Experimental deformation of two-phase rock analogues

Paul D. Bons*
Department of Earth Sciences, University of Utrecht, PO Box 80.021, NL-3508 TA Utrecht (Netherlands)

Janos L. Urai
Shell Research B.V., PO Box 60, NL-2280 AB Rijswijk (Netherlands)

Abstract

Organic crystalline rock analogues have proven to be useful materials to study microstructural developments during deformation. We describe a series of constant-load creep experiments with two-phase mixtures of these analogues, where these are used as mechanical analogues of polyminerallc rocks. The components are camphor and octachloropropane (OCP), which are both power-law creep materials. The strain rate difference is two to three orders of magnitude at the experimental stress values. Mixtures of OCP and camphor are also power-law creep materials within the experimental range of stresses (0.2–1.2 MPa). The soft phase OCP forms a matrix around the harder camphor inclusions and can accommodate most of the deformation. The OCP therefore dominates the flow behaviour of the mixtures, even at low volume fractions.

1. Introduction

Despite the amount of work done so far to determine the flow properties of monominerallc materials, our knowledge of the flow properties of polyphase rocks is still limited. Understanding the flow properties of polyphase materials is crucial for understanding of the flow properties and dynamics of the crust and mantle, because most rocks in the Earth's crust and mantle consist of more than one mineral.

A considerable amount of theoretical work has been published on the properties of polyphase materials. Starting with the properties of isotropic composites of linear elastic or newtonian viscous components (see e.g. ref. 1), the theory has been extended to cover non-linear properties of the constituent phases (see e.g. refs. 2 and 3) and anisotropic composites (see e.g. refs. 4 and 5). These extensions are important, since most rock-forming minerals have a non-linear rheology and rocks are mostly anisotropic. Relatively few attempts have been made so far to apply these theories to the flow properties of polyminerallc rocks in the Earth's crust and mantle [6]. It is common practice to use the flow law of a dominant mineral to estimate the flow properties of polyminerallc rocks: "wet quartz" for crustal rocks and "wet olivine" for mantle rocks.

Theoretical predictions of the flow properties of rocks should be complemented and tested with experimental data. One can do so by experimentally determining the flow properties of natural polyminerallc rocks such as granite, aplite, websterite, diabase and quartz-feldspar rocks (see refs. 7 and 8 and references cited therein). Another approach is to experiment with artificial rock-like composites of two or more materials. Examples are the work on composites of halite and calcite [9–11], halite and anhydrite [12] and camphor and ice or naphthalene [13]. An advantage of the second approach is the possibility to systematically vary the parameters that determine the properties of a composite of two or more components, such as the volume fraction of each phase.

In this paper we present results of a series of such experiments using two-phase composites of organic crystalline rock analogues. Our aim is to investigate the flow properties of such composites as a function of the volume fraction of each of the components with known flow properties. First we briefly describe the microstructural behaviour of the components and the experimental apparatus. Then we present and discuss the experimental results.

2. Organic crystalline rock analogues

2.1. General

Some crystalline organic materials can be used as model systems for high $T/T_m$ deformation of minerals because they deform by a combination of dislocation creep and diffusion creep, analogously to naturally deforming rocks. The advantage is that they
do so at room temperature and low stress. The softness of organic analogues permits creep tests at high strain rates in a simple apparatus together with transmitted light deformation experiments [14, 15]. Such experiments are more difficult or impossible to do with real rocks. Sample preparation is relatively easy. The materials can be cut with a razor blade and pressed in a hand press to obtain practically zero-porosity samples. A limiting factor is the small number of known crystal plastic organic rock analogues. An even smaller number can be used to make two-phase aggregates, since most of the known analogues form eutectic melts at room temperature. This has limited us to using mainly octachloropropene (OCP) and camphor so far. We have also done experiments with mixtures of OCP and quartz sand \((\text{SiO}_2)\), which is rigid and inert at the given low stress and temperature.

Both OCP and camphor are power-law creep materials at room temperature, as are rocks deforming by intracrystalline deformation mechanisms [16]. The effective viscosity of camphor is about two to three orders of magnitude higher than that of OCP at room temperature and differential stresses ranging from 0.2 to 1.2 MPa.

2.2. OCP

OCP \((\text{C}_2\text{Cl}_6)\) is hexagonal and melts at 434 K. Deformation usually leads to the formation of a crystallographically preferred orientation [17]. From this it is inferred that at room temperature OCP deforms by dislocation creep with slip mainly on the basal plane. Deformation is accompanied by grain boundary migration and subgrain formation [18]. Grain growth rates are relatively high and a coarse foam texture can be achieved from a fine-grained starting material within hours or days, depending on the temperature. At low strain rates and/or elevated temperature this foam texture can be largely preserved during deformation [19, 20]. At high strain rates and low temperature the grain size is reduced and mechanical twins or kinks are sometimes observed [21].

2.3. Camphor

Camphor \((\text{C}_{10}\text{H}_{16}\text{O})\) is rhombohedral below 365 K and cubic up to the melting temperature of 452 K. It mainly deforms by slip on the basal plane and by kinking or possibly twinning [22]. Continuing lattice rotation within the kink bands, subdivision of the kink bands and accompanying dynamic recrystallization can rapidly reduce the grain size during deformation. Camphor has a tendency to localize the deformation in fine-grained shear zones with a strong crystallographically preferred orientation [23]. A foam texture is re-established by static grain growth within hours or days after deformation.

3. Experimental method

Creep tests were carried out in a miniature triaxial gas apparatus (Fig. 1(a)). The apparatus consists of a vertical piston–sample assembly in a steel pressure vessel. A cylindrical sample (10 mm in diameter, 15–20 mm in length) is placed between the upper and lower pistons and jacketed with rubber. A confining pressure is applied on the sample by pressurizing the vessel with compressed air, typically 0.6 MPa. Seals are low friction, low clearance metal-to-metal ones that allow a small amount of air to leak during operation. The sample is loaded via a compensated piston assembly (see Fig. 18 in ref. 24) with a dead-weight (Fig. 1(b)). All load applied on the upper piston by the deadweight, calibrated for the friction of the piston in its shaft, produces the vertical differential stress on the sample. We will refer to this as the “stress” or \(\sigma\) for the rest of this paper. The relative displacement of the upper piston is measured with a linear variable displacement transducer (LVDI) and logged on a personal computer. The strain \((\varepsilon)\) is defined as the change in length relative to the undeformed sample length. The strain rate \((\dot{\varepsilon})\) is defined as the rate of change in length relative to the current sample length. A coiled heater element surrounds the piston assembly within the vessel and the temperature is measured with a thermocouple (K-type) near the sample. The temperature was 301 K for all experiments presented in this paper. The temperature was calibrated by inserting a second thermocouple through a hollow piston into a dummy sample of camphor. This showed that temperature...
variations over space and time were within ±1 K at a set temperature of 301 K.

The error in stress measurements is about ±0.01 MPa (approximately 1%–5%) due to variation in friction along the upper piston. With increasing strain the error increases as the sample deforms into a barrel shape. Some experiments were done with a piston of 10 mm diameter, but most with 12 mm diameter. The slightly greater diameter of the piston than the sample voids wrapping of the sample around the pistons. The stress is corrected by assuming a constant volume and a cylindrical shape of the sample during the experiment. The error of the LVDT is less than ±0.01 mm and the errors in measurement of the length of the sample before and after deformation are about 0.1 mm. The error in strain and strain rate values is therefore less than about ±2%.

Samples were prepared by cutting pure OCP and camphor with a razor blade into 1–2 mm cubes. These cubes were mixed thoroughly and pressed together in a die with an arbor press at approximately 100 MPa for 10 s. The result is a translucent cylindrical specimen with virtually zero porosity. The shape of the original cubes is largely lost, since the softer OCP flowed into all existing voids (Fig. 2(a)). After deformation, slices were cut off the sample with a microtome or razor blade. The distribution of camphor and OCP could then be observed (Fig. 2(b)) using reflected light microscopy or by making peels of etched surfaces. Ethanol was used for the etching and a two-component dentist’s putty* to make the peels. Thin sections cannot be made, since the material is too soft.

We carried out two series of two types of experiments: constant-load tests wherein the applied load was left constant during the entire experiment (Table 1) and variable-load or stepping tests wherein the load was changed every few percent of strain (Table 2) [25]. Each step was continued until the strain rate settled to a constant value, the strain rate value for that step. To increase the initial grain size, some of the samples were annealed at about 340 K for 2 h, followed by cooling to 301 K in about 1 h, prior to deformation. If samples were not to be annealed, they were placed in the apparatus immediately after manufacturing and the temperature controller was set at 301 K. The sample was then left for about 30 min for the temperature to settle, after which the load was applied. Annealing caused the grain size to increase from an average of less than 10 μm to about 100 μm in both phases, as shown by experiments with a transparent deformation cell under the same conditions. All stepping tests were done with unannealed samples.

*Coltene® President Putty Soft supplied by Coltène AG, Feldwiesenstrasse 20, CH-9450 Altstätten, Switzerland.

---

Fig. 2. (a) Two samples of a section through an undeformed sample, showing the distribution of camphor and OCP. (b) Sections through deformed samples of various compositions (samples PDB 33, 31, 32, 29).

4. Experimental results

4.1. Pure components

First we present the data on the pure components. Two creep curves for OCP are shown in Fig. 3(a), one for an annealed sample and the other for an unannealed sample. These curves show that there is an effect of annealing on the strain rate. The results of two stepping tests with OCP are shown in Fig. 4(a). These data were used to determine a flow law for OCP. Since all stepping test data correlate well in the log(σ)–log(ε) plot, we chose a power law of the form

\[ \dot{\varepsilon} = A \sigma^n \]

(1)

The values of the pre-exponential factor A and the stress exponent n were determined with a linear regression through the log(σ)–log(ε) data, with log(ε) as the dependent variable (Table 3). The actual temperature dependence was not determined, since all experiments were performed at the same temperature.

Two creep curves for camphor are shown in Fig. 3(b). Here we see a distinct difference in shape between the unannealed and the annealed sample. The unannealed sample has a constant strain rate up to about 20% shortening, after which the strain rate decreases. The annealed sample initially shortens at a slower rate. The strain rate increases from about 5% shortening. The increase in strain rate in the annealed sample is probably the result of a reduction in grain size, accompanied by localization of deformation as described by Urai and Humphreys [23]. Data of two stepping tests with camphor are shown in Fig. 4(b), together with a power-law best fit.

4.2. Mixtures

Both constant-load and stepping tests were carried out on mixtures of OCP and camphor. Figure 5 shows the results of the stepping tests with OCP fractions of 0.2, 0.4, 0.6 and 0.8. It can be seen that the data of the mixtures also fall on roughly straight lines in a
TABLE 1. Experimental details of the constant-load experiments

<table>
<thead>
<tr>
<th>Test</th>
<th>% OCP</th>
<th>Initial length (mm)</th>
<th>Sample mass (g)</th>
<th>Finite strain (5% strain)</th>
<th>Strain rate at 10% strain</th>
<th>Strain rate at 15% strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDB 25</td>
<td>0</td>
<td>15.6</td>
<td>1.21</td>
<td>18</td>
<td>3.6 x 10^-7</td>
<td>3.5 x 10^-7</td>
</tr>
<tr>
<td>PDB 24</td>
<td>25 ± 1</td>
<td>15.1</td>
<td>1.45</td>
<td>34</td>
<td>3.6 x 10^-6</td>
<td>3.7 x 10^-6</td>
</tr>
<tr>
<td>PDB 26</td>
<td>39</td>
<td>14.5</td>
<td>1.60</td>
<td>33</td>
<td>4.3 x 10^-6</td>
<td>4.3 x 10^-6</td>
</tr>
<tr>
<td>PDB 21</td>
<td>49 ± 3.5</td>
<td>15.1</td>
<td>2.64</td>
<td>42</td>
<td>5.1 x 10^-5</td>
<td>4.3 x 10^-5</td>
</tr>
<tr>
<td>PDB 22</td>
<td>74 ± 1</td>
<td>14.8</td>
<td>1.93</td>
<td>33</td>
<td>6.1 x 10^-5</td>
<td>3.6 x 10^-5</td>
</tr>
<tr>
<td>PDB 23</td>
<td>100</td>
<td>14.9</td>
<td>2.21</td>
<td>32</td>
<td>3.8 x 10^-5</td>
<td>1.9 x 10^-4</td>
</tr>
</tbody>
</table>

Series 2, OCP + camphor, 1.0 MPa, annealed

<table>
<thead>
<tr>
<th>Test</th>
<th>% OCP</th>
<th>Initial length (mm)</th>
<th>Sample mass (g)</th>
<th>Finite strain (5% strain)</th>
<th>Strain rate at 10% strain</th>
<th>Strain rate at 15% strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDB 28</td>
<td>0</td>
<td>15.3</td>
<td>1.19</td>
<td>35</td>
<td>2.1 x 10^-6</td>
<td>3.5 x 10^-6</td>
</tr>
<tr>
<td>PDB 33</td>
<td>19 ± 3</td>
<td>15.2</td>
<td>1.43</td>
<td>34</td>
<td>1.5 x 10^-5</td>
<td>1.7 x 10^-5</td>
</tr>
<tr>
<td>PDB 31</td>
<td>39 ± 1</td>
<td>14.7</td>
<td>1.59</td>
<td>33</td>
<td>5.6 x 10^-5</td>
<td>5.3 x 10^-5</td>
</tr>
<tr>
<td>PDB 32</td>
<td>59 ± 1</td>
<td>14.8</td>
<td>1.78</td>
<td>33</td>
<td>3.3 x 10^-4</td>
<td>2.3 x 10^-4</td>
</tr>
<tr>
<td>PDB 57</td>
<td>59 ± 0.5</td>
<td>15.2</td>
<td>1.85</td>
<td>32</td>
<td>4.0 x 10^-4</td>
<td>2.3 x 10^-4</td>
</tr>
<tr>
<td>PDB 29</td>
<td>79 ± 0.5</td>
<td>14.8</td>
<td>2.01</td>
<td>30</td>
<td>1.5 x 10^-3</td>
<td>7.5 x 10^-4</td>
</tr>
<tr>
<td>PDB 27</td>
<td>100</td>
<td>14.7</td>
<td>2.24</td>
<td>29</td>
<td>6.5 x 10^-3</td>
<td>2.8 x 10^-3</td>
</tr>
</tbody>
</table>

Series 3, OCP + camphor, 1.0 MPa, not annealed

<table>
<thead>
<tr>
<th>Test</th>
<th>% OCP</th>
<th>Initial length (mm)</th>
<th>Sample mass (g)</th>
<th>Finite strain (5% strain)</th>
<th>Strain rate at 10% strain</th>
<th>Strain rate at 15% strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDB 62</td>
<td>0</td>
<td>14.6</td>
<td>1.13</td>
<td>31</td>
<td>6.4 x 10^-6</td>
<td>6.3 x 10^-6</td>
</tr>
<tr>
<td>PDB 58</td>
<td>20 ± 1</td>
<td>15.2</td>
<td>1.42</td>
<td>29</td>
<td>3.1 x 10^-5</td>
<td>2.3 x 10^-5</td>
</tr>
<tr>
<td>PDB 59</td>
<td>40 ± 1</td>
<td>15.1</td>
<td>1.63</td>
<td>32</td>
<td>1.5 x 10^-4</td>
<td>9.0 x 10^-5</td>
</tr>
<tr>
<td>PDB 54</td>
<td>59 ± 3</td>
<td>15.1</td>
<td>1.79</td>
<td>30</td>
<td>6.0 x 10^-4</td>
<td>5.1 x 10^-4</td>
</tr>
<tr>
<td>PDB 53</td>
<td>75 ± 1</td>
<td>15.7</td>
<td>2.06</td>
<td>38</td>
<td>2.1 x 10^-3</td>
<td>1.1 x 10^-3</td>
</tr>
<tr>
<td>PDB 52</td>
<td>88 ± 1.5</td>
<td>14.5</td>
<td>2.05</td>
<td>34</td>
<td>8.0 x 10^-3</td>
<td>2.7 x 10^-3</td>
</tr>
<tr>
<td>PDB 50</td>
<td>100</td>
<td>15.2</td>
<td>2.31</td>
<td>43</td>
<td>7.0 x 10^-3</td>
<td>7.0 x 10^-3</td>
</tr>
</tbody>
</table>

Series 4, OCP + quartz, 0.35 MPa, not annealed

<table>
<thead>
<tr>
<th>Test</th>
<th>% OCP</th>
<th>Initial length (mm)</th>
<th>Sample mass (g)</th>
<th>Finite strain (5% strain)</th>
<th>Strain rate at 10% strain</th>
<th>Strain rate at 15% strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDB 75</td>
<td>100</td>
<td>15.0</td>
<td>2.23</td>
<td>16</td>
<td>6.0 x 10^-5</td>
<td>1.0 x 10^-5</td>
</tr>
<tr>
<td>PDB 77</td>
<td>92.4</td>
<td>14.9</td>
<td>2.27</td>
<td>21</td>
<td>4.3 x 10^-5</td>
<td>1.0 x 10^-5</td>
</tr>
<tr>
<td>PDB 78</td>
<td>87.1</td>
<td>15.6</td>
<td>2.41</td>
<td>19</td>
<td>3.0 x 10^-5</td>
<td>7.0 x 10^-5</td>
</tr>
</tbody>
</table>

TABLE 2. Experimental details of the stepping tests

<table>
<thead>
<tr>
<th>Test</th>
<th>% OCP</th>
<th>Initial length (mm)</th>
<th>Sample mass (g)</th>
<th>Number of steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDB 10</td>
<td>0</td>
<td>19.90</td>
<td>1.54</td>
<td>11</td>
</tr>
<tr>
<td>PDB 11</td>
<td>0</td>
<td>13.90</td>
<td>1.08</td>
<td>7</td>
</tr>
<tr>
<td>PDB 2</td>
<td>20 ± 2</td>
<td>15.05</td>
<td>1.39</td>
<td>8</td>
</tr>
<tr>
<td>PDB 1</td>
<td>39 ± 2</td>
<td>14.65</td>
<td>1.55</td>
<td>9</td>
</tr>
<tr>
<td>PDB 7</td>
<td>60 ± 3</td>
<td>15.02</td>
<td>1.81</td>
<td>10</td>
</tr>
<tr>
<td>PDB 16</td>
<td>80 ± 3</td>
<td>19.54</td>
<td>2.66</td>
<td>10</td>
</tr>
<tr>
<td>PDB 30</td>
<td>100</td>
<td>15.64</td>
<td>2.33</td>
<td>4</td>
</tr>
<tr>
<td>PDB 17</td>
<td>100</td>
<td>18.65</td>
<td>2.77</td>
<td>5</td>
</tr>
</tbody>
</table>

log(σ)-log(ε) plot. Linear regressions for the power-law behaviour are given in Table 3. A surprising result is that all stress exponents are about the same as for OCP, even at low fractions of OCP (Fig. 6). This causes the 20% OCP regression line to intersect the pure camphor line. There are few data in the low strain rate region, so we will not draw any conclusions from this cross-over.

Figure 7 shows the results of three series of single-load tests with various fractions of OCP and camphor.
The results are shown as strain rate–strain curves, since these show the relative strain rates and the softening–hardening behaviour. Series 1 was done with an initial stress of 0.6 MPa, series 2 and 3 with an initial stress of 1.0 MPa. The samples of series 1 and 2 were annealed prior to deformation, whereas unannealed samples were used for series 3 and 4. Two main observations can be made:

(1) The shape of the curves changes gradually from pure OCP (decreasing strain rate) to pure camphor (constant or increasing strain rate up to 10% shortening).

(2) The logarithm of the strain rate of the mixtures is roughly proportional to the fraction of the components (Fig. 8).

The size of the OCP and camphor chunks in the samples is relatively large compared with the size of the samples. There will be some effect of the distribution and shape of the pieces of OCP and camphor on the overall strain rate. One experiment was repeated under exactly the same conditions (series 2, 60% OCP, PDB 58 and 59) and yielded results that were accurate to within 10%.

4.3. OCP with rigid inclusions

The strain rate difference between camphor and OCP is about three orders of magnitude under the given conditions. One can therefore expect that camphor is virtually rigid when embedded in an OCP matrix. We therefore carried out some experiments in which the inclusions in the OCP were really rigid. We deformed samples of OCP with small fractions of well-rounded quartz sand (series 4). The grain size distribution was four equal fractions of between 0.1 and 1.0 mm. Samples were not annealed and the initial stress was 0.35 MPa. Results are shown in Fig. 8. The addition of a small fraction of rigid quartz has the same effect as the addition of a small amount of camphor, so at low fractions of camphor the camphor indeed behaves as a rigid phase. One difference in behaviour that was observed was a tendency of OCP to develop cracks and flaws emanating from the quartz grains. Experiments where this was observed showed a wide scatter in strain rate values and were not included in Tables 1 and 2. This behaviour was never observed in mixtures of camphor and OCP. The stress concentrations needed to initiate brittle failure in OCP can
Fig. 7. Strain rate ($\dot{\varepsilon}$) as a function of strain ($\varepsilon$) for all single-load experiments with mixtures: (a) series 1, initial stress 0.6 MPa, samples annealed; (b) series 2, initial stress 1.0 MPa, samples annealed; (c) series 3, initial stress 1.0 MPa, samples not annealed. Strain rates higher than about 0.01 s$^{-1}$ could not be measured. The strain rate data were derived from strain-time data with a moving three-point window scheme with $\dot{\varepsilon}_i = (\varepsilon_{i+1} - \varepsilon_{i-1})/(t_{i+1} - t_{i-1})$ and $t_i = (t_{i+1} + t_{i-1})/2$. Since the data were recorded at small intervals, the strain rate-time data were averaged over a range of $\Delta \varepsilon = 2\%$.

Fig. 8. Strain rate as a function of composition for series 1, 2 and 3 at 15% shortening and for series 4 at 5% shortening. The curves are the predictions of eqn. (5) assuming that camphor and quartz are rigid compared with OCP. A, annealed; N, not annealed.

probably not build up at camphor inclusions, since camphor is not completely rigid.

5. Discussion

The data presented here are useful for testing theoretical models to estimate the flow properties of polyphase materials. This has for instance been done by Tóth et al. [26], who applied their self-consistent model to these data and predicted the flow stress of the mixtures within 7% accuracy.

The stepping tests suggest that the camphor–OCP mixtures obey a power-law stress–strain rate relation. However, this cannot be true towards lower stresses than the range of stress values used for the experiments. Tullis et al. [27] suggested that the flow properties of a two-phase composite of power-law creep materials could be approximated with power laws as well, with the stress exponent of the composite ($n_c$) given by

$$n_c = 10^{F \log n_i + (1-F) \log n_j} \tag{2}$$

where $F$ is the fraction of each component and the subscripts represent the two phases. If we applied this to our case, we would get lower stress exponents than determined in the experiments. Equation (2) was derived from the assumption that a mixture of two power-law creep materials will also be a power-law creep material. For two power-law creep materials there will be one stress value at which the strain rates of the two materials are the same. Any mixture of these
materials must have the same strain rate at this "equiviscous point". In the log(σ)-log(ε) plot (Fig. 6) all regression lines of mixtures cross the pure camphor line at different stresses. This indicates that the assumption of a power law for mixtures is invalid over a range of stress-strain rate values extending towards the equiviscous point. Towards the equiviscous point the stress exponents of the mixtures must decrease, since the flow properties of the mixtures must remain within the bounds determined by the components. This implies that the log(ε)-fraction curve (Fig. 8) will become concave upwards towards the equiviscous point.

The reason why the experimentally determined stress exponents for OCP and camphor mixtures are of the same order as for the soft component OCP may lie in the fact that the contrast in flow properties is high under the given conditions. The difference in strain rate is about two to three orders of magnitude at a stress of 1.0 MPa. With high contrasts in flow properties between the phases the general equation for the properties of a composite \( P_c \) reduce to [28]

\[
P_c = P_c(P_{\text{matrix}}, F_{\text{inclusions}}, G)
\]  

(3)

The properties of the composite \( P_c \), which may for instance be viscosity or elasticity) are a function of the properties of the matrix phase \( P_{\text{matrix}} \), e.g. suspending fluid in a suspension), the fraction of the inclusion phase \( F_{\text{inclusions}} \) and the internal geometry \( G \) of the composite. The properties of the inclusion phase no longer play any role if the inclusion phase is effectively rigid or has no effective strength compared with the dominant or matrix phase (regimes 1 and 2 in ref. 29).

If the hard phase is the matrix phase, the mixture can be regarded as a porous aggregate of the hard phase with the pore space filled with a material with no effective strength. If the soft phase is the matrix phase, the mixture is analogous to a suspension of rigid particles in a fluid. Equations for the effective viscosity of a suspension \( \eta_s \) are of the same type as eqn. (3)[30, 31]:

\[
\eta_s = \eta_s(f(F_{\text{inclusions}}, G)
\]  

(4)

Here \( \eta_s \) is the effective viscosity of the suspending fluid and \( f \) is a function of the fraction of suspended particles and the internal geometry. This means that the flow law of the mixture \( \eta_s \) is a power law if the matrix is a power-law material (at a given \( G \)) and both will have the same stress exponent. This implies that the model of Tullis et al. [27] (eqn. [2]) may only be valid with a small contrast in effective viscosity between the phases. For a power-law matrix with rigid eqiaxed inclusions Yoon and Chen[32] propose the following equation:

\[
\dot{\varepsilon}_c = (1 - F_{\text{inclusions}})^{2 + n/2} A \sigma^n
\]  

(5)

Here \( \dot{\varepsilon}_c \) is the strain rate of the composite. In Fig. 8 one can see that there is reasonably good agreement between the strain rates predicted with eqn. [5] and our experimentally determined strain rates for fractions of OCP larger than 0.25. We therefore conclude that camphor behaves as virtually rigid inclusions and OCP as a matrix phase that dominates the flow properties of the mixtures, even at low OCP fractions. Similar results were reported by Price [33], who showed that the strength of aggregates of rock salt (soft)-anhydrite (hard) mixtures only increased significantly at anhydrite fractions of more than 0.75.

At a certain relative volume fraction of the components there will be a transition from the dominance of one phase to the other in the flow properties of a mixture. The fraction at which this occurs depends on the internal geometry of the mixture. Since the geometry of a mixture is strain dependent, so will the rheological behaviour of the mixture be strain dependent, especially near the transition fraction. Because the soft phase deforms more than the hard phase, it will have a tendency to deform into flattened inclusions that can line up to effectively become the matrix phase [9, 12, 34]. The flow properties of mixtures with low to intermediate fractions of the soft phase will become increasingly dominated by the soft phase with increasing strain. This implies major strain softening with high contrasts in flow properties. That the soft phase OCP behaves as the matrix phase in our experiments, even at low fractions of OCP, is probably due to the method of sample preparation, which causes the OCP to fill up the space between the pieces of camphor. In that situation, however, the composite properties should be nearer to the constant-stress (Reuss) bound than to the constant-strain rate (Voigt) boundary. This is not what is observed here: the mixtures are relatively hard. This may be due to the strain-sensitive behaviour of camp-hor. The flow properties of camphor were determined from experiments at up to 25% shortening. The camp-hor inclusions in the mixtures deform much less than this 25% and do not achieve steady state, because the deformation is accommodated by the OCP. Camphor may then be effectively much harder in the mixtures than determined with the experiments with pure cam-phor. The properties will move towards the constant-stress bound if one corrects for this.

The experimental results described here can be applied to deforming polymineralic rocks, where the difference in effective viscosity between the different minerals is of the same order. An example is a quartz-feldspar rock such as a granite, which is composed of about 60% feldspars and 40% quartz. Most deformation in a quartz-feldspar rock is accommodated by the quartz [29] during high temperature deformation. Although the feldspar usually forms a
connected network in an undeformed granite, the quartz usually forms a matrix phase with feldspar inclusions after some deformation [34]. One would then expect the stress exponent of the quartz–feldspar rock to be the same as that of the power-law creep material quartz. The strain rate would then be about 15–40 times lower (using eqn. (5)] than that for pure quartz at a given stress, depending on the stress exponent of quartz, which may range from 1.9 to 4 (depending on the water content) [7, 8].

6. Conclusions

We have used soft crystalline ductile power-law creep materials, OCP and camphor, as mechanical analogues to rocks. With these materials we have obtained a data set on the flow properties of two-phase rock-like mixtures.

Under the given experimental conditions the mixtures obey a power-law relation between the strain rate and stress. The stress exponent was approximately equal to that of the soft component OCP for all mixtures ranging from 20% to 90% OCP. It is argued that the flow properties of these mixtures are a function only of the flow properties of the soft phase and of the volume fraction and distribution of the hard phase. The hard phase camphor behaves as virtually rigid inclusions. This implies that a two-phase material can be modelled as a matrix with rigid inclusions, using models such as that of Yoon and Chen [32], if the contrast in effective viscosity of the components is more than two orders of magnitude.

The flow properties of both components determine the properties of a mixture with a lower contrast in effective viscosity (towards the equiviscous point). The flow properties of a mixture of two power-law creep materials with different stress exponents can therefore not be described with a single power law for a stress–strain rate range extending near the equiviscous point.

The flow properties of a mixture depend on the internal geometry of the hard phase and therefore on the strain at low to intermediate volume fractions of the soft phase.

Acknowledgments

The authors thank the two reviewers for the comments and useful suggestions. P.D.B. acknowledges the financial support by the Netherlands Organisation for Scientific Research (NWO).

References

22. J. L. Urai, F. J. Humphreys and S. E. Burrows, In-situ studies of the deformation and dynamic recrystallization of


