Rheological trends of civil engineering suspensions

Philippe Coussot

Laboratoire Navier, Université Paris-Est, Champs sur Marne, France

ABSTRACT

Most civil engineering or natural materials are concentrated suspensions in a liquid (see [1]). Here we review the main rheological properties of model systems made of either or both coarse and colloidal particles in a liquid. We also review the characteristics of displacement of coarse particles through a paste. A more complet review of rheophysical mechanisms may be found in [2].

INTRODUCTION

Most civil engineering materials, such as mortars, concrete, hemp concrete, drilling fluids, paints, asphalt concrete, etc, as long as natural materials such as lavas, mudflows or debris flows, are concentrated suspensions in a simple liquid. A good knowledge of the mechanical behavior of these materials before solidification is critical to control the energy needed for handling them, make them take an appropriate shape, avoid particle segregation, etc. Here I will review the fundamental rheological properties of these systems as a function of their basic common components.

We start with simple suspensions of coarse particles in simple (Newtonian) liquids. Then we discuss the impact of the presence of colloidal particles on the rheological behavior of the systems. Real systems are often made of a suspension of coarse particles in a colloidal system, we review the main properties of these systems. Finally we describe some original effects occurring with coarse particles suspended in a yield stress fluid: sedimentation under shear, and displacement inducing the formation of a very thin layer of material in the liquid regime.

SUSPENSION OF COARSE PARTICLES IN A SIMPLE LIQUID

Adding coarse (non-colloidal) solid particles in a Newtonian liquid leads to the simplest possible suspension, the viscosity (μ) of which is larger than that of the liquid alone (μ_0) because the liquid fraction is smaller and thus the liquid is more sheared under similar boundary conditions for the whole sample.

This viscosity increases first slowly with the concentration (ϕ), according to Einstein's law ($\mu = \mu_0(1+2.5\phi)$) valid for a volume fraction less than a few percents. For larger volume fraction, say up to about 40%, the suspension viscosity goes on increasing slowly.

The things dramatically change at the approach of the maximum packing fraction (ϕ_m). There the viscosity rapidly tends to infinity. This trend is rather well described by the Krieger-Dougherty equation:

$$\mu/\mu_0 = (1-\phi/\phi_m)^{-2.5\phi_m} \quad (1)$$

From this equation we see that at the approach of the maximum packing fraction the suspension viscosity is extremely sensitive to the exact value of ϕ_m. The problem is that we ignore the effective value for ϕ_m. We just know that it strongly depends on the geometrical configuration of the particles in space. If we assume a disordered loose packing it will be around 60% or slightly less. However the particle arrangement may vary during flow, leading to a change of this maximum packing fraction. In practice one cannot predict a priori the value to take into account in equation (1), it must be determined from tests.

An additional major problem occurs with suspensions of coarse particles: migration, i.e. variation in time of the particle distribution in space. From MRI density and velocity measurements it has been shown that this effect becomes significant after about one revolution of the inner cylinder in a Couette geometry[3]: the particles migrate towards regions of lower shear rates. For high mean concentrations this implies that the viscosity is strongly heterogeneous in the gap of such a geometry. We can suspect that such an effect occurs in almost any rheometrical test in which the shear rate distribution is heterogeneous. However it is difficult to quantify and thus take into account in practice.

COLLOIDAL SUSPENSIONS

Real materials are generally made of particles in a wide range of sizes. We can separate these particles in two classes. Those which do not interact (coarse) at distance within the liquid and those, i.e. colloidal, which interact at distance. Here we consider the rheological behavior of colloidal suspensions alone.

Different types of colloidal interactions may be identified which are either essentially attractive (van der Waals, depletion) or repulsive (electrostatic, steric). The sum of these interactions lead to a total interaction potential which, depending on the distance between particles imposed by the volume fraction in the liquid, can be considered as either mainly attractive or repulsive. For a volume fraction larger than a critical value we get a material which exhibits a yield stress. However, depending on the main type of interaction we get fluids with very different rheological behavior.

Various experiments including in particular Magnetic Resonance Velocimetry[4] show that when repulsive (colloidal) interactions dominate we generally have a simple yielding behavior, i.e. the dynamic yield stress associated with flow stoppage is identical to the static yield stress associated with flow start up. On the contrary when attractive interactions dominate we have a thixotropic yielding behavior, with a structure which catastrophically collapses during flow start up and progressively restore when the material is left at rest, leading to an increase of the static yield stress in time.

Basically it has been observe[5] that systems with mainly repulsive interactions, such as foams, emulsions, or physical gels, are simple yield stress fluids which exhibit a viscoelastic solid behavior below a critical stress (the yield stress). For such systems the spectacular trend is that the transition between the solid and the liquid regime is smooth, namely the material is homogeneously sheared in the solid regime, but it flows homogeneously too as soon as it yields, i.e. when it breaks and flows in the solid regime.

With these systems thixotropy is in general negligible so that the apparent flow curve is rather simple (see Figure 1): in a sweep test (shear rate ramp increase then decrease) we can observe first an increase of the stress in the solid regime, then the materials breaks and flows in the liquid regime; when the shear rate is decreased the stress follows the same curve ending with a plateau, which is the yield stress of the material.

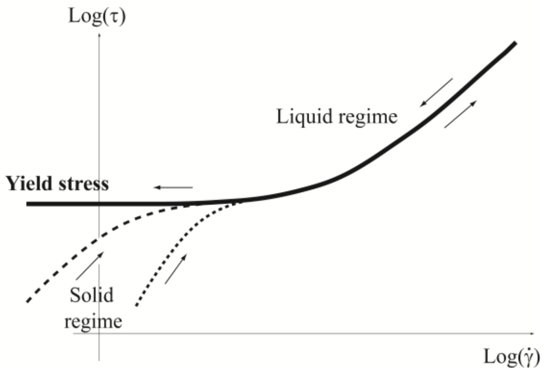

Figure 1: Apparent flow curve a colloidal system with mainly repulsive interactions during a sweep test.

On the other side we have systems which contains particles with essentially attractive interactions. At rest such systems progressively form a network of links of increasing strength. This is thixotropy: the yield stress increases with time at rest. Now when one applies a sufficiently large stress one breaks the network and the material flows. At this stage it is possible to maintain the flow by imposing a stress significantly lower than that needed to reach the liquid regime. This is again thixotropy: the apparent viscosity of the material decreases during flow. The resulting apparent flow curve is complex (see Figure 2).

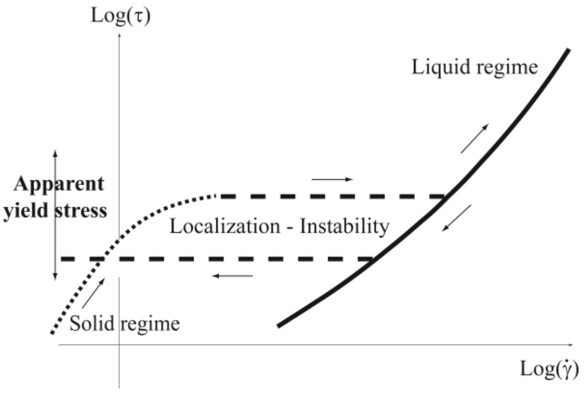

Figure 2: Apparent flow curve a colloidal system with mainly attractive interactions during a sweep test.

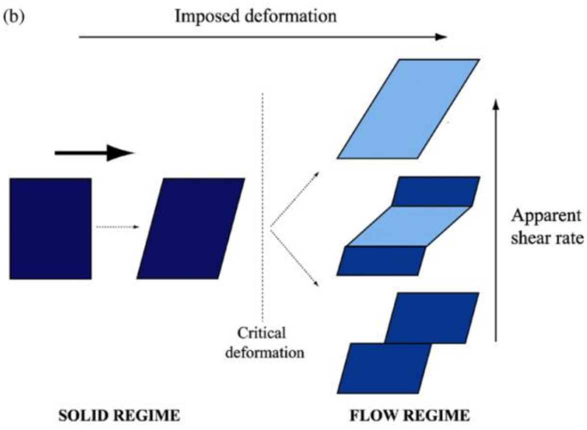

Figure 3: Aspect of the shear distribution depending on the flow regime and intensity in a colloidal suspension with mainly attractive interactions.

In fact this behavior for attractive suspensions is associated with shear-banding. Now the transition between the solid and the liquid regime is more abrupt. First the liquid regime forms only in a region of limited thickness. Then it remains in such a layer or grows depending on flow characteristics. From a general point of view the thickness increases with the macroscopic shear rate (see Figure 3). So the upper plateau observed in Figure 2 corresponds to a shear-band.

SUSPENSIONS OF COARSE PARTICLES IN A YIELD STRESS FLUID

As we mentioned real systems are suspensions of particles with wide grain size distribution, including colloidal and non-colloidal particles. A simple situation is that for which one can consider that the mixture of colloidal and water forms a paste in which the coarse particles are suspended. In that case we can discuss the impact of the presence of these particles on the rheological behaviour of the whole material.

Let us assume that the interstitial paste is a simple yield stress fluid (the case of a thixotropic fluid can easily be extrapolated from this simplest case), with a rheological behaviour well described by a Herschel-Bulkley model ($\tau = \tau_c + k\dot{\gamma}^n$). In that case it has recently been shown[6] that the addition of particles leads to a paste exhibiting the same type of behaviour, namely well represented by a Herschel-Bulkley with the same power n, and with a yield stress and a parameter k slowly increasing with ϕ In other terms the rheology of a paste is poorly affected by the presence of coarse particles in suspension.

The effect of inclusions on the yield stress can even be almost neutral if the inclusions are bubbles: now the yield stress remains approximately constant over a wide range of concentrations, which implies that here we significantly decrease the material density while keeping its mechanical strength.

Obviously the situation is more complex when the volume fraction tends to the maximum packing fraction. The rheological parameters tend to infinity in theory. But in reality we expect that direct contact between particles could play a significant role and the behaviour of the system would be that of a granular paste. In addition it can be mentioned that the nature of the frictional contacts in such a case is quite unclear since we have coarse particles separated by thin films of a mixture of (much smaller) solid particles in a liquid. This is nevertheless a common situation.

DISPLACEMENT OF COARSE PARTICLES THROUGH A PASTE

Another question of practical interest is how coarse particles are supported or displace through such materials. It is well known that due to the yield stress a sufficiently small particle can be suspended and remain at rest in a yield stress fluid at rest.

However the knowledge is still poor concerning the way a particle displaces through a paste. A drag force with a form analogous to that of the Herschel-Bulkley model is generally used and has been confirmed by systematic measurements[7]. However the way the material flows around the particle is unclear. In particular one can expect that only a thin region of paste flows in the liquid regime while the rest of material is only deformed in its elastic regime. These elastic deformations have not been taken into account in existing simulations for the displacement of spheres through a yield stress fluid[8] although they really can “support” a significant part of the displacement of the sphere. Recently it was shown that this is clearly the case for a plate moving through a yield stress fluid[9].

One original aspect of the suspension of coarse particles in a yield stress fluid is that although the particles can be at rest in the fluid at rest, as soon as the fluid is sheared (at a shear rate $\dot{\gamma}$) in a horizontal plane the particles will tend to fall[10]. This is so because when the fluid is sheared in another direction it flows in its liquid regime and thus loses its solid properties, so that the particles no longer see a solid a material but rather a simple liquid without yield stress and thus fall if their density is larger than that of the fluid.

Finally the particles see around them a fluid of viscosity approximately equal to $\tau_c/\dot{\gamma}$, and fall at a velocity deduced from the drag force associated with the motion through a Newtonian fluid with this viscosity.

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