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Effective non-linear viscosity of a crystal-bearing melt

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A better understanding of the complex rheological behavior of suspensions is essential in modeling magma ascent and emplacement and assessing volcanic hazard. The viscosity of a silicate melt is primarily dependent on temperature, water content and chemical composition, and a pure hydrous melt can be approximated as a Newtonian fluid. Laboratory experiments have shown that the introduction of a crystalline phase into a Newtonian liquid ubiquitously results in a stress-dependent, i.e. non-Newtonian, effective rheology. This non-Newtonian effect has been attributed to several mechanisms such as the development of shape preferred orientation, microstructural changes due to fracturing, shear heating, shear localization, and the development of the solid framework (percolation models).
To gain insights into the correct mechanisms operating, I study the effective non-linear rheological behavior of a suspension consisting of non-Newtonian crystals embedded in a linear fluid. The problem is approached using two- and three-dimensional finite element numerical simulations and the effective medium approach. Results obtained for a circular and spherical inclusion phase in a linear fluid exhibit a non-linear effective rheological behavior that manifests only for a narrow range of the apparent viscosity ratio close to unity. The apparent power-law exponent decreases significantly with increasing apparent viscosity ratio and is virtually equal to one for the apparent viscosity ratio of one hundred. Thus, a suspension of non-Newtonian inclusions effectively behaves as a linear fluid whenever the crystalline phase is significantly more viscous than the melt. Despite the high viscosity ratio, the resulting viscosity is only four times higher than the melt viscosity for circular inclusions at a fraction of fifty percent. On the contrary, laboratory experiments show non-linear mechanical behavior and a high relative effective viscosity for a comparable scenario. A common explanation is to assume that the crystalline phase is already at the percolation threshold and forms a skeleton that determines the effective mechanical behavior. We show that the inclusion phase can grossly affect the effective rheological behavior without necessarily forming an interconnected solid framework, provided that the aspect ratio of individual inclusions is high and the inclusion packing approaches the percolation threshold, which is at a significantly lower fraction in three-dimensions as compared to the two-dimensional models.