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Gelatins as rock analogs: A systematic study of their rheological and physical properties

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ABSTRACT

In a laboratory model the behavior of the selected analog material must be properly scaled to nature. Here, we systematically investigate both rheological and physical properties of a wide range of gelatins as functions of temperature, composition, concentration, ageing and applied strain rate. Results show that gelatins' behavior changes gradually from purely elastic to visco-elasto-brittle to purely viscous (nonlinear) rheology going from the gel- to the sol-state. The rheological variability of gelatins appears promising for the potential use of these analog materials to simulate crustal and lithospheric rheological behavior. In particular, we found that pig skin 2.5 wt.% at 10 °C has the required rheological properties for a suitable experimental set-up to model crustal deformation.

1. Introduction

An analog model is a simplified dynamic representation of the Earth. According to 'similarity criteria', the rheological and physical parameters in the model must be properly scaled to natural conditions (e.g. Weijermars and Schmeling, 1986). Analog models commonly use granular materials to simulate frictional Mohr–Coulomb plasticity (e.g. Hubbert, 1951; Ramberg, 1981; Davy and Cobbold, 1988, 1991; Krantz, 1991; Weijermars et al., 1993; Storti and McClay, 1995) and bouncing putties, paraffin waxes and glucose syrups to simulate ductile creep (e.g. Ramberg, 1955; Davy and Cobbold, 1991; Brun et al., 1994; Shemenda, 1994; Griffiths et al., 1995; Grujic and Mancktelow, 1995; Davaille, 1999; Funiciello et al., 2003). The predictive power of this methodology may be limited by a) the limited range of available materials properly scaling the behavior of the Earth; b) simplified rheologies and c) the necessity to use different experimental materials to simulate any rheological stratification in nature. Hence, a key requirement toward the improvement of this technique is the selection and calibration of suitable analog materials able to reproduce the complex rheological behavior of rocks. However, analog material knowledge is often restricted to the analysis of few physical parameters (e.g. Weijermars, 1986; Mancktelow, 1988; Cobbold and Jackson, 1992; Rossetti et al., 1999; Schellart, 2000; Galland et al., 2006). Only recently, ten Grotenhuis et al. (2002) and Boutelier et al. (2008) adopted an approach commonly used in Material Science for complete rheological characterization of materials and applied it to plasticines. Rheological behavior can be completely described by measuring the energy stored in the sample during deformation and the energy lost afterwards (Mezger, 2002). These two quantities are expressed by the storage (G') and the loss (G'') moduli, determined over a broad range of deformation rates (Nelson and Dealy, 1993).

In this paper, we adopt the same rheometric approach to perform an extensive study of the properties of a wide range of gelatins, including those commonly used in laboratory modeling. Usually, gelatins are assumed to have a simple elastic–brittle rheology. Hence, their use has been limited to models of shallow crustal processes such as propagation of dykes (Fiske and Jackson, 1972; McGuire and Pullen, 1989; Takada, 1990; Lister and Kerr, 1991; Takada, 1994; Koyaguchi and Takada, 1994; McLeod and Tait, 1999; Watanabe et al., 1999; Bons et al., 2001; Ito and Martel, 2002; Menand and Tait, 2002; Watanabe et al., 2002; Walter and Troll, 2003; Pasquare' and Tibaldi, 2003; Acocella and Tibaldi, 2005), emplacement of laccoliths (Pollard and Johnson, 1973; Johnson and Pollard, 1973; Hyndman and Alt, 1987), formation of sills (Rivalta et al., 2005; Kavanagh et al., 2006), and bubble growth in soft sediments (Boudreau et al., 2005). Most of these models provide an insufficient scaling of the gelatins, with consequent limitations on the kinematic similarity. Despite their use as a brittle–elastic analog, gelatins show a more complex mechanical behavior, strongly dependent on temperature, composition, concentration, ageing and applied strain rate (Bot et al., 1996a,b; Kavanagh and Ross-Murphy, 1998; Norziah et al., 2006; Barrangou et al., 2006). In particular, gelatins show a visco-elasto-brittle rheology in their gel-state and a viscous rheology in their sol-state. This behavior has the

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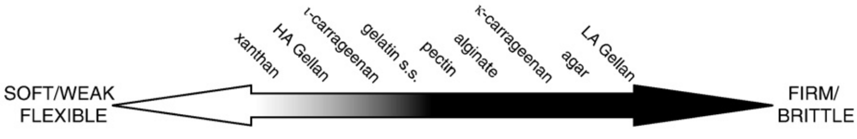

Fig. 1. Characterization of gelatins according to their gel strength.

twofold experimental advantage of: (i) reproducing the complex visco-elasto-brittle rheology representative of crustal/lithospheric behavior, until now simulated only by means of simplified rheologies; (ii) using a single material to model the Earth rheological structure, avoiding the use of different materials to simulate rheological layering. For these reasons, gelatins may represent a ground-breaking experimental material and a deeper knowledge of their rheological and physical parameters, as attempted in this study, is crucial for a proper modeling.

2. General properties of gelatins

2.1. Composition

In Material Science, "gelatin" is the ordinary name for particular biopolymers. In this work, as usual in Earth Sciences literature, the term is used for both plant and animal biopolymers. They are naturally occurring long-chain polymers either composed of amino acids (peptides, polypeptides, proteins) or of saccharides (mono-, oligo-, and polysaccharides). Such macromolecules, available in tasteless and odorless powder form, are water diluted in small quantities and used in food production, pharmaceutics and oil recovery to achieve appropriate rheological properties, i.e. to improve texture, prevent drainage, increase viscosity and stability of foodstuffs.

2.2. Structure and mechanical behavior

Gelatins are constituted by flexible linear chain-like polymers assuming complex 3-dimensional structures. When these polymers are able to entangle forming a continuous network in the entire sample volume, gelatins show the so called "gelling behavior" moving from a sol-like (i.e. fluid) state to a gel-like (i.e. solid) state. The gelation is primarily triggered by temperature, i.e. a sol-like state at higher temperature (approximately in the 40–80 °C range) becomes a gel-like state at lower temperatures (4–40 °C). However, other parameters (composition, concentration, and applied strain rate) play an important role.

A qualitative description of the gelatin structure can be obtained from texture analysis that considers its strength (firmness, hardness, brittleness, elasticity and cohesiveness) in the gel-state. Hence, gelatins can be soft/weak-flexible to firm-brittle (Fig. 1). However, this classification does not provide a comprehensive description of their rheological properties.

In general, gelatins in gel-state show an elastic response when a high stress is applied for a short time and a viscous response when low stress is applied for a long time. For a constant imposed strain, the initial elastic deformation is converted into permanent viscous deformation and the associated stress decays in time. Materials exhibiting such characteristics are called viscoelastic (*VE*) (e.g. Ferry, 1980).

3. Theory and methods

3.1. Basic theory

A complete characterization of material properties requires two complementary approaches. The solid-mechanic approach deals with elastic solids, which do not dissipate energy and follow Hooke's law: strain (γ) is always proportional to stress (σ), and the stress is independent of strain rate ($\dot{\gamma}$) (e.g. Chou and Pagano, 1992; Ranalli, 1995). The fluid-dynamic approach deals with viscous liquids that do not store energy but dissipate it, and in which there exists a proportionality between the stress (σ) and the strain rate ($\dot{\gamma}$), either linear (Newtonian) or nonlinear (e.g. Drozdov, 1996).

VE materials display a delayed, time-dependent, response when stress is applied and/or removed. The simplest rheological models to represent a visco-elastic behavior are obtained combining linear elastic and linear viscous elements in series (Maxwell model) or in parallel (Kelvin–Voigt model) (Barnes et al., 1989). To describe this behavior it is necessary to measure the deformation energy stored in the sample during the deformation and lost afterwards (Mezger, 2002). The rheological properties of a material can be studied by applying the theory of viscoelasticity when the material behaves "linearly", or strain-independently (i.e., its behavior does not depend on the strain history). Material characterization is carried out in terms of the storage and loss moduli (Ferry, 1980). These parameters are determined as functions of strain, strain rate (frequency), temperature and time providing a full characterization of the material behavior. To avoid possible ambiguities, a material is termed "linear" (i.e., linear visco-elastic) when its mechanical properties do not change with strain. When a linear relationship occurs between stress and strain rate, the material is said to show Newtonian fluid behavior.

In a linear *VE* sample the shear stress τ is out of phase with the applied strain following the relation (Ferry, 1980):

$$\tau = \gamma_o(G' \sin(\omega t) + G'' \cos(\omega t)) \tag{1}$$

where γ_o is the maximum amplitude of the strain and, G' and G'' are frequency-dependent functions. Measurements performed at a given frequency (ω) provide simultaneous determinations of G' and G'' (Mezger, 2002). *VE* behavior is illustrated in Fig. 2. In the region where

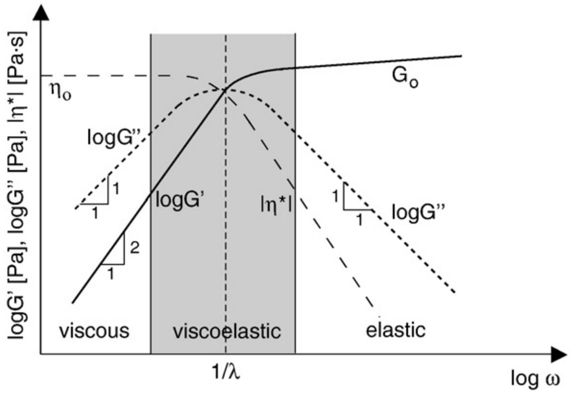

Fig. 2. Typical rheological properties of an ideal linear viscoelastic material. At low frequency (viscous behavior) $\log G'(\omega)$ increases with slope as 2:1 because $G' \sim \omega^2$ for $\omega \to 0$, while $\log G''(\omega)$ increases with slope as 1:1 because $G'' \sim \omega$. In this range the loss modulus G'' is always larger than the storage modulus G'. The complex viscosity $|\eta^*|$ is constant and equal to the zero-shear viscosity η_o. At high frequency (elastic behavior) $G'(\omega)$ reaches the constant plateau value G_o and $G''(\omega)$ falls with a slope (−1):1 because $G'' \sim 1/\omega$ for $\omega \to \infty$. The storage modulus is always larger than the loss modulus. At intermediate frequencies (viscoelastic behavior) G' and G'' are of the same order of magnitude. At the point $\omega \cdot \lambda = 1$, $G''(\omega)$ reaches its maximum and the intersection of G' and G'' determines the relaxation time, λ, of the system (modified from ten Grotenhuis et al., 2002).