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Rheology of pig skin gelatine: Defining the elastic domain and its thermal and mechanical properties for geological analogue experiment applications

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ABSTRACT

Gelatine is a viscoelastic polymer that has been employed widely in geological analogue experiments to study processes related to the elastic behaviour of rocks such as tensile fracturing, seismicity and magma intrusion. However, the elastic domain of this material has not yet been clearly defined by rheological tests. Here we describe the rheology and define the elastic domain of 250 bloom/20 mesh pigskin gelatine at concentrations ≤10 wt.% and temperatures of 5–25 °C; however, these results are strongly comparable with gelatine of 245–260 bloom. New equations are given for the shear and elastic moduli in relationship to temperature and gelatine concentration. It is found that at concentrations ≤3 wt.% the tested gelatine is best described by a rheological model composed of a combination of Kelvin-Voight and Maxwell elements and, therefore, is not suitable to model elastic behaviour in geological analogue experiments. At higher concentrations it is best described by a simpler viscoelastic model comprising a single Maxwell element. In order to ensure that geological analogue experiments remain within the elastic domain where the elastic component is far greater than the viscous component, strain rates should range between 0.1 and 10 s^{-1} and temperature values should be <15 °C. With a Poisson's ratio of ~0.45 for concentrations >3 wt.% analogue experiments using gelatine approximate the elastic behaviour of natural rocks more closely than previously assumed.

1. Introduction

Gelatine in its gel state is often assumed to behave elastically and thus it has been regarded a useful analogue for the Earth's upper crust in scaled laboratory experiments including those that simulate magmatic intrusions. It has specifically been used in experiments that involve tensile cracking for fracture mechanics and structural geological research (Touvet et al., 2011) and for understanding seismic variability along thrust faults (Corbi et al., 2011). Gelatine has also been used in analogue modelling experiments to study the formation and evolution of dykes (Pollard, 1973; Maaløe, 1987; Takada, 1990; Lister and Kerr, 1991; Heimpel and Olson, 1994; Takada, 1994, 1999; Menand and Tait, 2001; Ito and Martel, 2002; Menand and Tait, 2002; Taisne and Tait, 2009; Sumita and Ota, 2011; Le Corvec et al., 2013), laccoliths (Pollard and Johnson, 1973; Hyndman and Alt, 1987), sills (Kavanagh et al., 2006; Taisne et al., 2011; Ritter et al., 2013; Kavanagh et al., 2015), combinations of dykes and sills (Hyndman and Alt, 1987; Rivalta et al., 2005; Kavanagh et al., 2006; Menand et al., 2010), in studies of how dykes propagate under a (changing) load (Fiske and Jackson, 1972; McGuire and Pullen, 1989; McLeod and Tait, 1999; Muller et al., 2001; Watanabe et al., 2002; Walter and Troll, 2003; Acocella and Tibaldi, 2005; Cañón-Tapia and Merle, 2006) or extensional stress (Daniels and Menand, 2015), and how dyke and sill propagation is influenced by solidification of the intrusive fluid (Taisne and Tait, 2011; Chanceaux and Menand, 2014).

Although many geological processes such as tensile rock fracturing and magma intrusion can be understood from field research and geophysical techniques, in order to quantify and predict the variables controlling these processes numerical and analogue models are essential. Most processes occur at timescales far beyond human lifespans or are obscured from direct observation. Analogue modelling provides a powerful tool to describe such processes at a scale that is observable as well as controllable (Poirier, 1988). If such analogue experiments are conducted in a controlled environment with materials that are fully understood, the outcomes can be quantified and provide input to any numerical geodynamic model of the studied process. Gelatine is a useful material that is (semi)transparent depending on its concentration, and has elastic properties that can be utilised to model geological processes when the Earth's crust behaves elastically (cf. Pollard, 1973; Taisne and Tait, 2011; Kavanagh et al., 2013). Ideal elasticity is described either by models that are Hookean elastic (single spring) or that are like Gaussian elastic networks (interconnected springs; Tirion, 1996). Since gelatine is essentially a network of polymers, a Gaussian elastic network model

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would be anticipated. However, since gelatine is a viscoelastic material (e.g. te Nijenhuis, 1981; Bot et al., 1996; Groot et al., 1996; Di Giuseppe et al., 2009) it also has a viscous component that cannot easily be ignored. In order to use the elastic properties of gelatine in analogue experiments, the elastic domain, where the influence of viscous behaviour is negligible, needs to be carefully described and quantified.

The viscoelasticity of a material can be described using a variety of rheological models comprising a different arrangement of linear viscous (Fig. 1a) and elastic (Fig. 1b) elements. Two basic arrangements underpin such viscoelastic models: the Maxwell (Fig. 1c) and the Kelvin-Voigt (Fig. 1d) elements (Ferry, 1980). The Maxwell element represents the viscoelasticity of a material as a spring (elastic modulus; elasticity) and a dashpot (viscosity) in series. The (Maxwell) relaxation time (t_M) is then defined as the ratio of viscosity over rigidity (η_i/G_i); the material is elastic when the strain rate is equal or less than t_M. The Kelvin-Voigt element describes viscoelasticity as a spring and dashpot in parallel. In this case, the ratio of viscosity over rigidity is known as the retardation time (t_{KV}), which is the time required for the spring to return to its initial length whilst being retarded by the viscous dashpot. An important difference between these elements is that over time the Kelvin-Voigt element can return to its initial shape, whereas the Maxwell element will record permanent deformation with applied stress once a threshold stress is reached. The Maxwell element can deform permanently even before failure, provided the duration of strain equals or exceeds the Maxwell relaxation time and strain rates are low. More complicated viscoelastic models can contain multiple sequences of Maxwell and/or Kelvin-Voigt elements, making it difficult to describe how the viscous and the elastic domains of these elements interact.

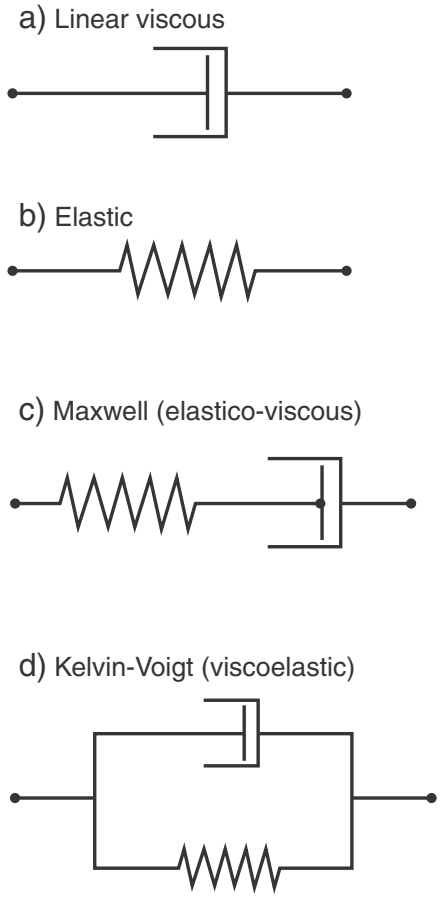

Fig. 1. Viscosity and elasticity are depicted as dashpot (a) and spring (b) elements respectively. The viscoelastic models of Maxwell (c) and Kelvin-Voigt (d) are represented using these schemes (after Ferry, 1980).

Gelatine is the name of a group of viscoelastic biopolymers consisting of proteins and peptides that are produced from the hydrolysis of collagen (see Djabourov et al., 1988a, 1988b; Ross-Murphy, 1992). Collagen can be obtained from animal by-products like skin and bones. In addition, the peptides and proteins making up gelatine can also be extracted from sea weed or bacteria resulting in the non-animal gelling alternatives of *agar* (cf. Sumita and Ota, 2011; Lister and Kerr, 1991) and *carrageenan* from the former and *gellan* and *xanthan gums* from the latter.

A comparison between the viscoelastic to viscous properties of a variety of these gelling agents, with particular emphasis on the elastic behaviour, has been studied by Di Giuseppe et al. (2009). However, this study did not define the elastic domain of the types of gelatine used which is important for the experimental studies mentioned above. In addition, no material details were given in this study other than providing generic descriptors, whereas the rheological properties of gelatine may depend strongly on manufacturing variables such as acidity and bloom value. The bloom value of gelatine is a comparative measure of strength, where the higher the bloom value, the stronger the gelatine. It is measured by pressing a standard plunger (12.5 mm in diameter) of the Association of Analytical Communities (AOAC) International to a depth of 4 mm in 6.67 wt.% gelatine; the corresponding weight in grams to produce such a force resulting in this indent is the bloom value (Jones, 2004). The bloom value is proportional to the length of the polymer chains in a particular type of gelatine (Groot et al., 1996).

A second rheological study (Kavanagh et al., 2013) focussed on the elastic properties, specifically the Young's (*or* elastic) modulus and the fracture toughness, of one specific type of gelatine (260 bloom/20 mesh pigskin gelatine). In that study the only variable was the gelatine concentration. Mesh in this case reflects the particle size of the granular gelatine, e.g. 20 mesh corresponds to particles of 0.85 mm in size. Kavanagh et al. (2013) found that the Young's modulus linearly increases with increasing gelatine concentration. However, whether the same relationship exists under varying thermal conditions or if the strain rate was varied has not been studied.

Despite these and other studies into the viscoelastic behaviour of gelatine, the elastic domain (i.e. when and how much the material behaves elastically) of gelatine remains poorly defined as well as the parameters (i.e. temperature, aging, strain rate) that control this domain and to which extent. The elastic domain and how gelatine behaves in this domain are important for laboratory analogue experiments where the elastic domain of geological materials is considered, i.e. seismic waves, rock fracturing and dyke propagation.

In order to address this knowledge gap we present results of new rheological tests of gelatine in order to measure these parameters. Although there are many types of gelatine available, we focus on acid pigskin gelatine because it has been the most commonly used in geological analogue experiments (cf. Heimpel and Olson, 1994; Menand and Tait, 2002; Acocella and Tibaldi, 2005; Kavanagh et al., 2006; Le Corvec et al., 2013). The aim of this study is therefore to define the viscoelasticity of pigskin gelatine in the gel state, especially what its elastic domain is, as well as define the relationships in greater detail between the parameters that control its rheology. The results are used to evaluate and validate the assumptions and findings of previous analogue experiments that have used pigskin gelatine. Our results also provide a means to quantify the mechanical variables of laboratory experiments using gelatine so that they can also be implemented and evaluated in numerical models. With these results such mechanical variables can be better manipulated, opening the way for further quantitative analogue experiments of geological situations that incorporate temperature- and time-dependent variables.

2. Experimental background

The elasticity of a polymer in general, and of gelatine specifically is strongly dependent on its concentration and thermal state (te