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Some observations on the rheological behaviour of dense suspensions

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With 5 figures

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1. Introduction

This paper deals with the rheology of “dense suspensions”, by which we mean solid-liquid mixtures in which the particle phase is present in very high concentrations, well in excess of what is normally termed “concentrated suspensions”. The volume concentration could be in the region of 60% or more with the pores completely filled with the liquid phase (saturated systems), it could be such that the solids are in close-packed configuration or near to it, or it could even be unsaturated so that the pores are only partially filled and air is present. Some isolated papers have been published on saturated systems. We shall refer to them below in appropriate paragraphs.

In the past few years, Warren Spring Laboratory has, mainly in cooperation with industrial sponsors, carried out extensive studies into the properties of both saturated and unsaturated dense suspensions. Examples are sand, mine tailings, coal, colliery waste, mineral concentrates, cement grouts, graphite-in-oil pastes. They also include fermentation broths, fruit puree, barley meal-water animal feed and sewage sludges. The results of these studies are ultimately applied to technological problems such as storage hopper discharge, pipeline design, reactor scale-up, stability of tailings dumps, stockpiles and ships’ cargoes, and manufacture of lead batteries, foundry moulds and welding electrodes. Some of these technological investigations are still in progress, but the observations on dense suspension behaviour are sufficiently advanced for a generalised description to be given. In this paper we will advance a qualitative description of this behaviour, and show that it constitutes a distinct category of rheological property which we will describe by the term “granulo-viscous”. We will show that both our results and those already noted in the literature are examples of granulo-viscous behaviour.

We first carried out numerous experiments on a wide range of materials. At first the results seemed quite chaotic, but on persisting distinctive patterns began to emerge, not just on repeat tests on the same sample, but also with different materials. From the standpoint of viscous behaviour, even non-Newtonian behaviour, such patterns would appear to be anomalous. However, it eventually became clear to us that these anomalies could be explained in terms of granular solids behaviour of the particles, which is well known in soil and powder mechanics. Once this explanation is accepted the anomalies are seen to be predictable. In this paper therefore we would use this approach to introduce granulo-viscous phenomena. We will show how one might have predicted them from a combination or interaction of prior knowledge of viscous behaviour and that of granular behaviour, and we will cite experimental results from our work and published papers as illustration.

2. Experiments

The instruments used in the WSL work included several rotational viscometers. In the Contraves Rheomat 15 FC Viscometer, samples were subjected to various shear cycles, using smooth-walled and roughened bobs and cups. In some experiments, the moisture concentration was measured as a function of height in the sample. The Ferranti-Shirley Cone-Plate Viscometer was used in the usual way and also
3. Viscous and granular bases of granulo-viscous behaviour

The discussion of granulo-viscous behaviour is best begun by recapitulating on viscous behaviour. Under steady shearing, viscous behaviour is described by the shear stress-shear rate relationship, or flow curve. This is characterised by the feature that the shear stress increases as the shear rate increases, and the flow curve has a positive slope. Unless extremely high pressures are involved, the flow curve is independent of pressure or normal stress. Viscous fluids are usually taken to be incompressible.

In contrast the behaviour of dry or nearly dry particulate solids (granular behaviour) is characterised, firstly, by the shear stress being dependent on normal stress and bulk density and not on shear rate, and, secondly, by compressibility, i.e. the propensity of the lattice of particles either to dilate or to compact/consolidate depending on the stresses current at the time. These conclusions are well known results from soil and powder mechanics (6). They also mean that, associated with any bulk density, there is a set of critical normal and shear stresses, which defines its dilation/consolidation behaviour. For stress within bounds, the solids are stable and do not undergo irreversible deformation. But on exceeding the bounds, the solids will deform irreversibly. On consolidation, the solids tend to densify en masse, but dilation tends to occur locally, resulting in the development of “slip planes”, of several particle-diameters in thickness, within the bulk. Over quite wide limits the shear stress in the slip plane is independent of the shear rate or velocity difference across the thickness, but increases as the normal stress in the slip plane increases. Under steady shearing conditions, the local bulk density in (the thickness of) the slip plane, varies with the normal stress also.

One can easily see that if a suspension contains a concentration of particles high enough for granular behaviour to be significant, this is going to modify the viscous behaviour which is obtained by virtue of the presence of the liquid phase. Hence the term “granulo-viscous behaviour” in describing dense suspensions. Some examples will illustrate how granular behaviour might affect viscous behaviour and what might be expected of granulo-viscous behaviour.

4. Features of granulo-viscous behaviour

4.1. Stick-slip phenomenon

The first example of granulo-viscous behaviour could be simply described as stick-slip, which is illustrated by fluctuating torque in a rotational viscometer at steady rotation. The relatively slow rise followed by rapid fall, and repeated at regular periodicity, can be readily explained in terms of jamming and release of the particles. We have found this behaviour to a greater or lesser extent in the materials we have studied. Kao et al. (7) observed fluctuating rotational speeds with glass beads in a Stormer viscometer (their fig. 12).

4.2. Changes in flow curve and packing density variation

That granulo-viscous material shows viscous behaviour (torque increasing as speed increases) is shown in figure 1 for a red lead oxide slurry in which are plotted the peak torques obtained.