Viscoelasticity and Shear Deformation of Foam during Solidification

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Pumices produced by caldera-forming eruptions have a characteristic structure in which bubbles are elongated in one direction. They are called tube pumices. This study is a part of the research project to elucidate the origin of tube pumices to understand the behavior of magma in caldera-forming eruptions. The research uses rigid polyurethane foam (PUF) as a magma analogue. PUF is porous plastic material generated by mixing polyisocyanate liquid and polyol liquid with catalysts, blowing agents, and/or foam stabilizers. PUF during solidification is viscoelastic, which foams and solidifies like magma during an eruption. Magma is also viscoelastic and its behavior depends on viscosity, gas volume fraction, temperature, and time-scale like strain rate. Viscoelasticity of magma in a vent is crucial to determine the types of volcanic eruptions.
To use PUF as magma analogue, it is necessary to understand the mechanical property of PUF itself. This study is made to quantify the viscoelasticity of PUF during chemical reaction by applying shear deformation in various time-scales. This paper describes the results of comparison between oscillatory deformation behaviors and constant shear-rate behaviors.
The PUF is made of mixing polyisocyanate (Hycel 360P) and polyol (Hycel HW-408 without foam stabilizers), both of which are provided by Toho chemical Industry Co., Ltd.
Viscoelasticity measurements were made with a customized rotating cylinder rheometer (AR 2000ex, TA Instruments). The outer cylinder (polypropylene beaker, diameter: 11.5 mm) is held in place. The inner cylinder (aluminum rod, diameter: 7.5 mm) is controlled by the motor and rotates. The gap of the bottom of cylinders is 8 mm.
The PUF stock solution was poured between the cylinders. It expanded with heat generation to 60% porosity. We recorded temperature of the side of the cylinder by an infrared thermometer. The state of expansion was recorded by a video camera. The length of the specimen touching the inner cylinder was measured in the video images. In the oscillation tests, the complex viscosity was determined by comparing the length, the torque, and the angle of rotation. The apparent viscosity was determined by applying constant shear-rate deformation.
Two types of experiments were performed.
First, we measured the complex viscosity to clarify strain-amplitude dependence by oscillation with an angular frequency of 20 [rad/s]. It was found that the reproducibility of the viscoelasticity measurements was good when the strain amplitude was lower than 0.01.
Second, by giving oscillatory deformation and constant shear-rate deformation alternately to the specimen, the complex viscosity and the apparent viscosity were measured. Most polymers follow Cox-Mertz rule which states that the absolute complex viscosity is equivalent with the apparent viscosity when the angular frequency of the oscillation measurement and the strain rate during constant shear-rate deformation are equal (Marrucci, 1996). In a bubble flow, semi-empirical theory shows Cox-Mertz rule being true. According to Llewellin et al. (2002a), apparent viscosity and absolute complex viscosity depend on dimensionless numbers, which are capillary number Ca ($\propto$ shear rate) and dynamic capillary number Cd ($\propto$ angular frequency). The measurement revealed that, Cox-Mertz rule could not be applied to PUF when Ca is larger than 0.1. As Ca increased, the apparent viscosity became significantly smaller than the absolute complex viscosity.
Decreasing the apparent viscosity with increasing Ca has been understood as the effect of bubble

elongation by shear deformation. However, in this experiment, the apparent viscosity decreases more significantly than the semi-empirical estimate. Because the PUF used in this study has a very large porosity. We think that decreasing the viscosity is the result of larger elongation of bubbles which might be caused by bubbles interaction.

Keywords: foam, complex viscosity, apparent viscosity, capillary number