



Gelatine as a crustal analogue: Determining elastic properties for modelling magmatic intrusions

J.L. Kavanagh ^{a,*}, T. Menand ^{b,c,d}, K.A. Daniels ^e

^a School of Geosciences, Monash University, Clayton Campus, Clayton, VIC 3800, Australia

^b Clermont Université, Université Blaise Pascal, Laboratoire Magmas et Volcans, BP 10448, F-63000 Clermont-Ferrand, France

^c CNRS, UMR 6524, LMV, F-63038 Clermont-Ferrand, France

^d IRD, R 163, LMV, F-63038 Clermont-Ferrand, France

^e School of Earth Sciences, University of Bristol, Bristol, BS8 1RJ, UK

ARTICLE INFO

Article history:

Received 14 February 2012

Received in revised form 17 September 2012

Accepted 28 September 2012

Available online 9 October 2012

Keywords:

Gelatine

Dyke sill

Magma

Analogue scaling

ABSTRACT

Gelatine has often been used as an analogue material to model the propagation of magma-filled fractures in the Earth's brittle and elastic crust. Despite this, there are few studies of the elastic properties of gelatine and how these evolve with time. This important information is required to ensure proper scaling of experiments using gelatine. Gelatine is a viscoelastic material, but at cool temperatures ($T_r \sim 5\text{--}10^\circ\text{C}$) it is in the solid 'gel' state where the elastic behaviour dominates and the viscous component is negligible over short to moderate timescales. We present results from a series of experiments on up to 30 litres of maximum 30 wt.% pigskin gelatine mixtures that document in detail how the elastic properties evolve with time, as a function of the volume used and gel concentration (C_{gel}). Gelatine's fracture toughness is investigated by measuring the pressure required to propagate a pre-existing crack. In the gel-state, gelatine's Young's modulus can be calculated by measuring the deflection to the free-surface caused by an applied load. The load's geometry can affect the Young's modulus measurement; our results show its diameter needs to be $\leq 10\%$ of both the container diameter and the gelatine thickness (H_{gel}) for side-wall and base effects to be ignored. Gelatine's Young's modulus increases exponentially with time, reaching a plateau (E_∞) after several hours curing. E_∞ depends linearly on C_{gel} , while T_r , H_{gel} and the gelatine's thermal diffusivity control the time required to reach this value. Gelatine's fracture toughness follows the same relationship as ideal elastic-brittle solids with a calculated surface energy $\gamma_s = 1.0 \pm 0.2 \text{ J m}^{-2}$. Scaling laws for gelatine as a crustal analogue intruded by magma (dykes or sills) show that mixtures of 2–5 wt.% gelatine cured at $\sim 5\text{--}10^\circ\text{C}$ ensure the experiments are geometrically, kinematically and dynamically scaled.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Analogue experimentation is an important technique in science and engineering. In practice, it is the selection of appropriate analogue materials that is often the biggest challenge in developing a set of experiments that are geometrically, kinematically and dynamically scaled (*sensu* Hubbert (1937)). Experiments that meet these criteria can be considered a laboratory-scale version of the natural counterpart. In this paper we detail a series of experiments carried out to document the properties of gelatine, a widely used analogue for the Earth's crust.

Gelatine is an ideal analogue for those modelling homogeneous, isotropic and elastic materials, for example it has been used by mechanical engineers (e.g. Crisp (1952), Richards & Mark (1966)) and as a biological tissue analogue in the medical sciences (e.g. Righetti et al. (2004)). The use of gelatine in geological sciences has taken advantage

of both its elastic and viscous properties, proving especially fruitful in developing our understanding of magmatic intrusions (dykes and sills) and volcanic feeder systems and providing constraints on their propagation dynamics in the Earth's brittle and elastic crust (e.g. Acocella & Tibaldi (2005), Cañón-Tapia & Merle (2006), Dahm (2000), Fiske & Jackson (1972), Heimpel & Olson (1994), Hyndman & Alt (1987), Ito & Martel (2002), Kavanagh et al. (2006), Kervyn et al. (2009), Maaløe (1987), Maccaferri et al. (2010), Mathieu et al. (2008), McGuire & Pullen (1989), McLeod & Tait (1999), Menand et al. (2010), Menand & Tait (2001, 2002), Muller et al. (2001), Pollard (1973), Pollard & Johnson (1973), Rivalta et al. (2005), Taisne et al. (2011), Taisne & Tait (2011), Takada (1990, 1994, 1999) Walter & Troll, (2003), Watanabe et al. (2002)). The photoelastic properties of gelatine have been of particular use to experimental geologists (e.g. Taisne & Tait (2011)) and civil engineers (e.g. Crisp (1952), Farquharson & Hennes (1940), Richards & Mark (1966), Tan (1947)), where the internal stresses of a deformed gelatine can be visualised with the aid of polarised light. The prolific use of gelatine in the food industry has made a wealth of information available on its rheological properties (e.g. Watase & Nishinari (1980)).

* Corresponding author. Tel.: +61 3 9902 0062; fax: +61 3 990 54903.

E-mail address: janine.kavanagh@monash.edu (J.L. Kavanagh).

However, relatively few studies have documented the elastic properties of gelatine or how these evolve with time (e.g. Di Giuseppe et al. (2009)).

We present results from a series of experiments that investigate the elastic properties of gelatine over a range of concentrations and volumes. Firstly the material properties of gelatine are detailed, followed by a description of the experimental setup and the theoretical basis for our measurements. The accuracy to which the experimentalist can determine the Young's modulus of the gelatine is evaluated by considering the uncertainties involved in the measurement, the effect of the properties of the applied load used to make the measurements and any apparatus side-wall or floor effects. In particular, our experimental results are focused on how the Young's modulus of the gelatine evolves with time. We also determined the gelatine's fracture toughness, a measure of the material's resistance to the growth of a crack. To aid the application of the results, we present some scaling laws that are appropriate for the use of gelatine as an analogue for the Earth's crust in geological studies focused on the formation controls and propagation dynamics of magma-filled fractures.

2. Material properties

Gelatine is a polypeptide formed from the hydrolytic degradation of collagen (Ross-Murphy, 1992). It is classified as a 'physical gel' (e.g. Peyrelasse et al. (1996)), meaning that during gelification Van der Waals forces lead to the development of a complex and continuously connected three-dimensional network (lattice) of macromolecules (Djabourov et al., 1988a). The hydrogen bonds that are formed in this process are reversible and can be broken by changing temperature or pH (Djabourov et al., 1988b). From the onset, those working with gelatine have commented on its "fickle" nature (Richards & Mark, 1966). In order to use this material for quantitative modelling purposes, control needs to be kept on a range of factors including temperature, pH and gelatine concentration.

Gelatine is a viscoelastic material so during deformation it can display both elastic and viscous behaviour. High stresses applied for a short timescale cause the gelatine to behave elastically, whereas small stresses applied over a long time period will produce a viscous response. Viscoelasticity is traditionally modelled with an arrangement of springs and dashpots that can reproduce a measured creep curve (e.g. Richards & Mark (1966)). The proportion of elastic to viscous behaviour can be quantified by a phase shift δ angle, also known as the "loss angle" (Mezger, 2002):

$$\delta = \arctan \frac{G''}{G'} \quad (1)$$

where G'' is the energy loss (viscous-related) and G' is the energy stored (elastic-related) for a given strain or strain rate. δ is equal to 0° for an ideal-elastic material and 90° for an ideal-viscous material. The transition from viscously dominated to elastically dominated behaviour (or vice versa) occurs at the 'gel-point' (Djabourov et al., 1988b), which is the condition where elastic and viscous energies are equal ($G'' = G'$ and $\delta = 45^\circ$). Gelatine is in the 'sol-state' (fluid) when $G'' > G'$ and $\delta > 45^\circ$, but is in the 'gel-state' (solid) when $G' > G''$ and $\delta < 45^\circ$ (Mezger, 2002; Nelson & Dealy, 1993; Ross-Murphy, 1992). For gelatine, this marked change in mechanical properties can be brought about by changing the extent of deformation (strain) or temperature; the gel-point itself depends on time, temperature and concentration (Askeland et al., 2010; Di Giuseppe et al., 2009).

The focus of this paper will be on the ideal-elastic behaviour of gelatine. When a 2.5 wt.% gelatine mixture at 10°C is deformed at low strain it has G' two orders of magnitude higher than G'' and $\delta < 1^\circ$ (Di Giuseppe et al., 2009). At these conditions the material is in the 'gel-state' and it is possible to assume an almost ideal-elastic behaviour. When this is the case, Hooke's Law is obeyed and deformation is

recoverable when high stresses are applied over short timescales: the applied stress (σ) is proportional to strain (γ) and independent of the strain rate ($\dot{\gamma}$).

The elastic properties of a homogeneous and isotropic solid can be described fully by a combination of the Young's modulus E (ratio of tensile stress to tensile strain) and the Poisson's ratio ν (the relative contractive to expansive response of the deformed material). For gelatine, $\nu \approx 0.5$ (e.g. Crisp (1952), Farquharson & Hennes (1940), Righetti et al. (2004), Richards & Mark (1966)) and is theoretically incompressible such that deformation results in no net volume change.

3. Experimental set-up and data processing

3.1. Young's modulus experiments

A series of twenty-six experiments were carried out to investigate the effect of time, gelatine concentration, volume, experimental apparatus dimensions and applied load properties on the calculated Young's modulus of solidified gelatine.

A gelatine solution was prepared by adding a measured quantity of approximately 80°C deionised water to the required weight of gelatine granules (260 Bloom, 20 Mesh, Pigskin Gelatine supplied by Gelita UK) to achieve the desired concentration (see Table 1). The use of deionised water is required to produce a clear and transparent mixture that hinders bacterial growth, which would otherwise produce a cloudy appearance to the gelatine solid. This hot mixture was then poured into a specified container and any bubbles were removed from the surface using a spoon. To prohibit the formation of a toughened 'skin' on the gelatine surface by water evaporation, a thin layer of vegetable oil was poured on top. The container was then placed into a temperature-controlled cold room at $5\text{--}10^\circ\text{C}$ (T_r), and the mixture temperature (T_0) and time were recorded. The gelatine was left in the cold room for several hours until the mixture temperature had equilibrated with its surroundings.

One way of calculating the gelatine's Young's modulus is to measure the deflection imposed by a load applied to the gelatine's surface (Timoshenko & Goodier, 1970):

$$E = \frac{M_L g (1 - \nu^2)}{D_L w} \quad (2)$$

where D_L is the diameter (m) of the cylindrical load, M_L is its mass (kg), w is the displacement (m) caused, and g is the gravitational acceleration.

Measurement of the Young's modulus commenced once the gelatine was able to support a load placed on its free surface. The container was removed from the cold room to make the measurements and then replaced afterwards. All of the oil was carefully removed from the surface of the gelatine prior to any measurement being taken, using a spoon and then paper towel in order to achieve complete contact between the load and the gelatine. The load was applied by carefully placing a rigid metallic cylinder of known mass and dimensions onto the gelatine surface (see Fig. 1 for a schematic sketch of the experimental setup and Table 2 for experimental load properties). Using a digital micrometer attached to a fixed reference position, the displacement of the free surface was measured (with an estimated error of ± 0.1 mm) and recorded by hand. The load was applied just prior to the measurement being made, and the total time in which it was in contact with the gelatine was approximately 30 seconds per measurement. E was calculated systematically for the duration of each experiment; measurements were made using each of the loads when possible, approximately every one to two hours for up to 140 hours after the gelatine was prepared (nearly six days). For each time interval, the gelatine was at ambient room temperature for an interlude of less than ten minutes before being returned to

Download English Version:

<https://daneshyari.com/en/article/4692526>

Download Persian Version:

<https://daneshyari.com/article/4692526>

[Daneshyari.com](https://daneshyari.com)