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Rheology and density of glucose syrup and honey: Determining their suitability for usage in analogue and fluid dynamic models of geological processes

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A B S T R A C T

Analogue models of lithospheric deformation and fluid dynamic models of mantle flow mostly use some kind of syrup such as honey or glucose syrup to simulate the low-viscosity sub-lithospheric mantle. This paper describes detailed rheological tests and density measurements of three brands of glucose syrup and three brands of honey. Additional tests have been done for one brand of glucose syrup that was diluted with water to various degrees (2%, 5% and 10% by weight). The rheological tests have been done to test the effect of shear strain, shear rate and temperature on the dynamic viscosity of the syrup. The results show that the viscosity of all glucose syrups and honeys is independent of shear strain (i.e. no strain hardening or softening). The viscosity of the glucose syrups is independent of shear rate ($\dot{\gamma}$), i.e. linear-viscous or Newtonian, in the range $\dot{\gamma} = 10^{-4}-10^{0}$ s^{-1} with stress exponents that are almost identical to one ($n = 0.995-1.004$). All the honeys show a very weak, but consistent, decrease in viscosity with increasing shear rate of 7–14% from 10^{-3} to 10^{0} s^{-1} and have stress exponents more distinct from one ($n = 1.007-1.026$). All syrups have a viscosity that is strongly dependent on temperature in the range 0–50 °C, where viscosity decreases with increasing temperature. Such decrease can be fitted with exponential and Arrhenius functions, with the latter giving the best results. Furthermore, the viscosity of glucose syrup decreases approximately exponentially with increasing water content. Oscillation tests indicate that the rheology of all the syrups is entirely dominated by viscous behaviour and not by elastic behaviour at frequencies of $10^{-3}-10^{2}$ Hz. Finally, the density investigations show that the density of glucose syrup and honey decreases approximately linearly with increasing temperature in the range 10 –70 °C, with coefficients of thermal volumetric expansion at 20 °C of 3.89–3.95 × 10^{-4} °C^{-1} and 4.57 –4.81 × 10^{-4} °C^{-1} for glucose syrup and honey, respectively. The new results demonstrate that glucose syrups and (to a lesser degree) honeys are well suited for usage in analogue and fluid dynamic experiments to represent linear-viscous strain independent and shear rate independent rheologies to model geological processes. Glucose syrups have the added advantage of being more transparent than honeys, allowing for accurately resolving and quantifying flow patterns in the fluid during a model run.

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1. Introduction

Geoscientists have used analogue modelling techniques of crustal deformation and mantle dynamics for some 200 years (Koyi, 1997; Ranalli, 2001; Schellart, 2002). In those 200 years, a large variety of analogue materials has been used to simulate the deformation of rocks at various pressure and temperature conditions. For most of these analogue materials extensive physical and rheological tests have been conducted to investigate the properties of these materials to determine their suitability for analogue

modelling. Examples include silicone polymers (e.g. Weijermars, 1986; ten Grotenhuis et al., 2002; Schrank et al., 2008; Boutelier et al., 2008), granular materials (e.g. Mandl et al., 1977; Krantz, 1991; Cobbold and Castro, 1999; Schellart, 2000; Rossi and Storti, 2003; Lohrmann et al., 2003; van Mechelen, 2004; Panien et al., 2006; Maillot and Koyi, 2006; Galland et al., 2006; Schreurs et al., 2006; Cruz et al., 2008), clay (e.g. Eisenstadt and Sims, 2005), water-oil emulsions (e.g. Verschuren et al., 1996), paraffin wax (e.g. Rossetti et al., 1999), gelatins (e.g. Di Giuseppe et al., 2009), rosins (e.g. Cobbold and Jackson, 1992), and plasticines (e.g. Schrank et al., 2008; Boutelier et al., 2008). In contrast, there are no detailed investigations in the Geology and Geophysics literature of syrups such as honey, glucose syrup, corn syrup and golden syrup, despite their extensive usage in scaled laboratory experiments of

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lithospheric and mantle-scale processes. There are, however, several detailed rheological investigations of honey in the food engineering literature (e.g. Mossel et al., 2000; Lazaridou et al., 2004; Yanniotis et al., 2006; Gómez-Díaz et al., 2009).

Syrups have been used in isothermal experiments of lithospheric-scale processes, in which the syrup simulates the asthenosphere to provide isostatic support to the overlying model lithosphere (e.g. Davy and Cobbold, 1988; Ratschbacher et al., 1991; Benes and Davy, 1996; Hatzfeld et al., 1997; Martinod et al., 2000; Schellart and Lister, 2005; Cruden et al., 2006; Schueller and Davy, 2008). Syrups have been used to simulate magma in analogue experiments simulating dike intrusions, sill intrusions and other types of intrusions (e.g. Mathieu et al., 2008; Kervyn et al., 2009). Syrups have also frequently been used to simulate the sub-lithospheric mantle in experiments of subduction, where the main role of the syrup is to exert a viscous drag on the sinking slab (e.g. Kincaid and Olson, 1987; Funiciello et al., 2003; Schellart, 2004, 2010; Guillaume et al., 2009). Then, syrups have been used in different types of thermal convection experiments, in particular to simulate mantle plume dynamics (e.g. Griffiths and Campbell, 1990; Jellinek et al., 2003; Kerr and Mériaux, 2004; Gonnermann et al., 2004; Kumagai et al., 2007; Davaille et al., 2011).

In several of these previous works, the dynamic viscosity (η) of the syrup is given as some rounded number (e.g. $\eta = 10$ or 100 Pa s) or as a range (e.g. 40–400 Pa s), suggesting that the viscosity was only roughly determined or estimated. In addition, it is mostly assumed that the rheology of such syrups is linear-viscous (Newtonian), meaning that there is a linear relationship between shear stress and shear strain rate, and thus that the viscosity of such syrups is constant and independent of strain rate. Furthermore, the viscosity of many syrups is thought to depend on temperature, but this dependence is not very well quantified. Preliminary investigations by Schellart (2009), using a sinking sphere viscometer, show that the dynamic viscosity (η) of a particular glucose syrup is roughly exponentially dependent on temperature with $\eta \approx Ae^{BT}$ (where A and B are constants and T is the temperature), while work from Davaille et al. (2011) indicates that the viscosity of a particular glucose syrup best fits a more complex exponential function $\eta = \exp(8.283 \times 10^{-4}T^2 - 0.1551T + 5.251)$.

This paper presents detailed rheological investigations of different types and brands of glucose syrup and honey, including glucose syrup diluted with water. These investigations are done in parallel with density investigations for these syrups. The results indicate that the viscosity of the glucose syrups and honeys is independent of strain, that the viscosity of the glucose syrups is independent of shear rate, and that the viscosity dependence on temperature best fits an Arrhenius function while that on wt% of added water satisfactorily fits an exponential function. The results further indicate that the density is approximately linearly dependent on temperature. Finally, it is found that the elastic behaviour of the glucose syrups and honeys is negligible, even at high frequencies, indicating that at laboratory strain rates (10^{-4}–10^{-1} s^{-1}) the syrups exert only a viscous response to an applied stress.

2. Methods

2.1. Materials

The materials investigated in this paper are different brands of glucose syrup and honey. Glucose syrup is a liquid starch hydrolysate of mono-saccharides, di-saccharides and higher-saccharides, and is most often made from corn starch. It is therefore also frequently referred to as corn syrup. Glucose syrup mostly consists of carbohydrates ($\sim$77–82% by weight, mostly glucose) and water. Honey is a natural product that is produced by bees using nectar from flowers and is mainly a mix of sugar carbohydrates (82–83% by weight) and water. The carbohydrates in honey mainly consist of fructose (38%) and glucose (31%), and also maltose, sucrose and complex carbohydrates. The average water content of honey is $\sim$17 wt%, but a wide range has been reported in previous studies, including 17–23% (Anupama et al., 2003), 13–19% (Lazaridou et al., 2004), 15–17% (Yanniotis et al., 2006), and 17–18% (Gómez-Díaz et al., 2009).

Three different brands of glucose syrup have been tested, namely Colonial Farms Glucose Syrup (derived from corn starch with 81% carbohydrates), Manildra Glucose Syrup (no details available) and Queen Glucose Syrup (derived from corn starch with 81% carbohydrates). In addition, three different brands of honey have been tested, namely Beechworth Honey (82.1% carbohydrates), Australian Rainforest Honey (83.1% carbohydrates) and Capilano Honey (83.1% carbohydrates). The honeys have a light brown-orange colour and are moderately transparent, while the glucose syrups have a light yellow-white colour and are significantly transparent. From the pure Colonial Farms syrup (Colonial 100%) three diluted versions have been produced to investigate the effect of water on the physical properties of glucose syrup. These three syrups, Colonial 98%, Colonial 95% and Colonial 90%, have been mixed with 2%, 5% and 10% water ($\pm$0.05%) (by weight), respectively. The nine different syrups and their physical properties are summarised in Table 1.

Table 1
Physical properties of the different glucose syrups and honeys. ρ is the density; α_V is the coefficient of thermal volumetric expansion; η is the dynamic viscosity; n is the stress exponent (i.e. $\tau^n = \eta^* \dot{\gamma}$, where τ is the shear stress and η^* is the effective viscosity), with $n = 1$ indicating a linear-viscous (Newtonian) rheology and $n \neq 1$ indicating a power-law rheology; T is the temperature; r^2 is the coefficient of determination; A and B are the factors in the exponential function $\eta = Ae^{BT}$; η_0 is the pre-exponential factor for the Arrhenius function; and E is the activation energy. Note that Colonial 100% is pure Colonial glucose syrup, while Colonial 98%, 95% and 90% have been diluted with 2.00%, 5.00% and 10.00% water ($\pm$0.05%) (by weight), respectively.

Material	ρ at 20 °C [kg m^{-3}]	α_V at 20 °C ($\times 10^{-4}$) [°C^{-1}]	η at 20 °C [Pa s]	n	Exponential function			Arrhenius function		
					A [Pa s]	B [T^{-1}]	r^2	η_0 [Pa s]	E [kJ mol^{-1}]	r^2
Glucose syrups:										
Colonial 100%	1426.77	3.91	454.7	1.0023	12434	−0.149	0.9824	1.33×10^{-17}	110.18	0.9933
Colonial 98%	1415.62	3.93	179.0	1.0016	3673.5	−0.137	0.9835	2.41×10^{-16}	100.79	0.9930
Colonial 95%	1397.82	3.95	59.5	1.0038	867.18	−0.122	0.9844	7.01×10^{-15}	89.80	0.9936
Colonial 90%	1373.26	3.95	11.4	0.9948	110.14	−0.101	0.9821	6.84×10^{-13}	74.64	0.9921
Manildra	1427.04	3.94	192.3	0.9985	5515.2	−0.151	0.9824	3.39×10^{-18}	111.44	0.9922
Queen	1430.48	3.89	515.7	1.0027	14975	−0.154	0.9824	3.07×10^{-18}	113.95	0.9923
Honeys:										
Beechworth	1429.16	4.57	33.3	1.0259	704.63	−0.139	0.9913	2.28×10^{-17}	102.38	0.9976
Rainforest	1430.28	4.81	37.3	1.0071	849.96	−0.137	0.9925	4.55×10^{-17}	101.23	0.9976
Capilano	1430.72	4.71	34.6	1.0215	774.50	−0.137	0.9916	4.36×10^{-17}	101.11	0.9974

2.2. Rheological tests

The rheological properties of the syrups were tested using a Physica MCR 301 rheometer from Anton Paar, which has a parallel plate geometry set-up with a fixed lower plate and an upper plate (referred to as geometry) that can rotate or oscillate (Fig. 1). The rheometer can do tests with controlled shear rate and controlled shear stress. For the measurements presented here, shear rate is imposed, while shear stress is measured. The viscosity of glucose syrups, honeys and other syrups is strongly dependent on temperature, and therefore a strong control on temperature during measurements is required. The rheometer has a Peltier plate at the bottom which controls temperature in the range −40 to 200 °C with an accuracy of 0.01 °C. Furthermore, to minimise vertical and horizontal temperature gradients in the sample, and to minimise temperature fluctuations during a test, an active Peltier-controlled hood was used as a cover (Fig. 1), which controls the temperature within the hood to match that of the bottom Peltier plate. With such a set-up, average sample temperature has a maximum deviation of ± 0.1 °C from the set temperature, while temperature gradients in the horizontal and vertical direction are lower than ± 0.2 °C (deviation from the average temperature) across the sample for the temperature range −40 to 150 °C (Anton Paar Physica MCR technical specifications). As the temperature range for the rheological tests described in this paper is smaller (0−50 °C) and closer to room temperature, temperature gradients and deviations from the set temperature are expected to be even less.

During the preparation of a rheological test, a thin layer of syrup is placed on the bottom plate of the rheometer using a syringe, after which the top plate is lowered to obtain the desired gap width (1 mm in all the tests presented here). Even very small gas bubbles (<0.1 mm) could be detected in the syrup in the syringe and were prevented from entering the sample located on the rheometer.

An unfortunate side-effect of the materials is that they dehydrate relatively quickly when exposed to air, in particular the glucose syrups. This results in formation of a dehydrated syrup skin whose viscosity is orders of magnitude higher than that of the non-dehydrated syrup. To avoid dehydration during the measurements, all syrups were coated with a layer of very low-viscosity vegetable oil ($\eta = 0.064$ Pa s at 20 °C) at their outer edge (Fig. 1). As the syrups and the vegetable oil are immiscible, this proved very effective. Fig. 2 shows six rotational constant shear rate tests for Colonial glucose (100%), Colonial glucose (95%) and Beechworth honey of which three are with and three are without the vegetable oil

Fig. 2. Apparent dynamic viscosity for Colonial glucose syrup (100%), Colonial glucose syrup (95%) and Beechworth honey as a function of time showing the progressive increase in viscosity as an effect of dehydration of the sample at its outer edge. In one test dehydration is minimised by coating the outside edge of the syrup sample with a very low-viscosity vegetable oil ($\eta = 0.064$ Pa s at 20 °C). In another test dehydration is significant, as the outer edge of the syrup sample is exposed to air (at 21 °C and 58% relative humidity for Colonial 100%, at 21 °C and 48% relative humidity for Colonial 95%, and at 20 °C and 47% relative humidity for Beechworth). Temperature of sample is constant and 20 °C; the shear rate is also constant and 0.05 s^{-1}.

coating. The coated Colonial 100% test shows an increase in viscosity of only 0.2−0.6% after 1 h of testing and only 2−3% after 6 h of testing. The coated honey test shows an increase in viscosity of 3% after 1 h of testing, and 11% after 6 h of testing. In contrast, the uncoated glucose syrup tests show a very rapid increase in apparent viscosity, in particular in the first hour when it increases between one and two orders of magnitude. The uncoated honey test shows a mild increase in apparent viscosity throughout the test with an increase in viscosity of 21% after 1 h of testing, and 49% after 6 h of testing.

The effect of the added vegetable oil on the accuracy of the measurements (due to the additional shear drag exerted by the vegetable oil) is minimal ($\ll 1\%$) considering that the sample viscosity varies between 1.9×10^2 and 1.6×10^6 times that of the oil and because the oil is only applied to the outer edge of the sample. The rheometer machine accuracy in the torque is $\pm 0.5\%$ (Physica MCR 301 user manual), while the accuracy due to sample preparation in the rheometer is estimated at $\pm 2.5\%$, resulting in a combined accuracy of some $\pm 3\%$.

For each material results from four main rheological tests are presented: (1) A rotation test at constant shear rate to investigate if the viscosity of the material is dependent on shear strain; (2) A rotation test at different shear rates to investigate if the viscosity of the material is dependent on shear rate; (3) A rotation test at different temperatures to investigate if the viscosity of the material is dependent on temperature; and (4) A shear strain oscillation test to investigate the elastic and viscous response of the material at different oscillation frequencies.

2.3. Density tests

The density measurements were done using a DMA 4500 M density meter from Anton Paar for a temperature range of 0−90 °C. The apparatus measures densities at an accuracy of 0.0001 g/cm^3 and temperature can be set with an accuracy of 0.01 °C. The coefficient of thermal volumetric expansion (α_V) can be calculated as such
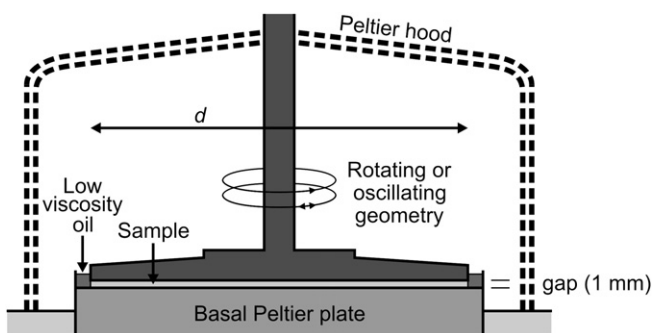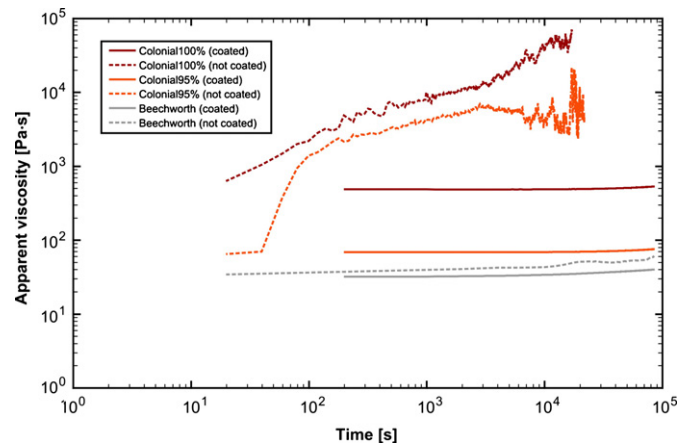

Fig. 1. Schematic drawing of the stress- or strain rate-controlled rheometer with a rotating or oscillating parallel plate geometry (geometry diameters (d) that were used were 25 mm and 50 mm), a fixed basal plate and in between a gap that is filled with the sample. The gap is constant during an experimental run (here 1.000 mm). The outer edge of the sample is coated with a very low-viscosity vegetable oil (η decreases from 0.18 Pa s at 0 °C to 0.02 Pa s at 50 °C, viscosity is strain and shear rate independent) to minimise dehydration of the sample during testing.

$$\alpha_V = \frac{1}{V_1} \frac{V_2 - V_1}{T_2 - T_1} \qquad (1)$$

where V_1 and V_2 are the volumes (in m^3) at temperatures T_1 and T_2, respectively. From measuring the density (ρ) of the sample at different temperatures, one can obtain α_V using

$$\alpha_V = \frac{1}{T_2 - T_1}\frac{\rho_1 - \rho_2}{\rho_2} \qquad (2)$$

Here, ρ_1 and ρ_2 are the densities at temperatures T_1 and T_2, respectively.

3. Results

3.1. Rheology

3.1.1. Viscosity dependence on strain (strain hardening/softening)

The potential dependence of a sample on the total amount of shear strain (γ) is investigated by applying a constant shear rate ($\dot\gamma = \gamma/t = 0.05$ s^{-1}, where t is time, $\gamma = \tan(\phi)$ and ϕ is the shear angle) to the sample for 2000 s, resulting in a shear strain that increases from $\gamma = 0$ to $\gamma = 100$. Temperature was held constant at 20.00 °C. The potential dependence of the viscosity of the different syrups on the total amount of shear strain is shown in Fig. 3a. The curves for all materials show nearly constant viscosity values with increasing strain. The mean deviation and median deviation from the mean value for each material never exceed 0.37% and 0.33%, respectively, and the maximum range of observed deviations is relatively small (from −1.4% to 1.1%). Such minimal deviations and relatively constant values indicate that the different syrups do not experience any strain hardening or strain softening, and that their viscosity does not depend on strain.

The viscosity of the three different brands of pure glucose syrup varies considerably (mean $\eta = 192.3$–515.7 Pa s), while the viscosity of the three different brands of honey is very similar (mean $\eta = 33.3$–37.3 Pa s).

The measurements for Colonial 100%, 98%, 95% and 90% indicate that the viscosity of glucose syrup is significantly dependent on its water content. Fig. 4 shows the viscosity for these four syrups as a function of weight fraction of added water at six different temperatures. For each curve the viscosity decreases with increasing water content following a trend that is approximately exponential. At 20 °C the viscosity of the Colonial glucose–water mix decreases some 30% for every 1% of water that is added to the mix. The curves become progressively steeper with decreasing temperature, indicating that the effect of addition of water on viscosity increases with decreasing temperature.

3.1.2. Viscosity dependence on shear rate

The potential dependence of the viscosity of a sample on shear rate is investigated by doing rotational stepwise shear rate tests at constant temperature (20.00 °C), where $\dot\gamma$ varies between 10^{-4} and 10^0 s^{-1}. Measurements have been done in which $\dot\gamma$ is imposed and the resulting shear stress (τ) is measured. With this type of test one can determine if the material is characterised by linear-viscous (Newtonian) behaviour (shear stress exponent $n = 1$) in the investigated shear rate range or if it shows power-law behaviour ($n \neq 1$). The potential dependence of the viscosity of the different syrups on the shear rate is shown in Fig. 3b. The curves for all the glucose syrups show nearly constant viscosity values with increasing strain rate from 10^{-3} to 10^0 s^{-1}. The maximum range of observed deviations from the mean value for each syrup is relatively small, from −6.0% to 2.0%. Such small deviations and relatively constant values indicate that the different glucose syrups essentially have a shear rate independent (linear or Newtonian) viscosity. Indeed, for the six glucose syrups summarised in Table 1, $n = 0.9948$–1.0038, which is very close to 1. In the range 10^{-4}–10^{-3} s^{-1} the spread in

data is somewhat larger and somewhat erratic, which is because at these shear rates the rheometer is close to its minimum resolvable torque value.

For the three brands of honey there is a consistent, although relatively small, decrease in viscosity of 7–14% with increasing shear rate from 10^{-3} to 10^0 s^{-1}. The viscosities of the honeys thus show a very small dependence on shear rate, as also indicated by their stress exponents, which are consistently larger than one ($n = 1.0071$–1.0259, Table 1).

3.1.3. Viscosity dependence on temperature

The dependence of the viscosity of a sample on temperature is investigated by doing rotational stepwise temperature tests at constant shear rate (0.05 s^{-1}). Temperature (T) was varied between 0 and 50 °C. Measurements were done at 2 °C intervals following a stepwise ramp. Control tests were carried out to investigate the duration of each temperature step to ensure thermal equilibration throughout the entire sample. A duration of 120 s for each individual step was found to ensure thermal equilibrium throughout the sample. An initial thermal equilibration time of at least 600 s (10 min) was introduced before the start of each test run. Measurements have been done in which strain rate is imposed and the resulting shear stress is measured.

Fig. 3c shows that for all the materials the viscosity rapidly decreases with increasing temperature following a non-linear convex-downward trend. With an increase in temperature from 0 to 50 °C the viscosity of the pure glucose syrups decreases by a factor of ~2000–2500, while that of the honeys decreases by a factor ~1100. The viscosity dependence on temperature decreases with increasing water content: for an increase in temperature from 0 to 50 °C the viscosity of Colonial 100% decreases by a factor of ~2000, while that of Colonial 90% decreases only by a factor of ~170.

The viscosity dependence of the glucose syrups and honeys on temperature can be approximately fitted with an exponential function, but the fact that all the lines in Fig. 3c show significant curvature indicates that this is a rough approximation. Nevertheless, exponential best-fit curves provide a reasonable fit with good correlation coefficients and coefficients of determination (r^2) (Table 1). The exponential best-fit lines for the three undiluted glucose syrups show very similar exponents, indicating that with every 1 °C increase the viscosity decreases by ~13.8–14.3%, while those for the three honeys also show very similar exponents, indicating that with every 1 °C increase the viscosity decreases by ~12.8–13.0%.

Fig. 3d shows typical Arrhenius plots for two glucose syrups (Colonial 100% and Colonial 95%) and one honey (Rainforest), showing approximately linear relationships between the inverse of temperature (T^{-1}) and the natural logarithm of viscosity, $\ln(\eta)$. This indicates that the viscosity dependence on temperature can be fitted using an Arrhenius type function

$$\eta = \eta_0 e^{-\left(\frac{E}{RT}\right)} \qquad (3)$$

where η is the dynamic viscosity, η_0 is the pre-exponential factor, E is the activation energy, R is the gas constant (8.314472 J K^{-1} mol^{-1}) and T is the temperature (in Kelvin). For all the investigated materials the fit is improved with an Arrhenius function compared to an exponential function, with higher r^2 values (Table 1). The activation energies for the undiluted glucose syrups are very similar ($E = 110$–114 kJ mol^{-1}), and those for the honeys are also very similar ($E = 101$–102 kJ mol^{-1}). In Fig. 3c it can be observed that with increase in water content of the Colonial glucose syrup, the curves become less steep, indicating a decrease in viscosity dependence on temperature with increasing water content.
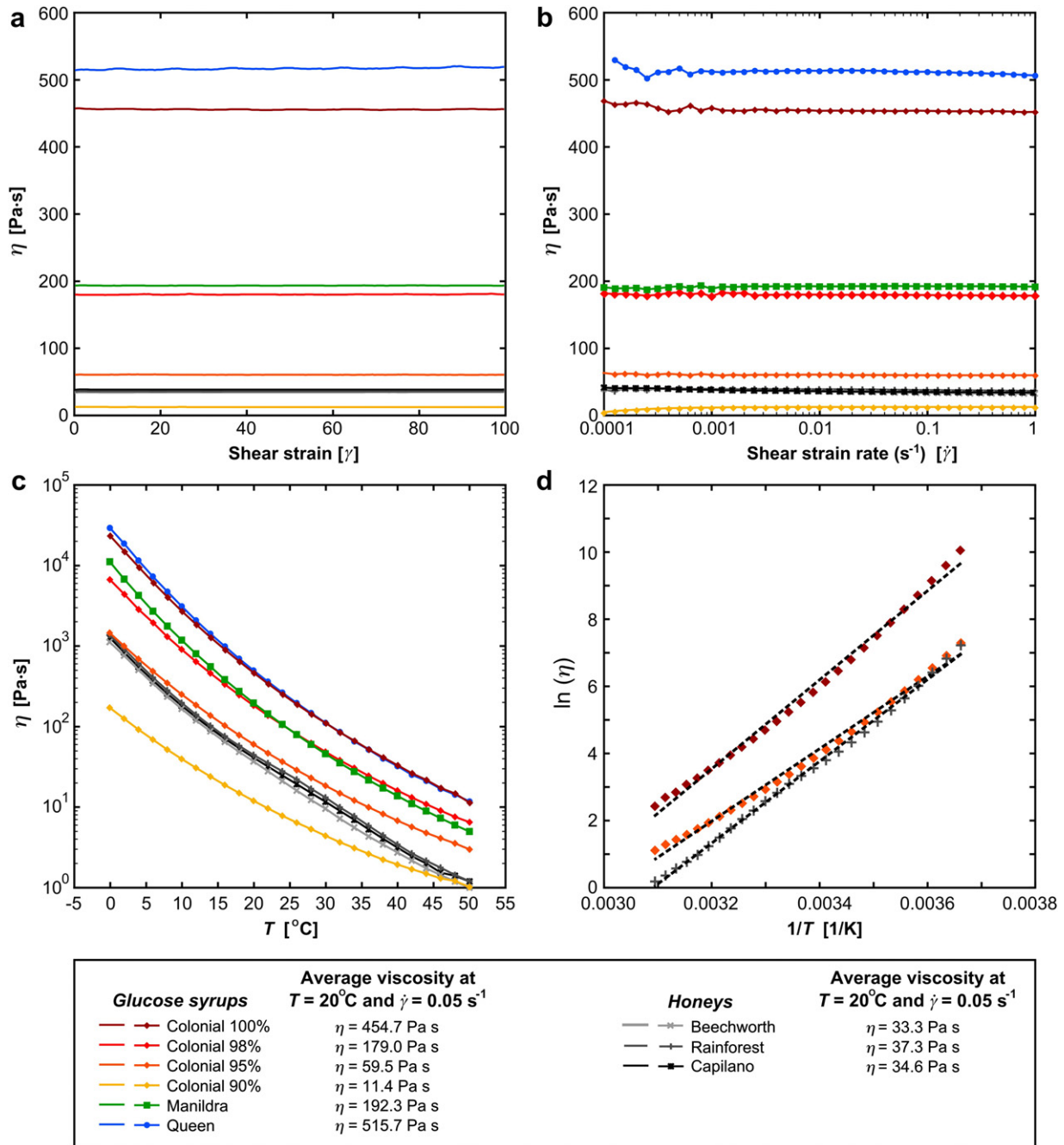
Fig. 3. Dynamic viscosity (η) for the different syrups as a function of: (a) shear strain (γ); (b) shear rate ($\dot{\gamma}$); and (c) temperature (T). (d) Typical Arrhenius plots for two glucose syrups (Colonial 100% and Colonial 95%) and one honey (Rainforest), showing an approximately linear relationship between the inverse of temperature (T^{-1}) and the natural logarithm of viscosity $\ln(\eta)$. Dashed lines in (d) are linear best-fit lines. In (a) and (b) the temperature is constant (20.00 °C). In (a), (c) and (d) the shear rate is constant (0.05 s^{-1}).

3.1.4. Viscous versus elastic behaviour

Oscillation tests were performed in which a sinusoidal shear strain function was applied to a sample to investigate its elastic and viscous properties. For an ideal elastic material, all the elastic energy is recoverable, the shear stress and shear strain are proportional and are in phase with each other. For an ideal fluid, none of the elastic energy is recoverable and the shear stress and shear strain are out of phase from one other by 90° (Ferry, 1980; Nelson and Dealy, 1993). For a linear-viscous (Newtonian) fluid, the shear strain rate and shear stress are proportional to one another. For a visco-elastic material the relation between stress, strain and strain rate is complex and involves both elastic and

viscous responses in the material. The resistance to deformation of a visco-elastic material is defined by the complex shear modulus (G), which contains a storage (elastic) modulus (G′) and a loss (viscous) modulus (G″) (Ferry, 1980; Nelson and Dealy, 1993):

$$G = G' + iG'' \tag{4}$$

where $i = (-1)^{1/2}$. The storage modulus is defined as the shear stress that is in phase with the shear strain in a sinusoidal shear deformation divided by the shear strain, while the loss modulus is defined as the shear stress that is 90° out of phase with the shear strain divided by the shear strain (Ferry, 1980). G′ and G″ can be calculated as follows:
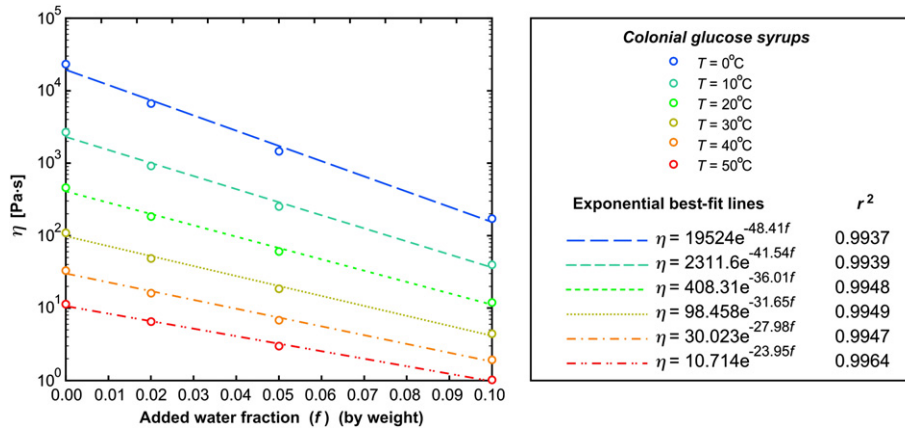
Fig. 4. Diagram illustrating the effect of added fraction of water to glucose syrup (fraction f by weight) on the dynamic viscosity (η) of the mix. Data points at $f = 0.00$ (0%), $f = 0.02$ (2%), $f = 0.05$ (5%) and $f = 0.10$ (10%) of added water are for Colonial 100%, Colonial 98%, Colonial 95% and Colonial 90%, respectively. Six datasets are plotted, each at a different sample temperature (0, 10, 20, 30, 40 and 50 °C). Dashed lines are exponential best-fit curves for each dataset (see inset). r^2 is the coefficient of determination for the best-fit curves.

$$G' = \frac{\tau_0}{\gamma_0} \cos(\delta) \qquad (5)$$

$$G'' = \frac{\tau_0}{\gamma_0} \sin(\delta) \qquad (6)$$

where δ is the phase shift angle, τ_0 is the shear stress amplitude and γ_0 is the shear strain amplitude. In case $\delta = 0$, the deformation is purely elastic; in case $\delta = 90°$ the deformation is purely viscous; and in case $0 < \delta < 90°$ deformation has both elastic and viscous components. The rheometer applies a given sinusoidal shear strain with amplitude γ_0 at different frequencies and measures τ_0 and δ from which G' and G'' can be calculated. One can then determine which is the larger of the two at the specified frequency. In case $G' > G''$, then the elastic behaviour of the material dominates; in case $G'' > G'$, then the viscous behaviour dominates. The inverse of the frequency at which $G' = G''$ is the Maxwell relaxation time.

Fig. 5 shows frequency plots for the six glucose syrups and the three honeys. The frequency (ω) was varied between 10^{-4} and 10^2 Hz, while a constant shear strain amplitude of $\gamma_0 = 0.05$ was applied. For all materials and at all the investigated frequencies G'' dominates over G', indicating that the viscous response dominates over the elastic response.

The strain rates that are operative at frequencies of $10^{-3}–10^{-1}$ Hz are most applicable to strain rates that occur in laboratory experiments, which are typically in the range $\sim 10^{-4}–10^{-1}\,\mathrm{s}^{-1}$. For example, typical shear rates in a glucose syrup "upper mantle" due to shear traction between a subducting plate and underlying mantle are of the order $0.2–2.3 \times 10^{-3}\,\mathrm{s}^{-1}$ (Schellart, 2004), while shear rates of the order $1.4 \times 10^{-4}\,\mathrm{s}^{-1}$ have been reported for a glucose syrup asthenosphere underlying a collapsing continental lithosphere (Schellart and Lister, 2005). At frequencies of $10^{-3}–10^{-1}$ Hz, G'' is between one and three orders of magnitude larger than G' (Fig. 5). This indicates that glucose syrups only provide a viscous response at experimental strain rates. Even at the highest frequency investigated (100 Hz), $G'' > G'$ for all materials investigated, indicating that the Maxwell relaxation time is smaller than 0.01 s.

3.2. Density and thermal expansion

Most solids and fluids expand with increasing temperature resulting in a decrease in density. This behaviour is also observed for the glucose syrups and the honeys, whose density has been measured in the temperature range 0–90 °C (Fig. 6a–b). At room temperature (20 °C), the pure glucose syrups and the honeys have very similar
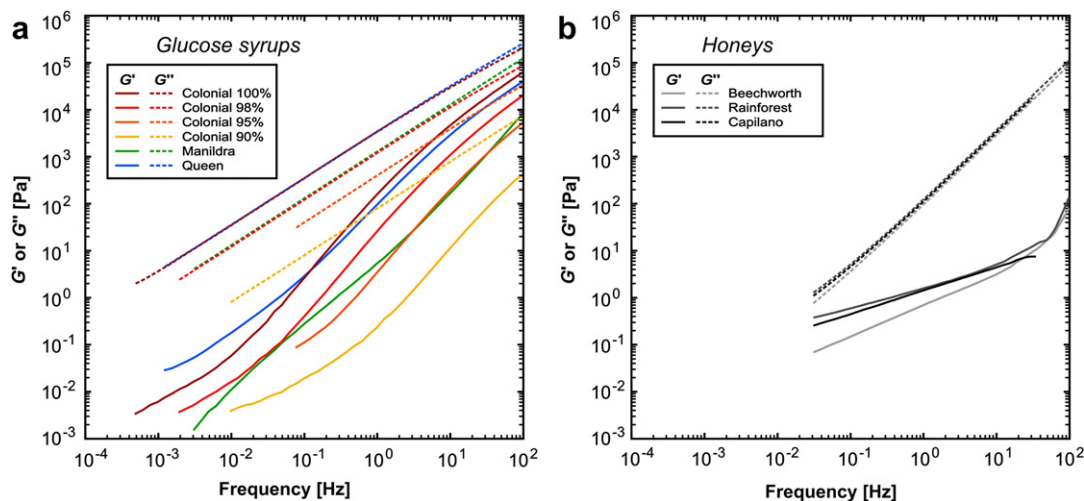

Fig. 5. Storage modulus (G') and loss modulus (G'') as measured with oscillation tests for (a) six types of glucose syrup, and (b) three types of honey. All glucose syrups and honeys are dominated by viscous behaviour, even at the highest frequency, because $G'' > G'$. Shear strain amplitude $\gamma_0 = 0.05$.
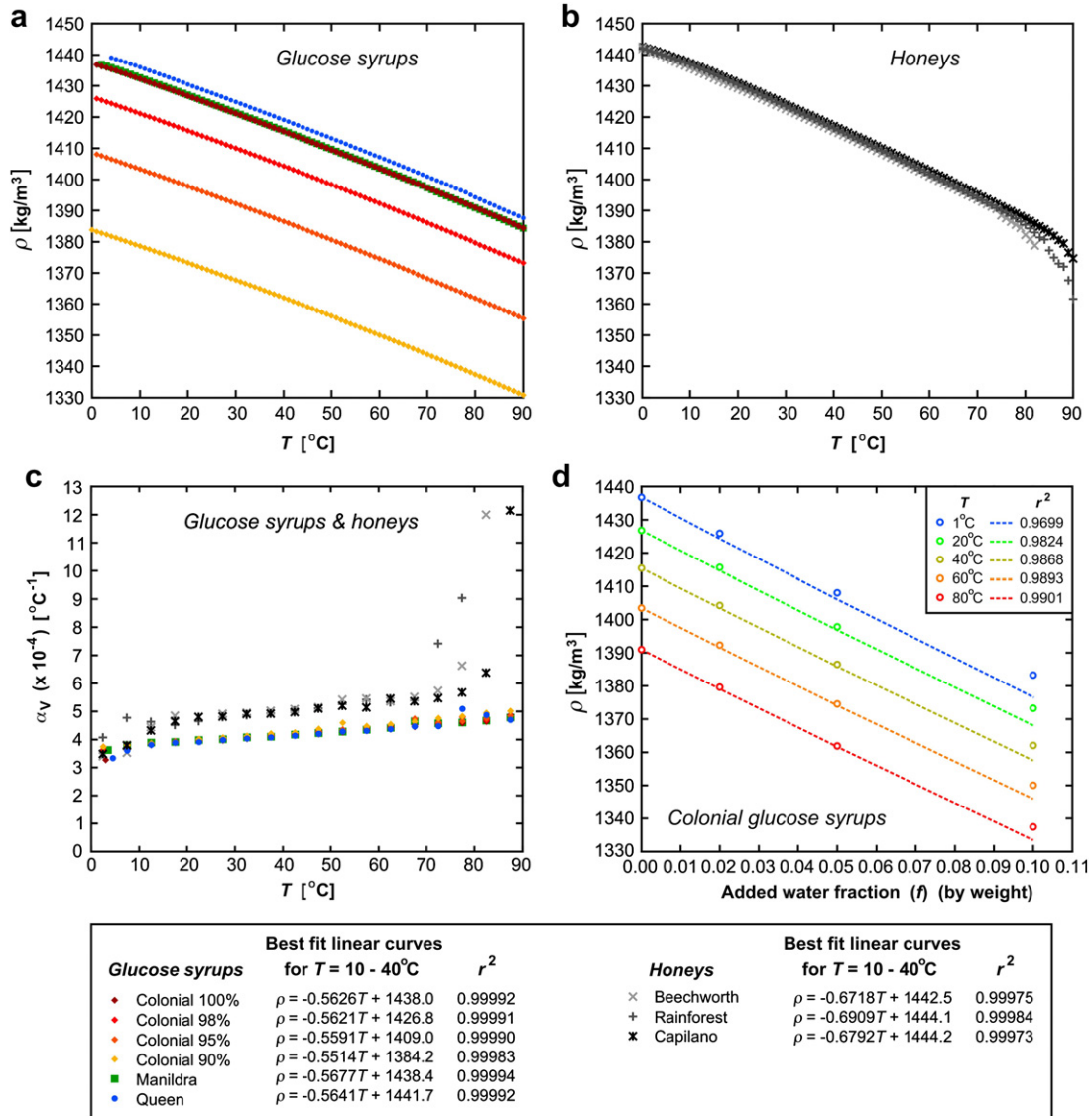
Fig. 6. (a) Dependence of the density (ρ) for six glucose syrups on temperature. (b) Dependence of ρ for three honeys on temperature. (c) Coefficient of thermal volumetric expansion (α_V) for the glucose syrups and honeys as a function of temperature as obtained from the data plotted in (a) and (b) using equation (2). (d) Dependence of ρ on weight fraction of water (f) for the Colonial glucose syrup. r^2 in inset of (d) is the coefficient of determination for the curves that were plotted using equation (7).

densities in the range 1427−1431 kg/m³. The density of the honeys has a larger dependence on temperature than that of the glucose syrups as indicated by the steeper curves for the honeys (cf. Fig. 6a and b) and by the larger coefficients of thermal volumetric expansion (α_V) (Fig. 6c). For all the glucose syrups α_V at 20 °C is limited to a small range of $3.89–3.95 \times 10^{-4}$ °C⁻¹. For the honeys the range is somewhat broader with $\alpha_V = 4.57–4.81 \times 10^{-4}$ °C⁻¹. As shown in Fig. 6c, α_V increases mildly following a sub-linear trend in the temperature range 10−70 °C from $\sim 3.8 \times 10^{-4}$ to $\sim 4.5 \times 10^{-4}$ °C⁻¹ for the glucose syrups and from $\sim 4.5 \times 10^{-4}$ to $\sim 5.5 \times 10^{-4}$ °C⁻¹ for the honeys. At $\sim 75–85$ °C the honey starts to boil by forming very small bubbles (~ 0.1 mm in diameter), which subsequently grow.

With increasing water content the density of the Colonial−water mix decreases. This is expected when a lower density fluid (water) is added to a higher-density fluid (syrup). The new density of the diluted glucose syrup (ρ_{MIX}) approximately follows:

$$\rho_{\text{MIX}} = \frac{(m_{\text{SYRUP}} + m_{\text{WATER}})}{\left(\dfrac{m_{\text{SYRUP}}}{\rho_{\text{SYRUP}}} + \dfrac{m_{\text{WATER}}}{\rho_{\text{WATER}}}\right)} \qquad (7)$$

where m_{SYRUP} and m_{WATER} are the mass of the syrup and the water, respectively; and ρ_{SYRUP} and ρ_{WATER} are the density of the glucose syrup and water, respectively. The misfit between predicted density (using equation (7)) and measured density for minor amounts of added water (2% and 5%) is only −2.0 to −0.3 kg/m³ (−0.14% to −0.02%) for the temperature range 1−90 °C (Fig. 6d). For 10% of added water the misfit is somewhat larger (−6.6 to −4.0 kg/m³), but is still only −0.49% to −0.30%.

4. Discussion

4.1. Effect of shear strain and shear rate on the viscosity of the materials

The rheological tests show that the viscosity of a variety of glucose syrups is independent of shear strain and shear rate, and that the viscosity of several honeys is independent of shear strain and only very weakly dependent on shear rate (Fig. 3). Previous works on the rheology of honey have mostly found that it is independent of shear strain (e.g. Mossel et al., 2000; Yanniotis et al.,

2006) and that it is independent of shear rate (Mossel et al., 2000; Lazaridou et al., 2004; Yanniotis et al., 2006), although thixotropic behaviour and diletant behaviour have been reported for some honeys (see discussion in Mossel et al., 2000). Note that in the previous works that report of independence on shear rate (Mossel et al., 2000; Lazaridou et al., 2004; Yanniotis et al., 2006), investigated shear rates were generally much higher (≥ 0.1 s^{-1}), while this work investigated shear rates in the range 10^{-4}–10^0 s^{-1}. The current work shows that the three investigated honeys are very weakly dependent on shear rate, with stress exponents that are distinct from 1 and in the range $n = 1.0071$–1.0259.

4.2. Effect of temperature on viscosity and density of the materials

The viscosities of the glucose syrups and honeys are very strongly dependent on temperature in the temperature range that is applicable for laboratory modelling of geological processes (~ 0–50 °C). A reasonable fit for the viscosity–temperature data can be achieved with an exponential function, but a better fit is achieved using an Arrhenius function. Previous works on the rheology of honey (e.g. Mossel et al., 2000; Lazaridou et al., 2004; Yanniotis et al., 2006; Gómez-Díaz et al., 2009) and sucrose solution (e.g. Quintas et al., 2006) have also found that the most satisfactory fit is achieved using an Arrhenius function. The activation energies reported here for the different glucose syrups ($E = 75$–114 kJ/mol) and honeys ($E = 101$–102 kJ/mol) are comparable to those reported for a variety of honeys by others (Mossel et al., 2000; Lazaridou et al., 2004; Yanniotis et al., 2006; Gómez-Díaz et al., 2009) (73–124 kJ/mol). The activation energies for the honeys reported here are most comparable to those of Mossel et al. (2000) (94–124 kJ/mol), who did tests at relatively low strain rates that are more comparable to (although still higher than) the strain rates investigated here.

The exponential best-fit lines for the three undiluted glucose syrups indicate that the viscosity decreases by ~ 13.8–14.3% for every 1 °C rise in temperature. This is in good agreement with a preliminary study from Schellart (2009), who used a falling ball viscometer to determine the viscosity of a glucose syrup at different temperatures. He found that in the temperature range 10–30 °C viscosity decreased following an approximately exponential curve with viscosity decreasing by 14% for every 1 °C rise in temperature.

The density of the glucose syrups and honeys is approximately linearly dependent on temperature with the density of glucose syrup decreasing by 0.55–0.57 kg/m^3 for every 1 °C increase in temperature in the range 10–40 °C and that of honey decreasing by 0.67–0.69 kg/m^3 (Fig. 6). These findings are in good agreement with those reported in Jellinek et al. (2003) and Schellart (2009), who reported a density decrease for different types of corn syrup and glucose syrup of 0.56 kg/m^3 and 0.59 kg/m^3, respectively, for every 1 °C increase in temperature.

4.3. Effect of water on viscosity and density of the materials

It was found that addition of water to the Colonial glucose syrup significantly reduces its viscosity following a function that is approximately exponential (Fig. 4). For example, at 20 °C the viscosity of the Colonial glucose–water mix decreases some 30% for every 1 wt% of water that is added to the mix. Such a strong dependence of the viscosity on moisture content is also evident from the dehydration test results presented in Fig. 2. The activation energy E decreases approximately linearly with added wt% of water to the Colonial glucose syrup, while the pre-exponential factor η_0 increases approximately exponentially; A linear best-fit line for E and an exponential best-fit line for η_0 (not shown) indeed give high coefficients of determination for E ($r^2 = 0.9916$) and η_0 ($r^2 = 0.9908$).

Such relationships for E and η_0 have also been reported by Yanniotis et al. (2006), who performed rheological tests on several types of honey with different water content.

The density of the Colonial glucose syrup also shows a dependence on water content, which, for low amounts of added water (≤ 5.0 wt%), can be accurately predicted with equation (7).

Following the discussion from above, it is likely that large variations in glucose syrup viscosity as reported in previous works are related to a large extent to variations in water content. For example, Belien et al. (2010) describe two glucose syrups with $\eta = 4.12$ Pa s ($\rho = 1320$ kg/m^3) and $\eta = 20$ Pa s ($\rho = 1421$ kg/m^3), and Schellart (2004) describes a glucose syrup with $\eta = 130$ Pa s ($\rho = 1420$ kg/m^3). These syrups are lighter than the ones reported here (Colonial 100% with $\rho = 1426.8$ kg/m^3, Queen with $\rho = 1430.5$ kg/m^3 and Manildra with $\rho = 1427.0$ kg/m^3 at room temperature), which have a higher viscosity. Therefore, glucose syrups with a high density (and thus relatively low water content) will generally have a relatively high viscosity, while those with a low density (and thus relatively high water content) will generally have a relatively low viscosity. It should be noted that if the density of a glucose syrup is known, this only gives a rough indication of its viscosity. For example, the densities of Manildra and Colonial 100% are nearly identical at 20 °C (1427.0 kg/m^3 and 1426.8 kg/m^3, respectively), but their viscosities differ by a factor of ~ 2.4 (192.3 Pa s and 454.7 Pa s, respectively).

4.4. Suitability of glucose syrup and honey for analogue modelling

When constructing scaled laboratory models for simulating geological processes one needs to pay significant attention that the model is geometrically, kinematically and dynamically scaled (Hubbert, 1937; Ramberg, 1967; Weijermars and Schmeling, 1986; Davy and Cobbold, 1991). For dynamic scaling, the rheological properties of the modelling materials need to be known in great detail. The relatively simple rheological behaviour of glucose syrup makes it an ideal material to represent the asthenosphere or sub-lithospheric mantle in analogue models of large-scale geodynamic processes, such as lithospheric deformation, subduction and mantle convection. Glucose syrup has a shear strain independent and shear rate independent viscosity at shear rates of 10^{-4}–10^0 s^{-1} (Fig. 3a and b), has negligible elastic properties at shear rates that are typical for analogue experiments (10^{-4}–10^{-1} s^{-1}) (Fig. 5a), and has a temperature-dependent viscosity that can be fitted with an Arrhenius function (Fig. 3c and d). The strong dependence of viscosity on temperature requires an accurate control on the temperature in the laboratory during an experiment and monitoring of the temperature of the syrup in the model apparatus. Honey is also well suited for models of lithosphere and mantle-scale processes, but the minor dependence of its viscosity on shear rate makes its behaviour less predictable. Another disadvantage of honey is that it is much less transparent than glucose syrup. The high transparency of glucose syrup is a significant additional advantage, as it allows for detailed investigations of flow patterns in the syrup (e.g. by tracking of passive markers in the syrup), and allows for accurate quantification of fluid velocities, deformation of objects sinking in the syrup (e.g. subducting slabs) and energy dissipation in the system. A disadvantage of glucose syrup is that it quickly dehydrates (within minutes) when exposed to air, thereby forming a thin high-viscosity skin (~ 0.1–1.0 mm thick) whose viscosity is orders of magnitude higher than that of the non-exposed glucose syrup. As such, analogue and fluid dynamic models that make use of glucose syrup that is exposed to open air, should either: (1) run the experiments in a very humid environment that prevents dehydration; (2) moisten the exposed glucose syrup surface at regular

intervals; (3) run the experiments at low temperature in a low-temperature environment such that dehydration is greatly suppressed; or (4) seal the experimental box such that the glucose syrup surface is no longer exposed to open air.

5. Conclusions

The following conclusions can be drawn from the rheological and density investigations for the glucose syrups and honeys:

1. The viscosity of all glucose syrups and honeys is independent of shear strain (i.e. no strain hardening or softening).
2. The viscosity of the glucose syrups is virtually independent of shear rate (i.e. linear-viscous or Newtonian rheology) in the range $\dot{\gamma} = 10^{-4}$–10^0 s^{-1} with stress exponents very close to one ($n = 0.995$–1.004).
3. All the honeys show a very weak, but consistent, decrease in viscosity with increasing shear rate from 10^{-3} to 10^0 s^{-1}, and have a stress exponent that is consistently above one ($n = 1.007$–1.026).
4. All syrups and honeys have a viscosity that is strongly dependent on temperature, where viscosity decreases with increasing temperature following a convex-downward trend in the investigated temperature range (0–50 °C). The data can be reasonably fitted with an exponential function, but a better fit is achieved using an Arrhenius function, where activation energies are in the range $E = 75$–114 kJ mol^{-1} for the glucose syrups and in the range $E = 101$–102 kJ mol^{-1} for the honeys.
5. The viscosity of glucose syrup decreases approximately exponentially with increasing water content, as shown by tests on one brand of glucose syrup; at 20 °C the viscosity decreases some 30% for every 1 wt% of added water.
6. Oscillation tests indicate that the rheology of all the glucose syrups and honeys is entirely dominated by viscous behaviour at frequencies of 10^{-3}–10^2 Hz and not elastic behaviour, indicating that at experimental strain rates ($\sim 10^{-4}$–10^{-1} s^{-1}) the syrups exert only a viscous response to an applied stress.
7. Density investigations show that the density of glucose syrup and honey decreases with increasing temperature in the investigated temperature range (0–90 °C); In the temperature range 10–70 °C the density decrease follows an approximately linear trend, with coefficients of thermal volumetric expansion at 20 °C of 3.89–3.95 × 10^{-4} °C^{-1} and 4.57–4.81 × 10^{-4} °C^{-1} for glucose syrup and honey, respectively. The density is also dependent on the amount of added water; the density decreases with increasing water content and can be accurately estimated using equation (7) for 0–5 wt% of added water.

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