosity or the shear modulus is an appropriate quantity.

2.4. Typical rheological behavior of polymeric liquids and polymeric liquids with fillers

In complex systems like polymers, structural units of considerably different size (i.e. monomers and polymer chains) relax with rates that differ by many orders of magnitude. Therefore, the observed frequency dependencies of G' and G'' indicate more than one relaxation region. Fig. 4 shows a typical example of viscoelastic behavior of a melt of a polyisoprene sample with linear chains of the molecular weight $M_w=130\,000$ (Pakula et al., 1996).

The two different relaxation ranges observed for the polymer melt at low and high frequencies correspond to structural rearrangements concerning two different structural units, i.e. monomers and polymers, respectively. The ranges characteristic of viscous and elastic response appear now at various deformation rates and correspond to different size scales in the system examined. Further complication of the structure, for example by introduction of fillers, can lead to creation of new structural scales and new relaxation processes with relaxation times, which depend on particle size and the structure that particles form in the matrix (Gohr et al., 1999). Such additional relax-

ation can shift the regions of typical deformation behavior (viscous, elastic and viscoelastic) of the material to different deformation rates.

The examples given above show that details of viscoelastic and, consequently, rheological response of polymeric materials can be strongly influenced both qualitatively and quantitatively. In complex polymers, having a broad chain length, distribution or fillers with a broad particle size distribution regions may exist where, for example, $G'' > G'$, the slope of G'' is not equal to 1, and the viscosity is a function of the strain rate. For such behavior, the relation between shear stress and strain rate is often empirically described by a power-law function

$$\dot{\gamma} = k\sigma^n \quad (13)$$

where k is a constant and n is the power-law index. A constant power-law index (n) for a range of strain rates is achieved if the slopes of the functions of $\log(G'')$ and $\log(G')$ vs. $\log(\omega)$ are both constant.

Power-law behavior in polymers is due to specific superposition of various molecular or supramolecular relaxation processes, whereas in rocks the power-law behavior is considered to be associated with disloca-

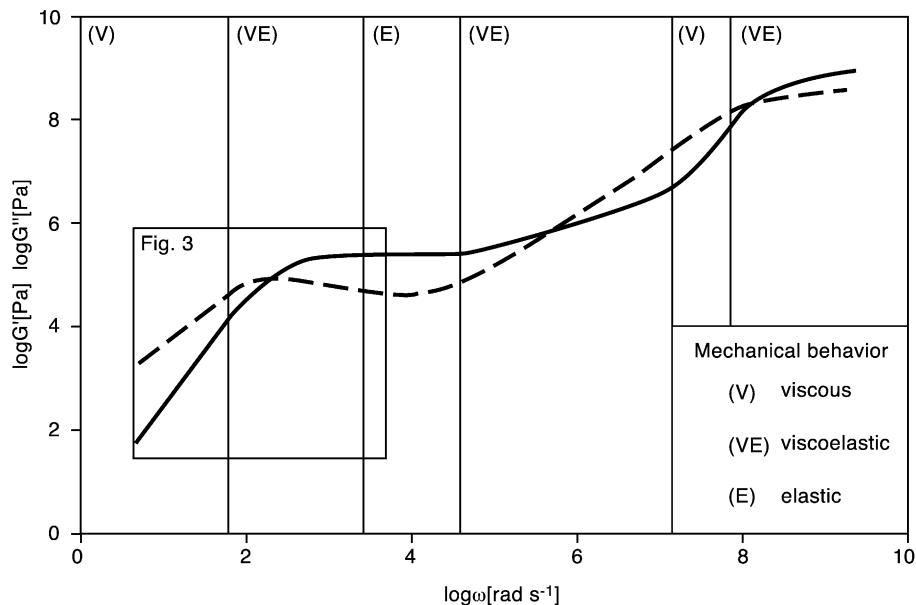


Fig. 4. Typical results for viscoelastic behavior of a melt of a polyisoprene sample (M_w 130000) with linear chains.

tion creep or relaxation. Hence, in polymers and rocks two structurally different mechanisms result in a similar macroscopic behavior.

3. Rheological measurements

A number of polymers that are commonly used in geological experiments have been tested. The first step in the rheological characterization of polymeric liquids and similar materials is the determination of whether the material is linear or nonlinear viscoelastic. This is done by deriving G' , G'' and η^* at a constant frequency but varying applied strain. The material is linear viscoelastic only if the values of G' , G'' and η^* are constant in the applied strain range. The second step is to derive G' , G'' and η^* over a range of strain rates.

3.1. Method

For measurements we used an oscillatory parallel-disk rheometer (Rheometric RMS 800). The rheometer cell consists of two equally sized parallel disks (Fig. 5) of radius $R=6.5$ mm and the distance between the disks $d=1.5$ mm. The sample is put between the two plates. At a given frequency of the sinusoidal strain, the phase angle δ and the amplitude of the stress response $\sigma(t)$ are measured.

The rheometer has a limited range of frequencies (10^{-3} – 10^2 rad/s) that can be applied. To obtain values for G' and G'' over a wider range of frequencies, a so-called master curve is constructed. To do this, measurements are performed at different temperatures and are later shifted along the frequency scale to positions that appear to correspond to the behavior at a chosen reference temperature T_{ref} according to

$$G'(\omega, T_{\text{ref}}) = G'(a_T \cdot \omega_m, T_m) \quad (14)$$

and

$$G''(\omega, T_{\text{ref}}) = G''(a_T \cdot \omega_m, T_m) \quad (15)$$

The value of the shift factor a_T is calculated according to

$$\log(a_T) = \log(\omega(T_m)) - \log(\omega(T_{\text{ref}})) \quad (16)$$

where T_m is the temperature and ω_m the frequency at which measurements were performed (Winter et al.,

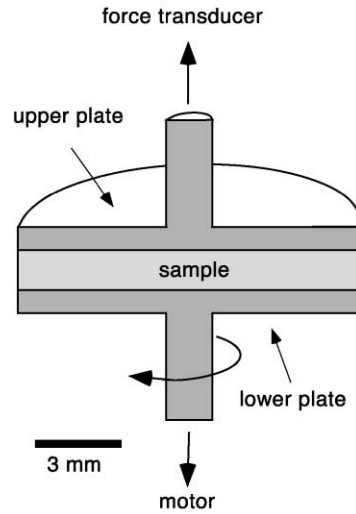


Fig. 5. Sketch of parallel-disk rheometer. The fluid (polymer) is sheared between oscillating lower and upper disks. Strain is applied with a certain amplitude and frequency and resulting stress is measured.

1993). Temperature-induced density changes are negligible in our measurements. This procedure works well for melts of amorphous polymers in which a temperature-independent structure and a temperature-independent relaxation spectrum can be assumed.

3.2. Results

3.2.1. PDMS and mixtures of PDMS and BaSO_4

PDMS (trade name: SGM 36; produced by Dow Corning, UK) is a transparent polymer with a density of 965 kg m^{-3} (Weijermars, 1986). To determine if PDMS is linear or nonlinear viscoelastic, measurements of rheological properties as a function of finite strain at constant strain rate (1 s^{-1}) were performed (Fig. 6). These revealed linear viscoelastic flow behavior. Fig. 7a shows the temperature dependence of the rheological properties for pure PDMS. Fig. 7b illustrates the calculated master curve of PDMS for a reference temperature of 20°C . The master curve for PDMS shows that at 20°C and strain rates below $5 \times 10^{-1} \text{ s}^{-1}$, the slope of G'' is 1 and of G' is 2, indicating viscous flow behavior. In this range of strain rates, the complex viscosity represents a meaningful value which is $3 \times 10^4 \text{ Pa s}$. For strain rates between 5×10^{-1} and 13 s^{-1} , $G'' > G'$.

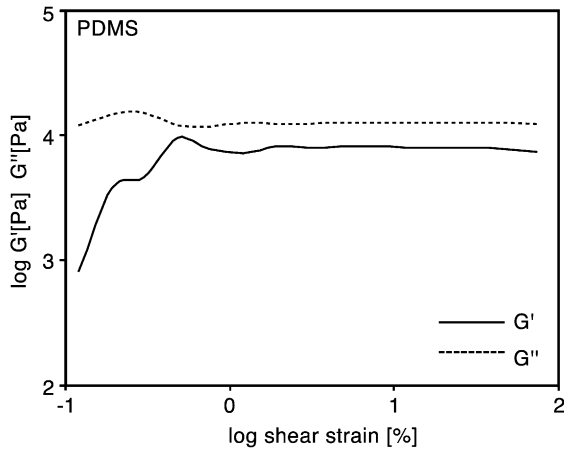


Fig. 6. Plot of finite shear strain versus G' and G'' for PDMS, confirming its linear viscoelastic flow behavior.

Rheological data for three different mixtures of PDMS with the filler material BaSO_4 (25, 33, 50 wt.%) are given in Fig. 8. The BaSO_4 powder has an average grain size of $1 \mu\text{m}$. For increasing filler content the values of G' and G'' increase. For mixtures with 33 and 50 wt.% BaSO_4 , $G' > G''$ over the range of measured strain rates, indicating viscoelastic behavior with a high elastic component. The mixture with 25 wt.% BaSO_4 has a $G' - G''$ crossover at a strain rate of 16 s^{-1} . Below this value, G'' is larger than G' . Below a strain rate of 1 s^{-1} , the slopes of G' and G'' have a constant value, indicating power-law behavior. The viscosity decreases from $1 \times 10^5 \text{ Pa s}$ at a strain rate of $4.3 \times 10^{-2} \text{ s}^{-1}$ to $3 \times 10^4 \text{ Pa s}$ at a strain rate of 1 s^{-1} . This corresponds to a power-law index (n -value) of 1.23.

3.2.2. Rhodorsil Gomme

The master curve for Rhodorsil Gomme (pinkish opaque bouncing putty; trade name: Silbione Gomme 70009, Société des Chimiques Rhône-Poulenc (France)) at T_{ref} of 20°C is shown in Fig. 9. Three strain rate ranges with distinctly different mechanical behavior can be distinguished. Below a strain rate of $1 \times 10^2 \text{ s}^{-1}$, the slope of G'' is 1, that of G' is 2, and $G'' > G'$. Thus, this material shows viscous behavior. The complex viscosity η^* in this range is $8 \times 10^3 \text{ Pa s}$. Between 1×10^2 and $2 \times 10^3 \text{ s}^{-1}$, the slopes of both G' and G'' are not constant; this is the viscoelastic range.

The crossover of G' and G'' occurs at a strain rate of $2.7 \times 10^2 \text{ s}^{-1}$. Above a strain rate of $2 \times 10^3 \text{ s}^{-1}$, G' approaches a plateau at $5 \times 10^5 \text{ Pa}$ in the elastic range.

3.2.3. Mixtures of Rhodorsil Gomme and white plastilina

Fig. 10 depicts strain versus G' and G'' at different frequencies for two different mixtures of white plastilina (PI; Swedish version of Harbutt's Plastiline; McClay, 1976) and Rhodorsil Gomme (RG) (32:68 wt.% PI/RG, 50:50 wt.% PI/RG, 75:25 wt.% PI/RG). The mixture of 32:68 wt.% PI/RG exhibits

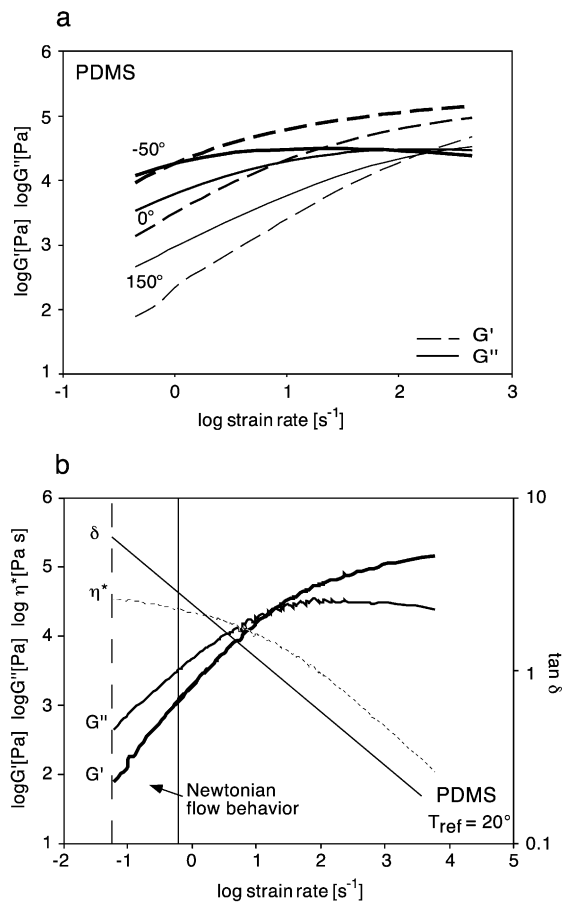


Fig. 7. Rheological data of PDMS; (a) plot of strain rate versus G' and G'' measured at different temperatures; (b) mastercurve for 20°C , showing G' , G'' , η^* and $\tan \delta$. Below a strain rate of 0.5 s^{-1} , PDMS shows viscous (Newtonian) flow behavior.

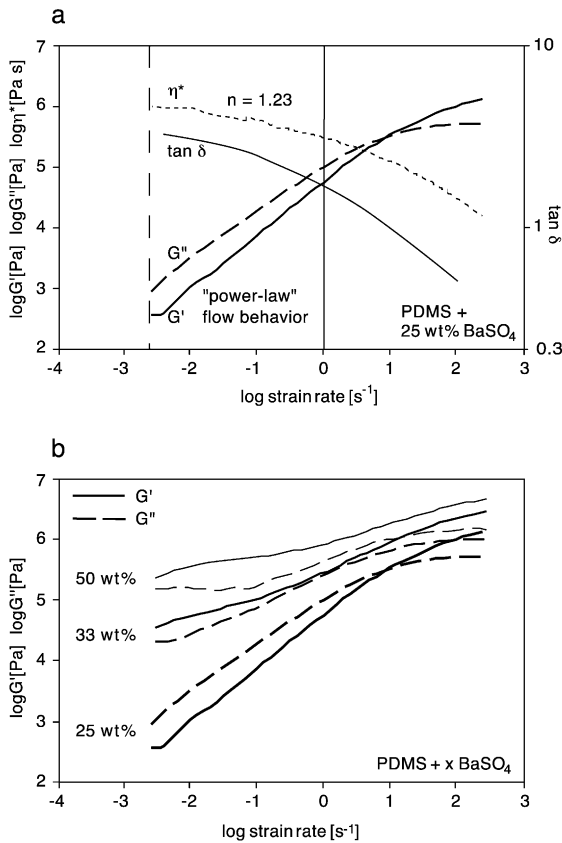


Fig. 8. Rheological measurements on three mixtures of PDMS and BaSO₄. (a) Results for PDMS with 25 wt.% BaSO₄; plot shows strain rate versus G' , G'' , η^* and $\tan\delta$. This material shows power-law behavior below a strain rate of 16 s^{-1} . (b) Results for PDMS with 33 and 50 wt.% BaSO₄; plot shows shear strain rate versus G' , G'' . Both materials behave viscoelastically with a high elastic component.

only a small decrease of G' and G'' with increasing finite strain. Thus, this mixture is linear viscoelastic. Fig. 11 depicts the corresponding master curve. Below a strain rate of 26 s^{-1} , the slopes of G'' and G' are constant, but not equal to 1 and 2, respectively. The calculated n -value assuming power law flow is 1.25. Above a strain rate of $5 \times 10^3 \text{ s}^{-1}$, the mechanical behavior is elastic. For mixtures of 50:50 wt.% PI/RG and 75:25 wt.% PI/RG, values of G' and G'' are not constant with increasing finite strain and therefore the material is nonlinear viscoelastic.

3.3. Comparison of results with existing data

Our data for PDMS closely resemble those given by Weijermars (1986) (Fig. 12) and confirm a Newtonian flow behavior below a strain rate of around $5 \times 10^{-1} \text{ s}^{-1}$ at room temperature ($20\text{--}25 \text{ }^\circ\text{C}$). Between strain rates of 2×10^{-1} and 13 s^{-1} , the flow behavior is viscoelastic, whereby $G'' > G'$. Above a strain rate of 13 s^{-1} , no viscous flow occurs as $G' > G''$. Our data additionally show that the mechanical behavior of PDMS changes significantly with temperature (Fig. 7). Treagus and Sokoutis (1992) measured the viscosity of PDMS mixed with 23 wt.% BaSO₄ at strain rates between 6×10^{-3} and $1 \times 10^{-1} \text{ s}^{-1}$ (Fig. 12). Their finding of non-Newtonian flow behavior for this mixture is confirmed by our data for a mixture of PDMS and 25 wt.% BaSO₄. The power-law index (n) for the mixture with 25 wt.% BaSO₄ is 1.23, which is slightly above the n -value of 1.1 for the mixture investigated by Treagus and Sokoutis (1992). Possible reasons for the discrepancy between our data and the data of Treagus and Sokoutis (1992) are either different measuring methods or different properties of the BaSO₄, since particle size and shape of the filler influence the rheology.

Viscosity measurements have been performed on Rhodorsil Gomme type GS1R by Weijermars (1986) and Sokoutis (1987) (Fig. 12) and on type Silbione Gomme 70009 by Nalpas and Brun (1993). Nalpas and Brun (1993) only give the viscosity as a function

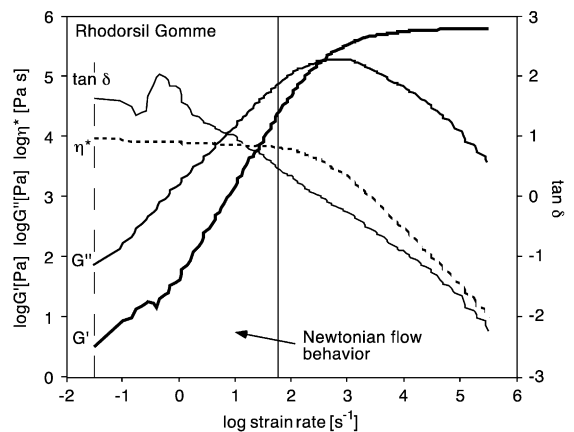


Fig. 9. Master curve of Rhodorsil Gomme, showing G' , G'' , η^* and $\tan\delta$ versus strain rate. Rhodorsil Gomme behaves viscously below a strain rate of $1 \times 10^2 \text{ s}^{-1}$.

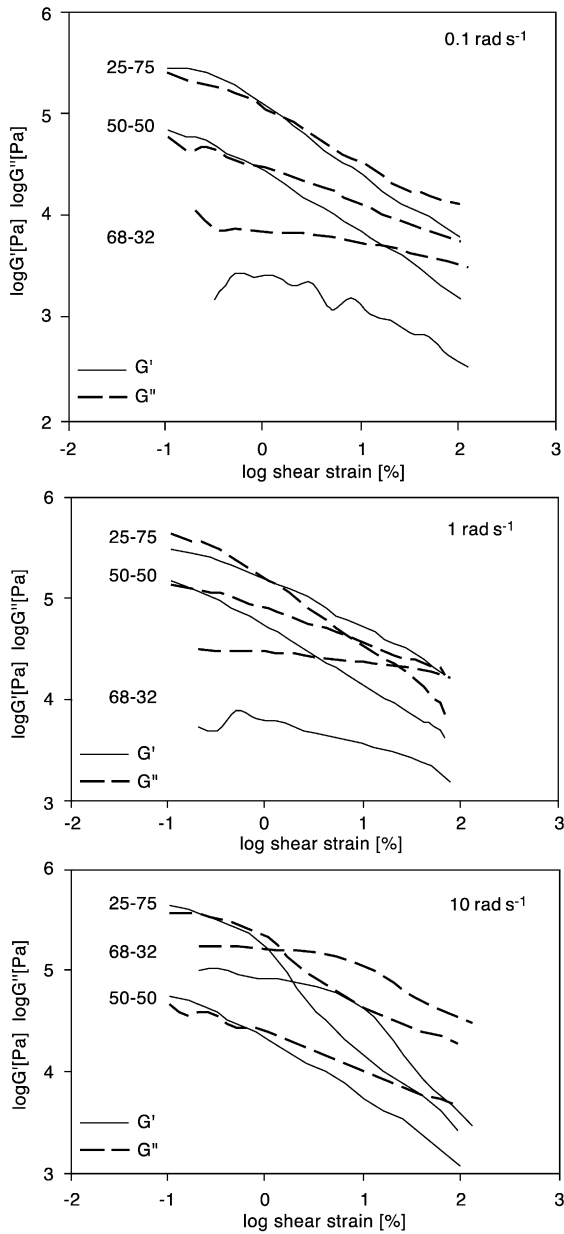


Fig. 10. Variation of G' and G'' with shear strain showing the nonlinear, strain-dependent viscoelastic behavior of mixtures of plastilina and Rhodorsil Gomme, 25:75, 50:50 and 68:32 being the weight ratios of Rhodorsil Gomme and plastilina.

of the temperature, therefore their data are not included in Fig. 12. Our data for Rhodorsil Gomme confirm the Newtonian flow behavior below a strain rate of $1 \times 10^2 \text{ s}^{-1}$, as determined from these measure-

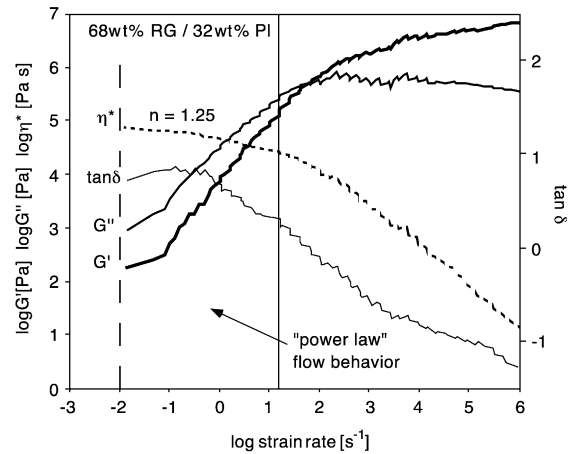


Fig. 11. Master curve for a the mixture of 32 wt.% plastilina and 68 wt.% Rhodorsil Gomme, showing G' , G'' , η^* and $\tan \delta$ versus strain rate. The mixture behaves like a power law material below a strain rate of 26 s^{-1} .

ments. The viscosity determined from our data is $8 \times 10^3 \text{ Pa s}$, in contrast to the value of $3 \times 10^4 \text{ Pa s}$ from earlier measurements for type GS1R (Weijermars, 1986; Sokoutis, 1987) and $1.6 \times 10^4 \text{ Pa s}$ for Silbione Gomme 70009 (Nalpas and Brun, 1993). Above a strain rate of $1 \times 10^2 \text{ s}^{-1}$, the material shows viscoelastic behavior and above $2 \times 10^3 \text{ s}^{-1}$, it shows elastic behavior. Earlier measurements were not performed in the latter range.

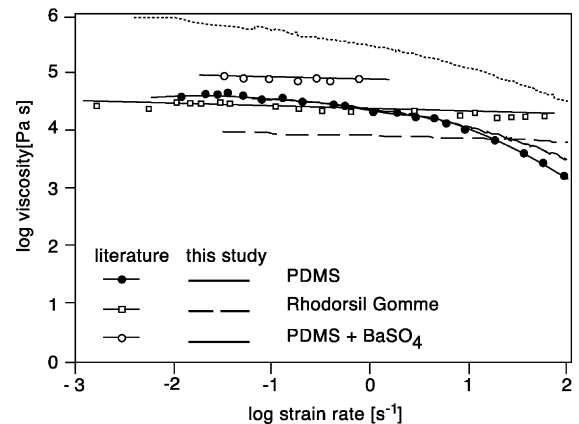


Fig. 12. Plot of apparent viscosity versus strain rate for data from literature. PDMS and Rhodorsil Gomme are from Weijermars (1986) and Sokoutis (1987); PDMS with 23 wt.% BaSO_4 from Treagus and Sokoutis (1992); curves for PDMS, Rhodorsil Gomme and PDMS with 25 wt.% BaSO_4 , from this study.

Our data for mixtures of white plastilina and Rhodorsil Gomme do not confirm comparable data of Weijermars (1986) and Sokoutis (1987). Our findings show that two of the three studied mixtures are nonlinear viscoelastic (Fig. 10), and therefore viscosity is not a meaningful rheological property. McClay (1976) and Kobberger and Zulauf (1995) measured the rheological properties of several types of plasticine and a mixture of plasticine and oil using a uniaxial compression apparatus. They investigated the response of the different materials at constant strain rate and a range of finite strains and used measured values only at a finite strain at which a constant stress response was seen to derive the power-law exponent of the materials. With this procedure, they assured linear viscoelastic behavior of the investigated materials. Therefore, the derived power-law exponents are meaningful for the specific range of strain percentage. Dixon and Summers (1985, 1986) investigated the rheological properties of a silicone putty with an annular shear rig. The plots (Fig. 10; Dixon and Summers, 1985) of time versus shear strain clearly show the time-dependent response of the material and therefore the significance of the elastic component in the rheological behavior of the material. Nevertheless, it is not clear whether the material is linear or nonlinear viscoelastic. Weijermars (1986) measured the viscosity of several mixtures of Rhodorsil Gomme and BaSO₄ with different ratios of the filler to matrix. The purpose of this work was (a) to derive power-law exponents for the different mixtures and (b) to determine a function to predict the power-law exponent of mixtures of Newtonian polymers and filler material. As shown by our data for mixtures of PDMS and BaSO₄ (Fig. 8), mixtures with a filler content of 33 and 50 wt.% are characterized by larger storage moduli than loss moduli. Therefore, mixtures of polymeric liquids and fillers do not necessarily flow viscously. If $G' > G''$, power-law exponents are meaningless. Hence, the general function given by Weijermars (1986) should not be used.

4. Implications for the use of polymers and related materials as rock analogs

Analogs are used as scaled-down models of rocks. Rocks have variable rheological properties depending

on their composition and parameters like temperature, pressure and strain rate. For example, rocks deforming by dislocation creep follow a viscous, power law flow law with $n=3-5$ (e.g. Carter, 1976; Kirby and Kronenberg, 1987). Rocks deforming by diffusion creep are Newtonian viscous (e.g. Frost and Ashby, 1983). To study geological problems, the analog material and the rock to be modeled should have similar rheological behavior. Therefore, a complete rheological investigation of the analog material is necessary. Analysis of polymers must include the determination of the storage and loss moduli.

The rheological behavior at a range of strains at a given strain rate should be known in order to determine if the material is linear or nonlinear viscoelastic. If it is nonlinear viscoelastic, the behavior of the material depends strongly on its deformation history. Therefore, the behavior of these materials is unpredictable. If the material is linear viscoelastic, the values for the storage and loss moduli must be determined. The relation of these two moduli is an expression of the different types of linear viscoelastic behavior. If the value of the loss modulus is below the value of the storage modulus, viscosity measurements are not meaningful as the elastic behavior dominates. For polymers, the rheological behavior is strongly dependent on strain rate and temperature. Therefore, it is necessary to know the rheological properties of a material exactly at experimental conditions.

As the rheological properties of polymers depend on the relaxation time of the structural units, mixing of polymers with different chain lengths or addition of filler may result in materials with rheological properties very different from those of the end-members. It should be possible to create materials with properties favorable for analog modeling of rocks.

5. Conclusions

The knowledge of the effective viscosity alone is not sufficient to describe the rheological properties of polymers and related materials. The values of the storage and loss moduli are necessary to evaluate the suitability of a polymer for analog modeling. First of all, the properties as a function of the finite strain must be known in order to determine if the material is linear or nonlinear viscoelastic. If the properties are

not constant with increasing finite strain, a material is nonlinear viscoelastic. In this case, its use as a rock-analog is problematic as the material properties (i.e. viscosity, storage and loss moduli) are a function of the deformation history. Examples of nonlinear viscoelastic materials are mixtures of Rhodorsil Gomme and plastilina, as used by Passchier and Sokoutis (1993) and Treagus and Sokoutis (1992) (weight percent ratio: 25:75, 50:50).

If a material is linear viscoelastic, the values of the storage and loss moduli as a function of strain rate determine the mechanical behavior at specific strain rates. Three types of mechanical behavior can be distinguished:

1. elastic (Hookean) behavior
2. viscoelastic (Maxwell) behavior
3. viscous (Newtonian) behavior.

Our results reveal that commonly used analog materials can only be used to model viscous deformation at specific strain rates. The upper limit for viscous deformation modeling is $5 \times 10^{-1} \text{ s}^{-1}$ for PDMS and $1 \times 10^2 \text{ s}^{-1}$ for Rhodorsil Gomme. To model power law behavior of rocks, mixtures of PDMS and BaSO₄ with a BaSO₄ content below approximately 30 wt.% and mixtures of Rhodorsil Gomme and plastilina with a plastilina content of 32 wt.% can be used at strain rates below 1 and 26 s^{-1} , respectively. For a mixture of PDMS and BaSO₄ with a BaSO₄ content of 25 wt.%, the power law exponent $n=1.23$ and for a mixture of Rhodorsil Gomme and plastilina with a plastilina content of 32 wt.%, $n=1.25$. For mixtures with a BaSO₄ content above 30 wt.% (mixture PDMS/BaSO₄), the elastic component dominates.

These results show that measurements of viscosity are not sufficient to determine the mechanical behavior of a material and therefore to assess its suitability for specific analog modeling requirements.

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