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ORIGINAL PAPER

RHEOLOGICAL STUDY OF LAVA FLOW ANALOG MIXTURES

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ABSTRACT

Laboratory and numerical modeling have been used to study and describe volcanic systems and magmatic processes for more than 100 years. The laboratory experiments, where the eruption parameters and material properties are firmly controlled, lead to finding lava flow behavior and the influence of various factors on flow evolution. Another advantage of our understanding of lava parameters and processes leads to the development of more sophisticated physical models improving the understanding of this phenomenon. In laboratory experiments, since the testing of silicate melt is difficult and dangerous, flow emplacement can be simulated by using analogous material. In this paper, we examined several materials to find a better analog that can be used as lava. We used PEG and wax as a substrate and added six additional materials in different proportions. To find out the behavior of the mixtures cone-and-plate type rheometer was used. Adding Si-acid to the mixture caused non-Newtonian behavior in both PEG and wax. In all mixtures the shear rate increases during decreasing viscosity which expresses shear thinning behavior. So, this new mixture can be used as an analog material to model the behavior of lavas during magma rise in conduits and when lava flows on Earth's surface.

INTRODUCTION

During most effusive volcanic eruptions lava forms slow-moving flows with an average speed that can be as high as 3 m/s. They rarely threaten human life, but they can cause enormous damage to the infrastructures and the environment, especially because the lava is molten rock and thus very hot. Lava flows can bury buildings, roads, and cover croplands during the spreading, they can swallow unliving objects, such as cars (lava flows in Hawaii), or living organisms, like trees or animals (ultra-alkali lava of Mt. Nyiragongo in the Democratic Republic of the Congo). On the other hand, they can contribute the global and local climate changes as huge amounts of toxic gases may release into the atmosphere (Prakash and Cleary, 2011). Therefore, recognition of lava flow and eruption processes is necessary, especially in densely populated areas. One of the best methods for data collection is observations of volcanological phenomena in nature that include eyewitness reports of the eruption, geological analysis of pre-existing deposits, and geodetic or geophysical monitoring of volcanoes, and they lead to numerical models and laboratory experiments (Kavanagh et al., 2018). It is crucial to understand the lava flow solidification process because this is essential if we would like to predict and estimate how far and how fast the lava can flow, especially when there is an inhabitant or forest near the volcanic mountain. For example, at Mt. Etna in Sicily (Italy), the lava flow has threatened settlements and tourist facilities, or at Mt. the Vesuvius close to Napoli (Italy) that has had effusive activity amongst the regular explosive periods throughout history (Scandone et al., 1993). For monitoring and recording lava flow in these two volcanoes, a well-equipped monitoring system has been installed (Garel et al., 2014). The lava flow path depends on the rheology of the lava, the effusion rate, the steepness of the slope, the topography, the coverage of the surface, the cooling condition, and the steepness and stability of lava domes (Bilotta et al., 2019). Taking account of these factors is vital to assess lava flow hazards in numerical and laboratory simulations. However, many additional aspects of lava flow behaviors that may occur in nature cannot be simulated, such as the bed roughness or vegetation coverage, or channel formation during the lava flowing and cooling. Moreover, simulations regularly neglect the effect of turbulence, the mechanical, and thermal erosion of the material, or the time dependence of the effusion rate. Laboratory experiments can help us to understand and model the lava flow behavior by using analogous materials. The most popular substances for laboratory experiments are organic materials such as wax, paraffin, and syrup, or inorganic materials such as slurries or molten rock

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(Lev et al., 2019). Laboratory analog models can provide tests for simple flow models and explore complex and unstable flow regimes that have not been addressed by theoretical or computational models (Griffiths, 2000).

PREVIOUS WORK

PEG (Polyethylene glycol) is a polyether compound, a commercial water-soluble wax that is dependent on temperature and has the propensity to develop a rigid crust like lava. PEGs depending on their molecular weights can be viscous liquids or solids with a low melting point. Previous studies used PEG to simulate mafic lavas on the Moon and Earth (Greeley and Womer, 1982; Huppert and Sparks, 1985; Hallworth et al., 1987). These studies were often qualitative and compared flows observed in nature with flow specifications obtained in the laboratory. Some of these experiments were performed under subaerial conditions (not underwater), which caused unrealistically large surface-tension effects at small scales. Fink and Griffiths produced four separated flow morphologies with the application of different cooling and effusion rates (Fink and Griffiths, 1992). In this series of laboratory simulations, PEG was extruded from a point source onto a smooth flat floor under cold sucrose solution at a constant rate.

Experiments with the highest cooling and lowest effusion rates created by large contrast between the temperature of the erupting wax and the sucrose solution produced radially symmetric flows which rapidly crusted and advanced by creating tiny toes or “pillows”. As cooling rates decrease and effusion rates increase, pillowed flows become rifted flows. Rifted flow yielded the flows in which surface crusts are folded cross to the flow direction. The lowest cooling rates and the highest effusion rates created leveed flows, which solidified only at their margins. These results were used by Griffiths and Fink to explain the morphology of submarine lava flows (Griffiths and Fink, 1992). According to their works, laboratory pillowed flows look like submarine pillow lava, rifted flows are similar to submarine lobate flows, and folded flows are analogous to submarine ropy flows, while leveed flows correspond to submarine jumbled sheet flows. Gregg and Fink (1995) refined this classification by using more detail from mid-ocean ridge lavas. Griffiths and Fink (1992) displayed the effect of the different planetary environments on morphologic transition for specific composition flows (Gregg and Fink, 2000).

THE RHEOLOGY OF LAVA

The rheological behavior of viscous fluid is classified by the relation between the shear stress and shear rate. If the relation of shear stress and shear rate is linear, it is called Newtonian, otherwise, it is a non-Newtonian fluid.

If lava was Newtonian fluid, it would go downhill and continues even after the ceasing of volcanic eruption until it reaches the deepest structure where it can finally set. But observations and laboratory experiments show different behaviors. Generally, it comes to rest on the slope as soon as volcanic eruptions cease. So, it is clear that there is another limitation process called cooling, which causes the lava flow to behave as a non-Newtonian fluid (Hulme, 1974; Chevrel et al., 2013). Although the rheological properties of lava flow are measured and estimated by petrological studies, it is difficult to find a straightforward relationship between lava properties and their morphologies because they may change in time and space (Miyamoto and Sasaki, 1997).

The rheology of lava depends on temperature, composition, volatile and crystal content, and time (during cooling, crystallization and vesiculation). The viscosity of lava at any given temperature above the liquidus is estimated by its chemical composition. However, lava more often flows at a lower temperature than its liquidus, and suspended crystals and gas bubbles (vesicles) cause the rheology properties of lava to change from simple Newtonian to more complex (Bagdassarov and Pinkerton, 2004).

Crystal content in lava shows a wide range: from 5 % in many basalts and rhyolites up to 30-50 % for andesite and dacites at the vent, and it increases by getting far from the vent (Cashman et al., 1999). Gas bubbles occupy volume from a few percent up to 90 % in highly vesiculated portions of a lava flow (Griffiths, 2000). One of the consequential characteristics of a non-Newtonian solid-liquid mixture in heterogeneous systems is its shear-dependent behavior that has two types: shear thinning (pseudoplastic), where the viscosity decreases with the increasing shear rate, and thickening (dilatant) when the viscosity increases with the increasing shear rate (Liu et al., 2018).

ANALOG MATERIAL

The choice of materials that can be used as analog materials in laboratory experiments depends on their availability and practicality. In this case, materials can be chosen to cover various aspects of lava rheology. For example, sugar syrups and silicone oils are one of the cheapest and simplest temperature-dependent materials used as analogs (Garel et al., 2012; Tingay et al., 2015).

PEG (polyethylene glycol) is usually used as an analog material for lava flow simulations because it can develop surface crust during cooling and slow down the cooling process of the underlying material. One of the first studies to find these analog materials were performed by Fink and Griffiths (1990). They carried out an experiment using a tank of cold sucrose solution and injected PEG from the bottom of the tank onto an almost horizontal surface. In order to prevent sliding of the surficial crust and to simulate roughness they used wire mesh at the bottom of the tank. The

Table 1 Materials used in the laboratory experiment.

	Rock salt (NaCl)	Carbon	Si-acid		$CaCO_3$	Sand	Bentonite clay
PEG 4000 (10 g)	0.1g 1g	0.1 g 1 g	0.1 g 0.5 g	0.3 g 1 g	0.1 g 1 g		
Wax (5 g)		0.5	0.05 g 0.3 g	0.1 g 0.5 g	0.05 g	0.05 g 0.5 g	0.05 g 0.5 g
Wallpaper adhesive (WPP) 1g	30 ml water						
Polyvinyl alcohol (PVA) 5 % solution	water+3 drops of borax						

experiment was recorded by using 3 cameras around the tank. Gregg and Fink (2000) examined the effect of slope on the characteristic morphologies identified by Fink and Griffiths (Garel et al., 2014).

Recently molten rocks have been used to approximate lava properties. For example, several experiments were conducted at Syracuse University of New York (Karson et al., 2012), and in all cases, basaltic material has been used. Basalt was melted to super liquid temperature (higher than 1300°C). In these experiments, molten basalt was extruded onto three different types of slopes. The first one was a sheet of ice, the second one was a platform made of ice blocks and the last one was shaved ice and flow velocities were recorded. Nonetheless, molten natural rocks have different characteristics compared to natural lavas in vesicularity, cooling rate, crystallinity, and crust formation and it is hard to work with hot basalt (Edwards et al., 2013). In this paper, we use PEG 4000 and oil wax as substrates, and we add various ingredients as additives to obtain the best mixture that can be used as a lava analog.

MATERIALS AND METHODS

The key to counteracting lava flow and mitigating its effect is to prepare for it before the volcano erupts. To reach this aim, it is necessary to recognize the traveling distance and location of future lava flows. As mentioned before, laboratory experiments can provide valuable information in this area, but the first step is to find a mixture that can be used as a lava analog in laboratory experiments. Here we used six additives (common rock salt (NaCl), carbon powder, Si-acid, pulverized $CaCO_3$, sand, and bentonite clay) with different portions which were mixed with 10 g PEG and 5 g wax. We prepared 48 samples and measured their rheology properties to find the effect of additional material on the behavior of wax and PEG. To prepare a soft and uniform mixture, we grounded wax and the PEG, respectively. During the mixing and melting of the admixture, some of the samples could not mix and melt properly, and the presence of unmingled coarser grains in the samples caused an error during the examination. In this case, we had to skip these samples. We also investigated combinations of wallpaper adhesive with water, as well as polyvinyl alcohol with water and borax. Samples that were used during the measurements are shown in Table 1.

To examine the rheological properties of the material, we used a cone-and-plate rheometer (AR 550 rheometer- TA Instruments) with a 40 mm diameter plate geometry at a gap size of 500 µm, and to find the thermal behavior of wax and PEG, we used Differential Scanning Calorimetry (DSC).

RESULTS

The first step to figuring out the effect of additives on the rheological properties of wax and PEG is to know their rheology behavior without any additives. In this case, we examined pure PEG and wax without adding additional material. As it was mentioned before, the temperature affects the rheological properties of these kinds of materials, so according to Figure 1, the melting point of PEG is ca. 55 °C, and for wax, it is almost 37 °C. So, we performed all examinations at 60 °C which is higher than their melting point.

Figure 2 shows the relation of shear stress with viscosity in PEG and wax. The results indicate that PEG and wax have Newtonian behavior at 60 °C. so we wanted to know how the additives material can affect their rheology. In this case, we added additional material, some of the results are shown in Figure 3.

As shown in Figure 3, adding rock salt, calcium carbonate, carbon, sand, and clay could not change the behavior of the mixture and did not convert it from Newtonian to non-Newtonian.

According to the results, the mixtures where Si-acid was added show a better effect. Figure 4 represents the rheological behavior of PEG with different proportions of Si-acid.

Si-acid of 0.1 g has little effect on the rheological behavior of the mixture. As we used more Si-acid in the admixture (0.3 g and 0.5 g) viscosity increased and the mixture having 0.5 g Si-acid showed non-Newtonian behavior as the viscosity decreased with increasing shear rate. But when we used 1 g Si-acid, the results were reversed, as the Si-acid probably could not mix up with the PEG. So, the presence of non-melted grains in large amounts caused a decrease in viscosity. Figure 5 shows the change of viscosity in the function of shear rate for various wax/Si-acid mixtures.

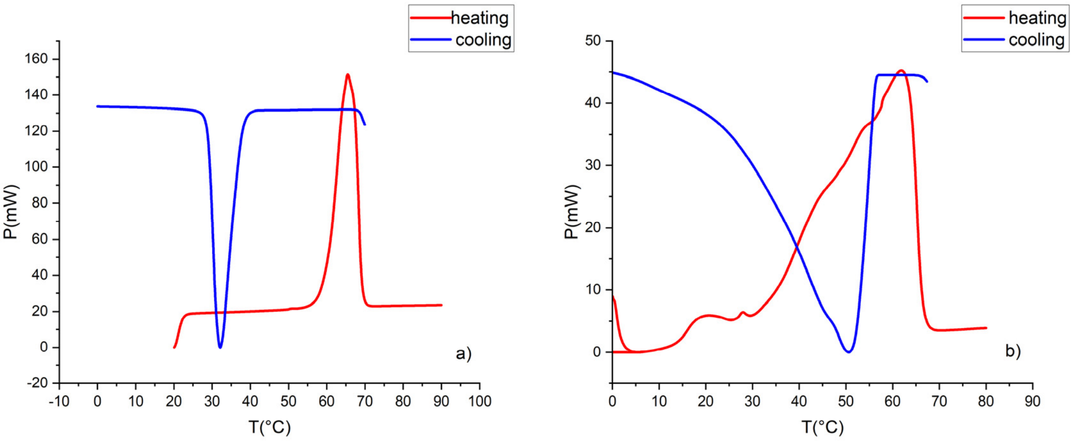

Fig. 1 Differential Scanning Calorimetry (DSC) thermograms of a) PEG and b) wax.

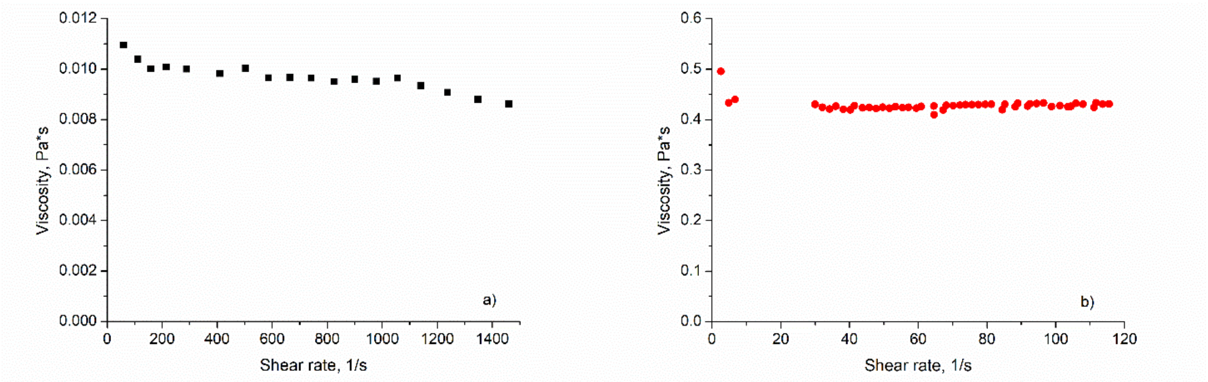

Fig. 2 Viscosity versus shear rate diagram for (a) PEG and (b) wax.

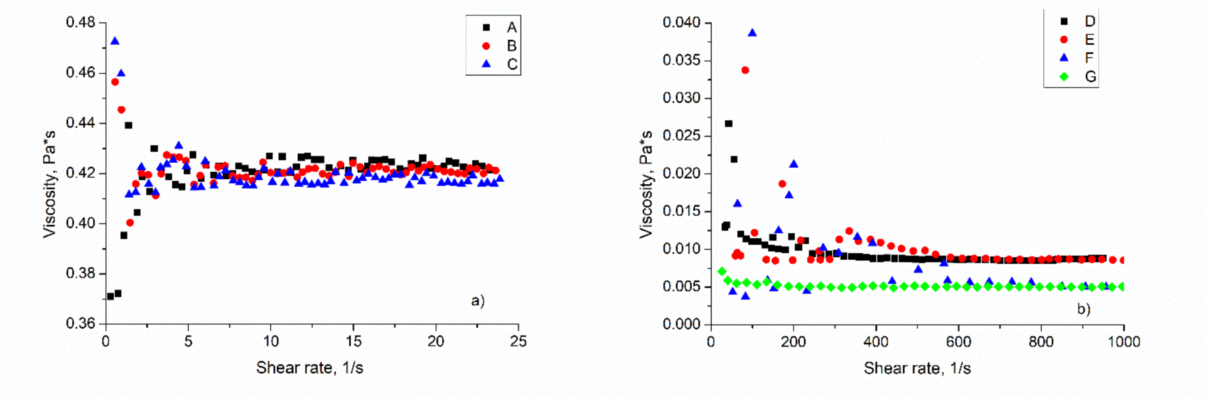

Fig. 3 Viscosity versus shear rate diagrams for (a) 10 g PEG mixed with A: 0.1 g carbon, B: 0.1 g $CaCO_3$, C: 0.1 g rock salt, (b) 5 g wax mixed by D: 0. 5 g carbon, E: 0.05 g $CaCO_3$, F: 0.05 g bentonite clay, G: 0.05 g sand.

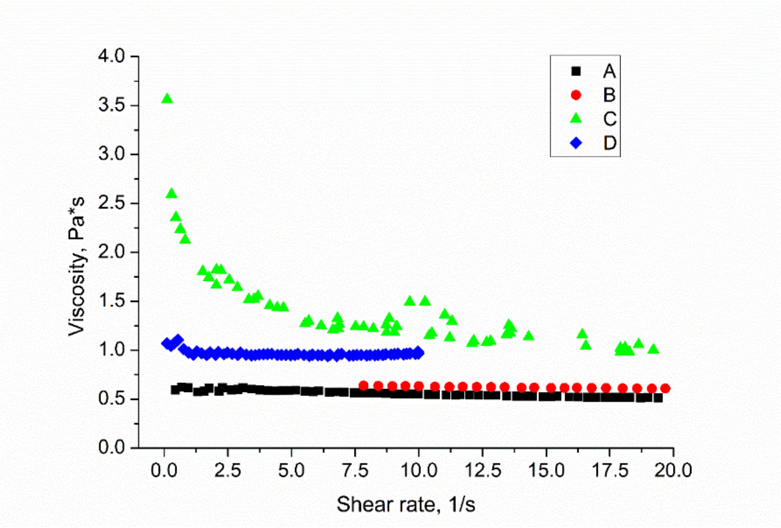

Fig. 4 Viscosity versus shear rate diagram of 10 g PEG mixed with A: 0.1 g, B: 0.3 g, C: 0.5 g, and D: 1 g of Si-acid.

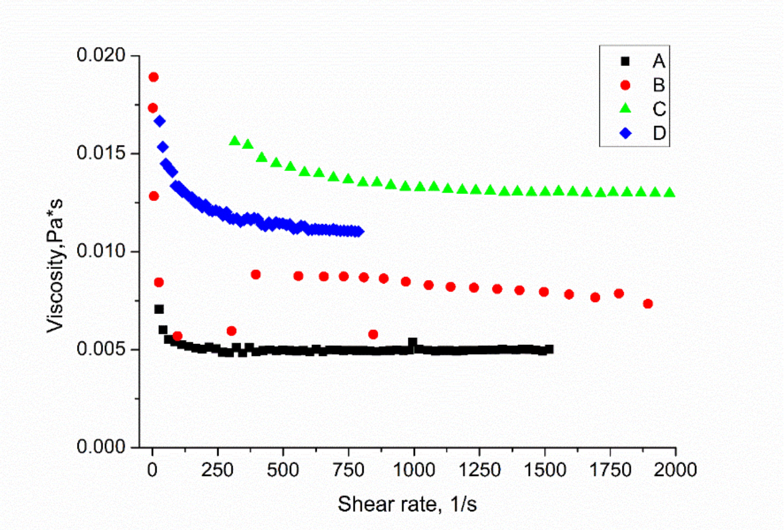

Fig. 5 Viscosity versus shear rate diagram of 5 g wax mixed with A: 0.05 g Si-acid, B: 0.1 g Si-acid, C: 0.3 g Si-acid, D: 0.5 g Si-acid.

According to the results, adding 0.05 g and 0.1 g Si-acid to the wax caused an increase in viscosity but could not have much effect on the rheological behavior of the mixture as it showed Newtonian behavior. Increasing the proportion of Si-acid to 0.3 g and 0.5 g, resulted in better outcomes and the mixture showed shear-thinning behavior as a non-Newtonian flow.

We also examined the behavior of wallpaper adhesive and polyvinyl alcohol mixed with water and borax. The measured viscosity at various shear rates is shown in Figure 6.

As mentioned before, in shear-thinning liquids the viscosity decreases with the increasing shear rate, which can be seen in Figure 4 (especially for WPP with water).

To examine the effect of temperature on the rheological behavior of the mixture the same portion of Si-acid (0.3 g) mixed with wax was used. We investigated the effect of temperature changes at three different temperatures (56 °C, 60 °C, and 90 °C). Additionally, we examined the effect of the temperature below 56 °C, but in this case, the mixture started to cool to around the melting point and the rheometer could not give accurate results (Fig. 7).

Based on the result, with increasing temperature, viscosity decreases but at 56 °C, the relation between the viscosity and shear rate is nonlinear. When the temperature rises to 60 °C the relation between the viscosity and shear rate is still nonlinear but closer to linear (it shows non-Newtonian behavior at a temperature higher than its freezing point) and at

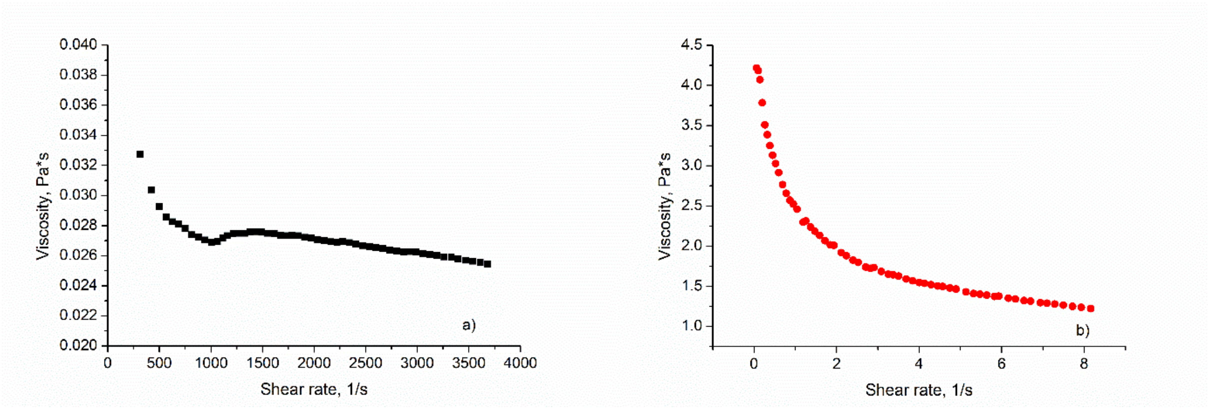

Fig. 6 Viscosity versus shear rate diagram of (a) 5 % PVA with water and three drops of borax, (b) 1 g WPP with 30 ml water.

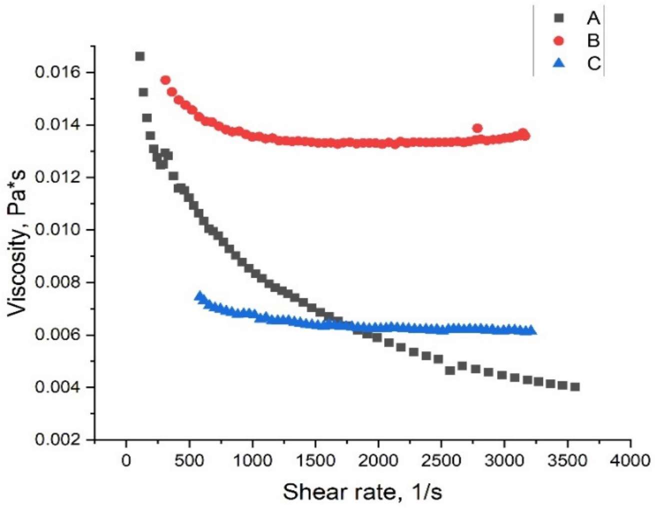

Fig. 7 Viscosity versus shear rate diagram of 0.3 g Si-acid mixed with wax at A:56 °C, B: 60 °C, C: 90 °C.

90 °C it is almost linear. In the report of the previous studies, when the lava flows at a high temperature, it behaves as a Newtonian flow but, during cooling and decreasing the temperature e, it becomes more viscous and behaves as a non-Newtonian liquid which is visible in Figure 7.

DISCUSSION

We are looking for a material that can be used as a lava analog in laboratory experiments and simulations. Lava has a complicated non-Newtonian behavior and a cooling process that is dependent on temperature. Wallpaper adhesive and polyvinyl alcohol mixed with water have non-Newtonian behavior. They can be used as a lava analog to show non-Newtonian behavior. Still, they cannot support cooling processes because they are liquid and do not show solidification in the examined temperature range.

Lava has a complex rheological behavior and as it was mentioned before that is closer to a Newtonian type at high temperatures or near the vent, and as it moves away from the vent or crater (during cooling) it becomes non-Newtonian. However, due to the dissolved volatiles, vesicles (bubbles), and various crystals scattered in the lava, it can show a non-Newtonian behavior at a temperature that is much higher than its solidus. Our goal is to find mixtures that have non-Newtonian behavior in a wider temperature range than other lava analog materials and are closer to the rheological behavior of lava.

As it was mentioned before wax and PEG are commonly used as analog materials to study the behavior of lava flows because they have similar physical properties from a given point of view. For example, both materials can be heated and melted (their melting temperature range is suitable for laboratory applications), and they can solidify as they cool. But there are many differences between the behavior of PEG and wax with lava. PEG is a type of polymer that can exist in both liquid and solid forms, depending on the molecular weight and temperature.

However, PEG is not classified as a non-Newtonian fluid. On the other hand, wax can exhibit non-Newtonian behavior under certain conditions. Since the lava has non-Newtonian behavior and an analog material that has properties that are closer to real lava is generally better for studying lava and volcanic phenomena, using PEG and wax as analog materials to study lava behavior may not accurately replicate the non-Newtonian behavior of real lava flows. While PEG and wax can be useful analog materials for some aspects of lava behavior, such as flow properties and cooling behavior, they may not be ideal for studying non-Newtonian behaviors. Adding Si-acid improves the properties of wax and PEG to have non-Newtonian behavior. According to Figure 1, wax has a wider range of cooling while PEG gets solid fast as it reaches the freezing point. So, the wax may be a better choice because it has a slower cooling process and by adding Si-acid, it shows non-Newtonian behavior in a wider range of temperatures which gives the users enough time to simulate lava flowing and show the cooling process.

CONCLUSION

In order to investigate lava flows during their propagation scientists have proposed several methods. In some experiments, molten rocks were used, while in other cases, analog materials were used. Lava can exhibit both Newtonian and non-Newtonian behavior at different temperatures, but the exact temperature at which lava changes behavior from Newtonian to non-Newtonian cannot be specified. Scientists have previously proposed some materials that could be used as lava analogs, such as sugar syrups and silicone oils, but these materials tend to behave as Newtonian liquids, and some of them cannot show cooling processes. Our goal was to find a material that acts as a non-Newtonian material in a wide temperature range and is not dependent on freezing point and can show cooling processes. We tried several materials and additives with various mixing ratios, but in the end, we used PEG and wax mixed with Si-acid and melted them at the temperature of 60 °C. The results obtained from the rheological tests were satisfactory. In the presence of Si-acid, the mixtures exhibit non-Newtonian behavior in a wide range of temperatures that is not solely determined by freezing point. Furthermore, we demonstrated that mixed materials' behavior changed as the temperature decreased during cooling from Newtonian to non-Newtonian.

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