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Experimental investigation on viscosity of crystal-bearing magma; a case study for the 1778 Izu-Oshima basalt

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In this study, laboratory viscosity measurements combined with textural analyses were performed on the tholeiitic basalt erupted in A.D. 1778 from the Izu-Oshima volcano, Japan, to evaluate the effect of suspended crystals on viscosity of magma in relation to textural characteristics. We used the atmosphere-controlled high-T concentric cylinder rotational viscometer at Kobe University. Measurements were done at temperature from 1531K to 1395K under Ni-NiO oxgen buffered conditions and a part of melted sample was collected after each measurement, quenched and processed to thin section for textural analyses using an electron microprobe. During measurement, apparent viscosity at first decreased with increase of total strain and then achieved to steady state (thixotropy). Large amount of strain ($>$ 100) is required to achieve steady state of viscosity. The obtained viscometry datasets at steady state were analyzed based on Bingham fluid models to determine Bingham viscosity and yield stress.

Crystallization of plagioclase started at ca. 1446K followed by pigeonite at ca. 1413K, and trace amount of augite and magnetite crystallized at ca. 1395K. Crystallinity increased monotonously up to 0.29 as cooling. Plagioclase crystals are tabular; 50% of them have apparent width/length ratios lower than 0.25. Their crystal size distributions show similar pattern with those of natural lavas and

Bingham viscosity increased from 42 to 1765 Pas and relative viscosity (defined as the ratio of Bingham viscosity to melt viscosity) increased up to ca. 9. Shear thinning behavior was found at temperatures below 1413K (crystallinity above 0.13) and apparent yield stress monotonously increased up to 210 Pa with cooling.

When crystallinity is relatively lower, the effect of crystals on viscosity of magma is known to be well described by the Krieger-Dougherty (KD) equation,

ln relative viscosity = -vFm ln (1-F/Fm)

where F is crystallinity, Fm is maximum packing fraction, and v is an intrinsic viscosity. The Einstein-Roscoe (ER) equation, which is conventionally used to describe the effect of uniform equant crystals, is a specific case of the KD equation with vFm = 2.5 and Fm = 0.6. The Casta equation, which is proposed to describe relative viscosity in full range of crystallinity, can be simplified to the KD equation when F is well lower than Fm. The obtained relative viscosity increased sharply against crystallinity compared with both the ER equation and the Costa equation. The deviation of our data from these equations are chiefly attributable to difference in crystal shapes. The values of vFm and Fm were determined by least square fitting of the KD equation to be 2.3 and 0.47, respectively. Note that the obtained value of vFm is similar to that of the ER equation, indicating that the effect of crystal shape on relative viscosity can be evaluated only by adjusting the value of Fm. The obtained value of Fm is significantly lower than the numerical one calculated for randomly oriented, uniform oblate particles with the same mean width/length ratio. This may be due to the effect of crystal shape distribution; more anisotropic crystals effectively affect on relative viscosity of magma.

The critical crystallinity for onset of yield stress, Fc, is at least lower than 0.13 and yield stress increased with crystallinity. The value of Fc is lower than the numerical one calculated for randomly oriented, uniform oblate particles with the same mean aspect ratio. This discrepancy may be also explained by the effect of crystal shape distribution; only small amount of crystals with very low width/length ratios may contribute to yield stress generation and therefore the effective aspect ratio for onset of yield stress is lower than those expected for the mean value for this sample.

Keywords: viscosity, crystal, texture, non Newtonian fluid, Izu Oshima, basalt