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Rheological tests of polyurethane foam undergoing vesiculation-deformation-solidification as a magma analogue

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Magma exhibits a variety of rheological behaviors in an eruption process, including non-linear, time-dependent, and non-recoverable changes. It is not well established how to characterize such rheological properties and how to apply them for understanding volcanic processes. Developing a good analogous system is useful for studying this problem. Here we use polyurethane foam (PFU) which undergoes vesiculation, deformation, and solidification by chemical reactions of two polymeric liquids. The evolution of rheological properties is measured using a rotational rheometer with controlled temperature.

First, we conduct small-strain oscillatory tests with frequency sweeps to characterize the viscoelastic property of PUF and compare it with those of magma. We focus on G''/G' and $d(G''/G')/d\omega$, where G' and G'' are the real and the imaginary parts of the complex modulus, respectively, $\omega is the angular frequency, and$d()/d$\omega$ represents a derivative by ω. $d(G''/G')/d\omega$. When the temperature is kept below 45 degrees Celsius, $d(G''/G')/d\omega$ is always negative as G''/G' changes from fluid-like (>1) to solid-like (<1) with the solidifying reaction. We regard that this rheological evolution is similar to the Maxwell viscoelasticity with temporally increasing relaxation time, which is expected as simple analogous materials of magma. When the temperature is higher than 45 degrees Celsius, on the other hand, "gelation" is observed in the early stage of the reaction. Gelation is one of the most prominent transitional behavior during the solidifying reaction of polymers including PUF. It is characterized by $d(G''/G')/d\omega = 0$ in a certain range of ω. As passing the gel point, $d(G''/G')/d\omega$ changes from negative to positive, and frequently it accompanies a transition of G''/G' from fluid-like (>1) to solid-like (<1). This transition is not the so-called glass-transition noted as a cause of brittle fracture of magma but is related to an appearance of yield strength. When stress larger than the yield stress is applied, the material tends to flow rather than to break. Gelation is known to occur not only in polymeric fluid but also in suspensions. We consider the solidification conditions of PUF including the gelation are comparable with rheological evolutions of magma containing crystals.

Next, we compare the oscillatory rheology with viscosity measured by finite-strain creep tests with a constant strain rate. The specimen's rheological evolution is monitored before and after each creep test by the oscillatory method with ω equal to the given strain rate. The viscosity during the creep test is about a half of the expected dynamic viscosity at the time expected by the interpolation of the measured values by the oscillatory test before and after the creep test. The bubble structures are analyzed by the X-ray CT after solidification. We found highly deformed bubbles in specimens from creep tests at large Capillary numbers (the ratio of viscous stress to the surface-tension stress), while only spherical bubbles in specimens from oscillatory tests.