
Naturally occurring volcanic lavas typically consist of liquid melt, solid crystals and gaseous bubbles. The rheological behavior of lava is complicated by the fact that these three phases are chemically interactive. The composition of the liquid silicate phase varies during the emplacement of a lava flow due to: (i) crystal nucleation and growth, and (ii) the exsolution of volatiles. The viscosity of the liquid phase is a function of its chemical composition and temperature, whereas the apparent viscosity of the bulk lava depends upon the liquid viscosity, the concentration of crystals and bubbles, and the stress conditions under which the lava is flowing. Natural lavas are open chemical systems. Consequently volatiles can be lost by degassing during an eruption, and crystal phases can be effectively removed by sedimentation or flotation. Under these circumstances it is extremely difficult to characterize the rheological properties of a naturally occurring lava over the complete course of flow emplacement.

The mechanical behavior of two phase solid-liquid suspensions has been investigated theoretically by Einstein and Roscoe. For the case of rigid spheres entrained in a Newtonian liquid (i.e., a liquid in which the ratio of shear stress to shear rate is constant) the bulk viscosity of the suspension ($\eta_S$) is given by:

\[
\eta_S = \eta_L (1 - 1.35 f_V)^{-2.5}
\]

for uniform spheres

\[
\eta_S = \eta_L (1 - f_V)^{-2.5}
\]

for diverse sized spheres

where $\eta_L$ is the viscosity of the liquid phase in poise and $f_V$ is the volume fraction of the suspended solid phase. Shaw has previously suggested that these relationships could be used to estimate the bulk viscosity of natural lavas if crystal content and liquid viscosity were known at successive stages of crystallization, and if crystals behaved as rigid particles. Experience with emulsions indicates that the suspended particulate phase can be effectively considered to be rigid solids if the viscosity of the particulate phase is 50 times greater than the liquid phase viscosity. This is a reasonable assumption for volcanic crystals over the temperature range 1000°C-1300°C at which terrestrial lava flows are commonly emplaced. Therefore volcanic crystalline phases can be treated as rigid particles.

Variations in crystal content, crystal chemistry and residual melt composition over the complete range of crystallization temperatures have recently been reported by Wright and Okamura for a Hawaiian tholeiite basalt. These measurements are based upon detailed geochemical and petrological studies of samples obtained from the 1965 Makaopuki lava lake. These measurements characterize the near-equilibrium crystallization of a naturally occurring basalt at surface pressure. On the Earth, basaltic lavas are responsible for the construction of a variety of volcanic landforms (shield volcanoes, lava plains) and the longest terrestrial lava flows are typically basaltic in composition.

The Makaopuki data can be used to determine residual melt compositions at successive cooling stages by selectively removing elements from the liquid silicate phase as specific mineral phases nucleate and grow. Suspension viscosities at different crystallization temperatures have been calculated for the Makaopuki basalt employing: (a) crystal concentration data reported in, assuming a constant 6.0 wt pct olivine below 1181°C and no mechanical separation of crystals, (b) a constant composition for olivine (Fo75), clinopyroxene (En45 Fs18 Wo37), and plagioclase (An60) over the temperature range 1205°C-1080°C for calculation of residual melt composition, (c) the methods of Bot-
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tingsa and Weill, and Shaw to determine the viscosity of the residual silicate liquid, and (d) the Einstein-Roscoe equations to determine $n_s$.

Calculated suspension viscosities are compared with laboratory measurements of apparent viscosity ($n_a$) and field measurements of plastic viscosity ($n_p$) reported by Shaw in Table I. Laboratory measurements were performed on degassed samples and have absolute accuracies of $\pm 10^\circ C$ and $\pm 20\%$ at over the temperature range 1300$^\circ C$ to 1150$^\circ C$; field measurements were performed upon in-situ samples which contained some small volume fraction of bubbles at absolute accuracies of $\pm 5^\circ C$ and $\pm 10\%-20\% n_p$. The Makaopuki basalt has been characterized as a Bingham fluid which means that it has an appreciable yield stress at high crystallinity and/or low shear rates. However, at the relatively high shear rates (>1 sec$^{-1}$) presumed to exist over a major portion of a flow's emplacement history, apparent viscosity ($n_a$ = shear stress/shear rate) would be essentially equal to the plastic viscosity estimated by a Bingham fluid model.

Calculated suspension viscosities agree with measured viscosities to within a factor of two in most cases (agreement is actually better than this if experimental error estimates are taken into account). Calculated suspension viscosities are also in agreement with estimates of Bingham fluid plastic viscosity presented by Moore and Schaber for a Makaopuki basalt (better than factor of two agreement over temperature range 1200$^\circ C$-1080$^\circ C$). These comparisons indicate that at high shear rates the rheological behavior of the Makaopuki basalt can be represented by either a Bingham fluid model or a Newtonian suspension model. This discovery has several implications:

1. Newtonian suspension models can be used to estimate the apparent viscosity of lavas whose rheological properties have not been studied experimentally (e.g., basaltic andesites and trachybasalts). If variations in crystal content and crystal chemistry can be specified as a function of temperature, calculated suspension viscosities would be representative of bulk flow viscosities at the high shear rates that exist over a wide range of flow emplacement conditions.

2. The agreement between measured viscosities and suspension viscosities calculated by the Einstein-Roscoe equations indicates that bulk lava viscosity is not critically dependent on crystal shapes at high shear rates (>1 sec$^{-1}$). Note that the Einstein-Roscoe equations were developed for spheres whereas volcanic clinopyroxene and plagioclase crystals have tabular shapes.

3. Newtonian suspension models can be modified to account for the effect of gas bubbles upon lava rheology as theoretical or empirical data become available. The relationships between bubble content and flow resistance are not well established for silicate liquids at the present time. The presence of bubbles appears to increase viscosity at low shear rates and low bubble concentrations (gas pressure and surface tension oppose deformation); whereas lava viscosity tends to decrease under conditions of high shear rate and/or substantial bubble volume concentrations (bubbles tend to deform more easily than an equivalent volume of fluid). Field observations and sample analyses reported by Swanson and Fabbi indicate that significant quantities of volatiles ($H_2O$, $O_2$, $CO_2$) are degassed from Hawaiian basalt flowing at average velocities less than 1 m/sec. These observations tentatively suggest that the influence of entrained bubbles upon lava viscosity may be largely restricted to areas near a flow's source vent. Basaltic lavas travelling over distances of 50 km or more may be accurately characterized as two phase (crystal-liquid) suspensions over the major portion of their flow length.

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Table 1.

<table>
<thead>
<tr>
<th>TEMPERATURE (°Centigrade)</th>
<th>MEASURED VISCOSITY (poise)</th>
<th>SHAW CALCULATION METHOD</th>
<th>BOTTINGA AND WEILL CALCULATION METHOD</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>¹</td>
<td>SUSPENSION VELOCITY</td>
<td>SUSPENSION VELOCITY</td>
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<td></td>
<td></td>
<td>Spheres</td>
<td>Spheres</td>
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<tr>
<td></td>
<td></td>
<td>(poise)</td>
<td>(poise)</td>
</tr>
<tr>
<td>1200°</td>
<td>n_a = 320</td>
<td>235</td>
<td>233</td>
</tr>
<tr>
<td>1190°</td>
<td>n_a = 480</td>
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<td>n_a = 780</td>
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</tr>
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<td>n_a = 1900</td>
<td>1240</td>
<td>1060</td>
</tr>
<tr>
<td>1132.5°</td>
<td>n_p = 7000</td>
<td>2340</td>
<td>1780</td>
</tr>
</tbody>
</table>

n_a = apparent viscosity determined by laboratory measurement
n_p = Bingham fluid plastic viscosity determined by field measurement