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Using candle gel to simulate the frictional instability of earthquake faults in the laboratory : rheological characterization

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Résumé :

Nous avons étudié le gel de bougie comme un matériau analogue pour simuler les instabilités qui ont lieu pendant les tremblements de terre. Une caractérisation viscoélastique de ces gels n'a pas encore été réalisée. Ici, nous rapportons la rhéologie de deux types de gels de bougie qui se distinguent par leurs points de fusion. De plus, les propriétés tribologiques du gel de bougie avec du papier abrasif ont également été caractérisées en utilisant un nouveau appareil expérimental.

Les gels de bougie étudiés ici sont un mélange d'huile de paraffine blanche et de polymères. Des tests oscillatoires, à savoir un balayage d'amplitude, un balayage de fréquence et un balayage de température, ont été réalisés à l'aide d'un rhéomètre hybride pour mesurer les propriétés viscoélastiques. La caractérisation rhéologique a montré que le comportement du gel de bougie présente une viscosité progressivement croissante par rapport à l'amplitude de la déformation. La faible viscosité pour une plage de déformation de 0 à 15% semble prometteuse pour simuler les instabilités en laboratoire.

Abstract :

We investigated the candle gel as a potential new surrogate material for mimicking the frictional instabilities that take place during earthquakes. A complete viscoelastic characterization of such gels has not yet been done. Here, we report the rheology of two types of candle gels distinguished by their melting points. Further, the frictional properties of the candle gel with sandpaper was also characterized using a novel double-shear experimental setup.

Candle gels studied here are a mixture of white paraffin oil and polymers. Oscillatory tests, i.e. amplitude sweep, frequency sweep and temperature sweep were performed using a hybrid rheometer to probe the viscoelastic properties. The rheological characterization showed that the behavior of the candle gel has gradually increasing viscosity with respect to the strain amplitude. The low viscosity for a strain range of 0 – 15% seems promising to simulate an earthquake in the laboratory.

Mots clefs : paraffin gel, viscoelasticity, analogue material, characterization, fault mechanics

1 Introduction

Geophysical analogue modelling has been in practice since decades. For this purpose, the properties such as length, time and the forces observed in the prototype need to be scaled down to the model level. Based on the scaling approaches observed in the literature [11, 10], the material being used to model the phenomena is crucially important to satisfy the different model parameters such as density, shear modulus, Young's modulus, viscosity; to name a few. A diverse range of materials have been used till now in order to reproduce earthquakes in the laboratory. These include gelatins [13, 8], foams [4, 9], 3D printed sand blocks [5], polycarbonate [6], absorbent kitchen paper [12] to name a few.

The material being chosen depends on its properties, which in turn depends on a rigorous characterization of these properties. A model can be properly designed with a good knowledge of the rheological and physical properties of the material. Measurement of the storage (G') and the loss (G'') moduli, which represent respectively the energy stored in the material during deformation and the energy lost [2, 3], gives a complete characterization of the material rheology.

We report in this study, a new rock analogue material, *candle gel*. No literature can be found with respect to the characterization of this material, at least to the knowledge of the authors. In the following, characterization of the rheology behavior of two types of candle gels has been reported. Consequently, it was possible to identify the candle gel as a typical viscoelastic material. The frictional properties of candle gel with sandpaper has also been investigated and reported. Finally, we discuss the potential use of this material in the upcoming analogue earthquake modeling.

2 Materials and Methods

Candle gel is a mixture of white paraffin oil and polymers. The candle gel used in this study is commercially manufactured by Candelis (<https://www.candelis.fr>). Two types of candle gels have been studied which are distinguished by their respective melting temperatures. Both the gels have a density of 838 kg/m^3 , and are transparent in color. In order to distinguish between the two varieties, we have adopted the nomenclature which will henceforth be used in the entire study. The gel "paraffin1" has a melting temperature of 55°C and gel "paraffin2" has a melting point of 72°C .

2.1 Rheology characterization

The rheology behavior of candle gels was investigated using the TA Instruments Hybrid Rheometer HR-2. A parallel plate geometry of 40mm diameter and 1mm gap (between geometry and static base plate) was used in conjunction with the static peltier base, which has an embedded Active Temperature Control (ATC) system. The schematic of the setup has been shown in Figure 1 (a).

For the rheology characterization, the sample size being quite intricate, it was important to prepare samples with consistent diameter and height. The required sample dimensions were 40mm diameter and 1mm height. The sample preparation procedure is as follows :

1. The required quantity of candle gel was measured based on the diameter of the glass petri dish, the required sample thickness and the density of the gel.
2. The petri dishes with the candle gel were then placed in the oven with the temperature set at 110°C for 30 – 45 min. Before placing the samples in the oven, a check with the help of a digital inclinometer was done for the horizontal levelling of the platform on which the sample was being placed.

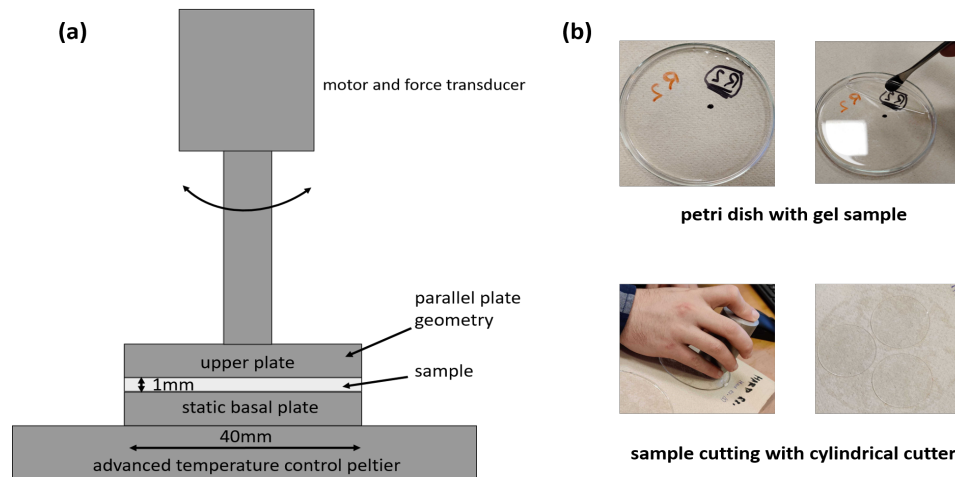


FIGURE 1 – (a) Schematic of the parallel plate geometry setup used in this study and (b) Measured quantity of gel sample melted and cooled in petri dish, cut into required size (sample diameter = 40mm) using the cylindrical cutter.

3. A check for the presence of air bubbles can be done during the melting of the sample at regular intervals. If any air bubbles are present, then the temperature of the oven can be increased which facilitates the removal of the bubbles.
4. Once ensured that the candle gel has melted homogeneously without any air bubbles in it, the samples were then allowed to gradually cool down in order to avoid sudden temperature changes. Moreover, with the sample still in the liquid state, it is advisable not to move the sample in order to avoid disturbing its levelling.
5. Given the size of the petri dishes, we finally obtained 3 test samples from each of them which were cut using a 38mm diameter, hollow, cylindrical tool (see Figure 1 (b)).

The samples obtained after cutting were then carefully placed on the base of the rheometer and the top plate was lowered slowly onto it. The different test routines have been explained as follows :

The viscoelastic behavior of candle gels can be investigated with the help of oscillatory tests. During these tests, the geometry oscillates around the rotor axis instead of constantly rotating in one direction. Consequently, both elastic and viscous properties are measured.

The amplitude sweep test was performed in order to define the linear viscoelastic region of the candle gels. In this test, the samples were subjected to an increasing oscillatory strain (10^{-1} to 10^3 %), with a constant temperature ($T = 20^{\circ}C$) and angular frequency ($\omega = 1\text{rad/s}$). The measured storage modulus (G') and loss modulus (G'') are plotted as a function of the strain amplitude (Figure 4). The threshold limit for the strain (γ_L) is determined as the value where the G' and G'' show a constant plateau and just before the structure integrity starts to break, indicated by a change in the plateau of the curves (see Fig.4).

Knowing the linear viscoelastic range of the gels helps to set the parameters for the further tests. Thus, all the further tests are performed well below the threshold limit of the strain amplitude.

Frequency sweep test was performed to verify the frequency or shear strain rate dependence of the material. Consequently, the strain amplitude ($\gamma = 15\%$) and temperature ($T = 20^{\circ}C$) were kept constant and the oscillation frequency (ω) is varied between 1 rad/s to 100 rad/s.

Temperature sweep tests were performed in order to quantify the temperature dependence of the material.

In this case, a heating rate of 5°C per minute was applied to the sample from 0°C to 50°C . For every step the measurement duration was 3 minutes, during which the strain ($\gamma = 10\%$) and angular frequency ($\omega = 1 \text{ rad/s}$) were kept constant. The results of all the tests performed have been reported in Section 3.

2.2 Characterization of frictional properties

The frictional properties of candle gel with sandpaper was investigated in this study. Given the low stiffness of the candle gel, a robust experimental protocol had to be designed to capture its frictional behavior with sandpaper. The double shear experimental apparatus shown in Figure 2 was used [7].

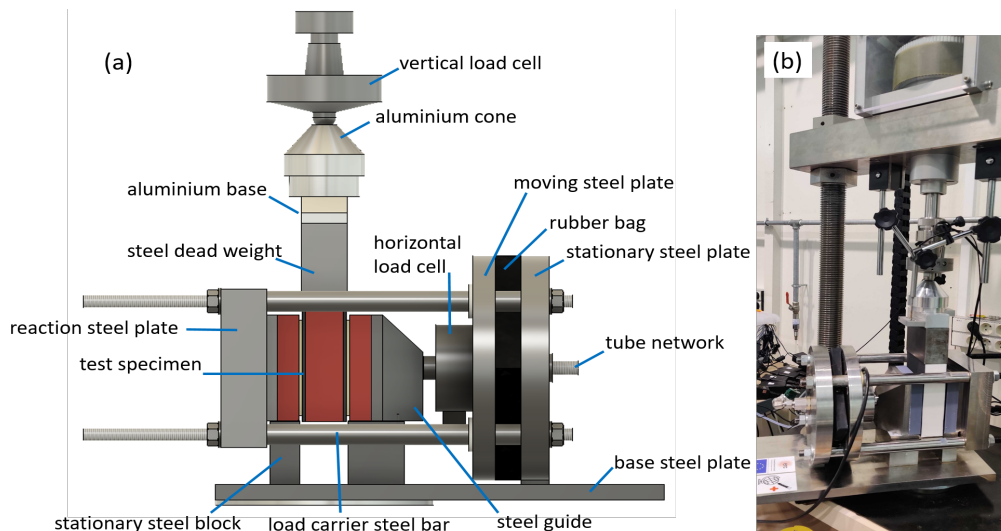


FIGURE 2 – The double shear device used for characterizing the frictional properties between candle gel and other materials, (a) Schematic of the setup, (b) Actual configuration in place.

The setup consists of two loading systems, *viz.* pressure controlled horizontal loading and displacement controlled vertical loading in order to apply the stresses on the test specimens (see Figure 2). The test specimen consists of 3 blocks, of which the middle block slides against the two side blocks, and hence consequently there are 2 shearing interfaces. The vertical loading system consists of a ram attached to the loading frame which applies the required displacement rate in order to push the middle block. Concerning the horizontal loading system, an electropneumatic pressure regulator applies the pressure to inflate/ deflate the rubber bag which transfers the stress to the moving steel plate, thus consequently loading the specimens. The experimental protocols adopted, *i.e.* rate of vertical loading, initial horizontal pressure, etc. will be discussed in detail in Section 3.

The corresponding stresses are captured by the horizontal and vertical load cells and the displacements are measured by two, vertically placed LVDTs. The readings of the LVDTs are averaged in order to eliminate the errors arising due to possible rotation of the middle block. The horizontal load cell is a 50kN compression load cell with a measurement error of $\pm 0.02\%$, whereas the vertical load cell is a 2kN load cell with a measurement error of $\pm 0.1\%$. The LVDTs used have a stroke range of $\pm 25\text{mm}$ and a measurement error of $\pm 0.01\%$. All the transducers are connected to an acquisition device and further processed using the LabView data acquisition software.

The middle and the side holding blocks have been fabricated using a commercial filament 3D printer (ULTIMAKER S5) with acrylonitrile butadiene styrene (ABS) as the filament material. As stated before, the candle gel is a soft material. Hence, a block of ABS was designed in such a way as to hold the candle gel inside it (see Figure 3).

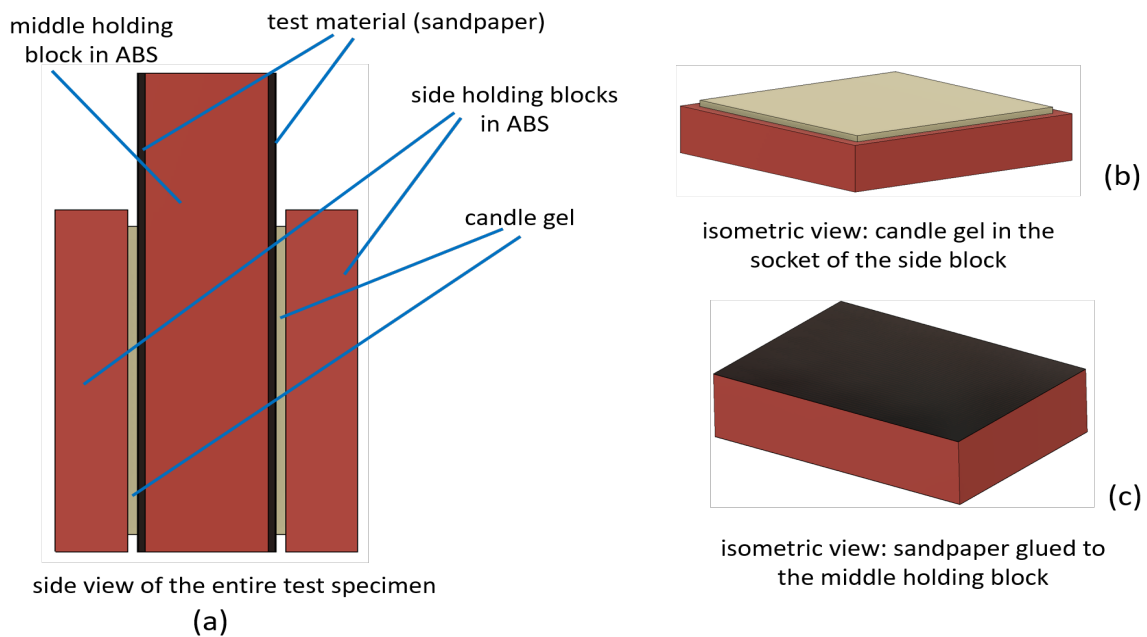


FIGURE 3 – Schematic view of the test specimen showing an isometric view of the side and the middle blocks with the test specimens.

The thickness of the side holding block is 1mm smaller than the candle gel in order to avoid any contact of the side holding block with the testing material, *i.e.* sandpaper. The sandpaper was glued to the middle block on the faces which are in contact with the candle gel.

A silicon mould was used for melting the candle gel samples. The dimensions of the mould are 300 x 240 x 70 mm (lxbxh) and the dimension of the sample required are 90mm in length, 90mm in height and 20mm thick. For one test, two such samples are needed. Hence, we calculated the quantity of the gel on the basis of the mould length, width and sample thickness along with the density of the sample. Required quantity (≈ 2 kg) of candle gel is placed in silicon mould and then put in the oven at 110°C for 3-4 hours for the gel to melt. The gel is allowed to melt homogeneously without any air bubbles. If any air bubbles present, the temperature of the oven was increased. Before allowing the samples to cool, it was verified that no air bubbles are present. In order to avoid a sudden temperature change, the samples are cooled gradually. Finally, the samples can be cut of the required sizes as required for the tests. Further, sandpaper of dimension, 140mm x 100mm was glued to the two faces of the middle block. The sandpaper used was 180 grit size.

3 Results

3.1 Rheology tests

The results of the amplitude sweep tests have been shown in Figure 4 for both types of candle gel. For both the varieties, the linear viscoelastic (LVE) region (indicated by the dotted black line) is nearly the same ($\gamma = 30\%$). The strain amplitude at which the material failure occurs, indicated by the crossover of G' and G'' is around $\gamma = 100\%$.

Between $\gamma = 30\%$ and $\gamma = 100\%$, we can see a sharp increase in the loss modulus for both the gels, whereas the value of G' shows a slightly decreasing trend.

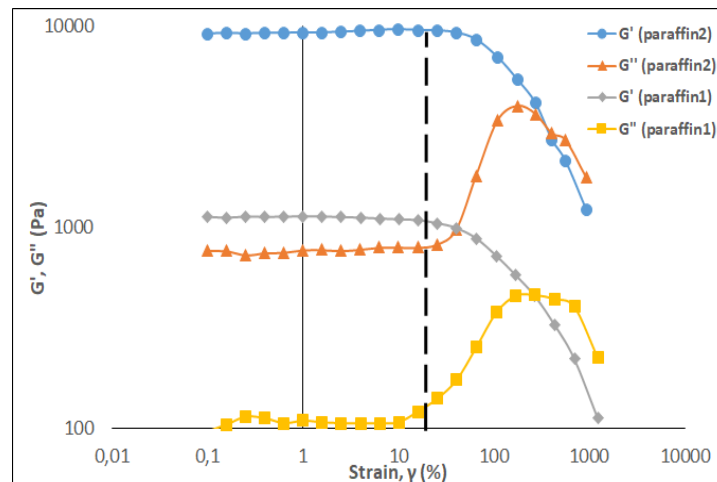


FIGURE 4 – Storage and loss moduli (G' and G'' (Pa)) for paraffin 1 and paraffin 2 as a function of applied strain (%).

Since the experiments are based on a number of variables, a variance in the data can be observed if the tests are repeated under the same conditions. A majority of this variance can be due to slight variations in the sample preparation procedure. Nevertheless, the coefficient of variation over 5 such tests was found to be around 5%.

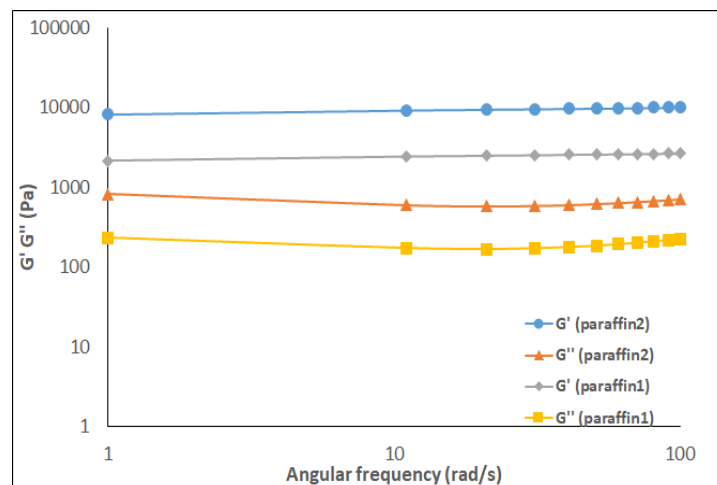


FIGURE 5 – Storage and loss moduli (G' and G'' (Pa)) for paraffin1 and paraffin2 as a function of angular frequency (rad/s).

Figure 5 shows the data for the frequency sweep tests. It can be observed that for both the gels, the amplitude of the storage and loss moduli remains constant over the range of tested frequencies, *i.e.* $\omega = 1$ to $\omega = 100$ rad/s. Note that the tests were performed within the linear viscoelastic limit ($\gamma = 15\%$). Thus, the gels show a regular behavior wherein the moduli are independent of frequencies below the critical strain limit.

Temperature sweep tests were performed with an aim to study the variation of the moduli over a range of temperatures. This test was critical since it would affect the design of the upcoming earthquake instability experiments. It can be seen in Figure 6, that the value of the moduli is nearly constant upto 30°C and then the storage modulus starts decreasing for both the gels. The crossover point of the storage and loss moduli will indicate the sol-gel transition temperature. In other words, for paraffin1, the gel transitions

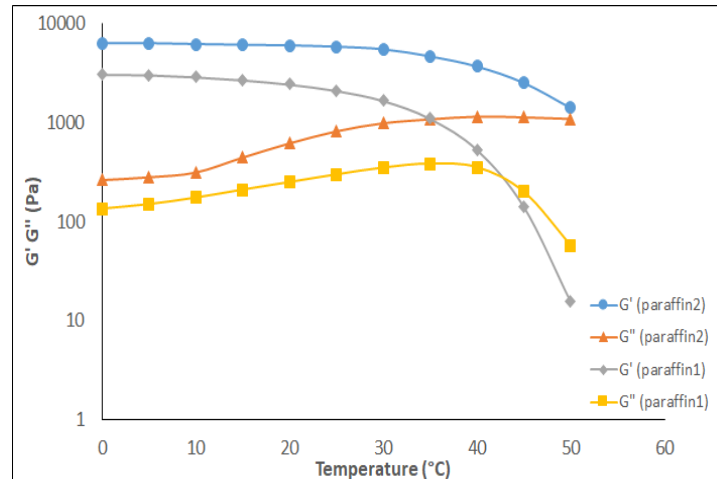


FIGURE 6 – Storage and loss moduli (G' and G'' (Pa)) for paraffin1 and paraffin2 as a function of temperature ($^{\circ}C$).

from the solid to semi-solid/ liquid phase at a temperature of nearly $45^{\circ}C$, whereas for paraffin2, it is observed to be around $50^{\circ}C$.

3.2 Friction characterization

For characterizing the friction properties, the test setup shown in Figure 2 was used. An initial horizontal pressure of 10kPa was applied in order to confine the samples. With the help of the loading frame, a constant vertical displacement of 0.5mm/min was applied on the middle block. This allowed for a slow sliding of the middle block against the two side blocks and consequently, the vertical displacement, horizontal force and the vertical force were measured by the LVDTs, horizontal load cell and vertical load cell respectively. The data acquisition and control was done using the LabView software.

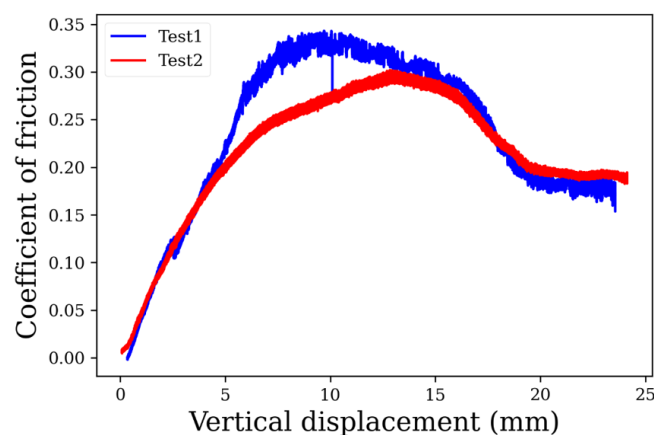


FIGURE 7 – Coefficient of friction vs vertical displacement for candle gel-sandpaper interface, measured in two different tests with similar initial conditions ($\sigma_h = 10\text{kPa}$ and vertical loading = 0.5mm/min).

With this data, the friction coefficient can be calculated using :

$$\mu = \frac{F_v}{F_h} \quad (1)$$

where, F_v is vertical force and F_h is the horizontal force. Since, the number of shearing interfaces in this case is 2, hence the vertical force needs to be divided by 2. Consequently, the friction coefficients measured have been shown in Figure 7. The response of the material was found to be quite similar as reported in the literature by [1]. Ofcourse, in this case, the material used was gelatin as against the candle gel in the current study.

The friction coefficient was observed to increase with the vertical displacement till it reached a peak value of ≈ 0.35 , indicating the shear strengthening behavior of the material, and followed by a decrease upto ≈ 0.2 and then it stabilizes around this value. The decrease in the friction coefficient can be attributed to several reasons, a few being the loss of material integrity and slip weakening.

4 Conclusion and ongoing work

The rheology tests performed helped to reveal the viscoelastic character of the candle gels. It was possible to completely characterize the behavior of these gels with an aim to model analogue instability experiments at the laboratory scale. The shear modulus obtained as a result from these tests was found to be 8.5kPa which is well within the limit of the required value as per the scaling laws adopted. Further, a novel experimental protocol was designed and validated to measure the frictional properties of different material interfaces. A part of the ongoing work includes the measurement of coefficient of friction for different interfaces such as candle gel–teflon, candle gel–plexiglas, candle gel–plastic and candle gel–glass. Moreover, the shear rate dependence of the frictional properties of the material also needs to be checked and the experiments are in progress for the same.

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