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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

W.P. Schellart*

School of Geosciences, Monash University, Melbourne, VIC 3800, Australia

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ABSTRACT

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.

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

* Tel.: +61 3 9905 1782; fax: +61 3 9905 4903.
E-mail address: wouter.schellart@monash.edu.

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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 (~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 ~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 (±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 (±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