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Apparent friction and cohesion of a partially wet granular material in steady-state shear

H. Louati [*], D. Oulahna, A. de Ryck

Centre RAPSODEE, Mines Albi, CNRS, Université de Toulouse, Campus Jarlard, F-81013 Albi Cedex 09, France

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ABSTRACT

The shear resistance of glass beads with wetting liquid incorporated (polyethylene glycol of molecular weight of 400 g/mol) is experimentally and theoretically investigated in a large range of both liquid content (from 0.007 % to 20 % in volume) and normal loading, in a steady-state flowing situation. It is observed that the behaviour is not purely frictional (shear stress proportional to the normal stress) except for the lowest liquid content (up to 0.1 %) for which it is observed that the friction coefficient of wet granular material is slightly higher than the dry material. At high normal loading, an apparent cohesion is observed and the behaviour may be interpreted as frictional, with the same friction coefficient plus an additional normal stress due to the capillary forces between the beads. At low normal loading, the apparent cohesion is less and may be qualitatively explained by the diminution of broken capillary contacts during shearing when the porosity of the granular bed increases. This result is corroborated by a theoretical approach estimating the capillary forces in play.

1. Introduction

Many powder processing methods such as granulation or coating require humid environments. The presence of liquid affects the properties of the granular material. One common problem is to evaluate the flow resistance of wet powder during transport, mixing and emptying processes. This can be caused by very small amounts of liquid (for example condensed airborne humidity).

Hornbaker *et al.* (1997) [1] reported that the changes in behaviour of granular material induced by moisture are primarily caused by adhesive forces associated with interstitial liquid bridges between grains. For dry granular material, adhesive forces are the results of inter-particle forces, mainly Van-der-Waals and electrostatic forces. In the latter case the attractive forces are long range forces and cannot be considered as independent adhesive forces. Van-der-Waals' forces are created between permanent dipoles, induced dipoles or permanent and induced dipoles. These forces depend on the size of the particles and the distance between them. Electrostatic forces are created by differential electrical potentials of particles surfaces caused by friction between particles and the wall of the equipment being used [2].

For wet granular materials, capillary forces prevail due to the liquid bridges formed between particles. Depending on the amount of liquid in wet granular material, different states of liquid saturation have been distinguished. Newitt and Conway (1958) [3] introduced the notions of pendular, funicular and capillary states. In the pendular state, with small quantities of liquid, particles are held together through separated liquid bridges formed at the contact points. Particles are attracted to each other due to the surface tension of the liquid and the capillary pressure. An increase in the saturation of the liquid leads to a transitional situation, the so-called funicular state, in which the liquid partially fills the spaces between particles. The capillary state is reached when all available spaces are filled with liquid. Another state of adsorption layers preceding the pendular one was introduced by Pietsch [4], where liquid is bonded to the particle surface. These adsorption layers can increase inter-particle forces such as Van-der-Waals forces.

We focus here on the adsorption layers and on the pendular states. For monodisperse particles, the pendular state prevailed when the volumic liquid saturation S was lower than 25%. This corresponds to a liquid volume of 17% of the volume of the solid, for the monodisperse porosity $\varepsilon = 0.41$ (S is defined as the volume of pores filled by liquid relative to the total pore volume [5]).

Many authors have studied the mechanical influence of the presence of liquid in granular material in the pendular state. Rumpf (1962) [6] studied the relationship between tensile strength and liquid bridge forces, and proposed a model to estimate this tensile strength. This model will be used in this study to evaluate the capillary forces acting on the wet monodispersed glass beads. Hornbaker *et al.* (1997) [1], Fraysse *et al.* (1999) [7] and Bocquet *et al.* (2002) [8] focused on the static properties of powder. They demonstrated the influence of humidity on the angle of repose. They observed that a small quantity of liquid increases the value of this angle. The latter is related to the maximal ratio between shear and normal stresses. In these studies the flow of granular material occurs at low levels of normal stress since they are located close to the free surface. This is not the case in the quasi-static and

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[*] Corresponding author. Tel.: +33 5 63 49 31 09.
E-mail addresses: haithem.louati@mines-albi.fr (H. Louati), driss.oulahna@mines-albi.fr (D. Oulahna), alain.deryck@mines-albi.fr (A. de Ryck).

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dynamic states studies performed in shear cells or mixers, where the applied or established normal stresses may influence the flow properties [9,10]. However, these studies focus on the yield criterion rather than steady state situation in the case of quasi-static experiments in shear cells or are not able to quantify or vary the normal stresses in steady-state flows in mixers. None of these articles explores the relationship between steady-state shear and normal stresses for different normal loadings when liquid is added.

In this paper, we focus on the effects of both liquid content and loading on the shearing behaviour of wet granular materials, using glass beads of 70–110 μm in diameter, in steady-state low velocity shear situations. Experiments are performed for a wide range of normal stress (from 0.3 to 11 kPa) and liquid content (from 0.007 to 20% in volume).

2. Materials and methods

2.1. The wet granular bed and its porosity

The granular media used consists of glass beads provided by SOVITEC, with diameter sieve ranging from 70 μm to 110 μm. They have a spherical shape (sphericity index $\psi = 0.96$) and a smooth surface. The true density of glass beads is $\rho_s = 2.47$ g/cm^3 and the porosity in dry conditions is $\varepsilon = 0.41$.

Glass beads were wetted using polyethylene glycol of 400 g molar weight (PEG$_{400}$) from Alfa Aesar. This liquid was chosen since it wets the glass beads well and has a low volatility. The other characteristics are the density $\rho_L = 1.128$ g/cm^3 at 20 °C; viscosity $\eta = 99.01$ mPa s at 25 °C and the surface tension $\gamma = 56.74$ mN/m at 23.5 °C. PEG$_{400}$ is also slightly hygroscopic, non-toxic and nonhazardous.

Small amounts of PEG$_{400}$ were added to glass beads. Thirteen samples of wet glass beads were prepared by doubling the quantity of liquid each time starting from 27.5 μl/kg. Then, the wet glass beads were mixed to ensure the distribution of the liquid in the granular material (using a Kenwood mixer). The concentration of liquid is expressed by a volume ratio V_R which represents the volume of liquid relative to the volume of particles.

In order to study the influence of liquid saturation on the density configuration of wet glass beads, the mean bulk density ρ (weight of particles divided by the total apparent volume) and the wet porosity (the volume of the void relative to the total volume of the wet granular material)

$$\varepsilon_{wet} = 1 - \frac{\rho}{\rho_s} \frac{1 + V_R}{1 + V_R\left(\frac{\rho_L}{\rho_S}\right)}, \tag{1}$$

were estimated before starting the shear test, and consolidated with a normal stress of 12 kPa in another apparatus.

Fig. 1 shows the variation of the porosity of the bed as a function of the volume ratio V_R of liquid added on a semi-logarithmic scale. For a small addition of liquid, the porosity of the glass beads decreases slightly. This decrease is possibly due to the lubrication at some contact points between particles, allowing denser configurations.

When V_R increases beyond 0.05%, a clear increase in porosity is observed. This transition is due to the capillary forces. Indeed, when the concentration of liquid reaches a certain value, the capillary forces exceed the weight of the particles. As a consequence, the liquid bridges created between particles are able to sustain a loose assembly of particles, with larger gaps in the granular material leading to a lower density configuration. Then, the porosity tends towards saturation when V_R reaches between 1% and 7%, where the increase in liquid content may contribute to an increase in the volume of liquid bridges without greatly affecting the porosity. The decrease of the wet porosity beyond 7% of V_R is explained by the filling of the inter-particle spaces by the liquid.

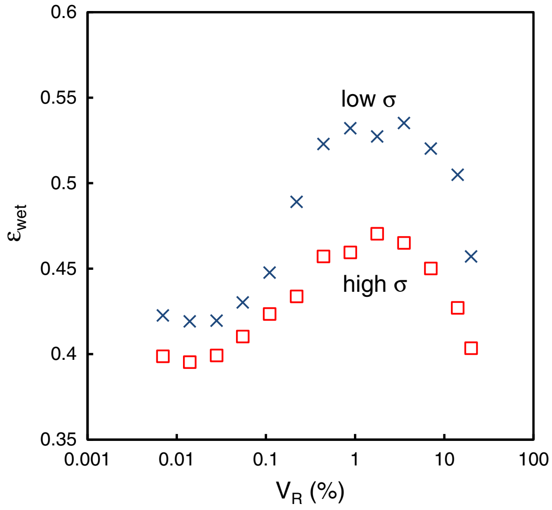

Fig. 1. Mean porosity versus the liquid volume ratio for the different samples at the filling of the shear cell (low σ) or pre-consolidated at 12 kPa (high σ).

The relationship between porosity, capillary forces and liquid content was studied by Feng and Yu (1998) and Yu *et al.* (2003) [11,12]. They found that the dry porosity of glass beads of different sizes (250, 1000, 2000 and 4000 μm) increases with the liquid content to reach a maximum value at a critical point. This relationship may be explained by the creation of liquid bridges when adding liquid to the granular material which induces a capillary force. This limits the particle motion to form a packing and therefore rises the porosity. Above the critical point, the saturation of the capillary forces also leads to a saturation of porosity. They also assumed that an increase in the amount of liquid added (beyond the maximum quantities) results in capillary forces vanishing and, thus, to a decrease in porosity.

The porosity of wet glass beads has also been studied for the same maximal normal stress (about 12 kPa) used in the shear experiments, in order to examine the loading effect on the porosity. Fig. 1 compares them with the porosities at low normal stress. It shows the same variation of the ε–V_R curves (slight decrease, leap, saturation and decrease), but with a lower magnitude. This result shows that this application of normal stress did not prevent the increase of the porosity caused by the capillary forces.

2.2. The shear test in steady-state conditions

A Schulze shear cell was used to study the flow properties of the wet glass beads (see Fig. 2). This equipment consists of an annular trough with an inner diameter of 10 cm and an outer diameter of 20 cm. Normal force N is applied through an annular lid, so as to exert a normal stress. A counterweight system exerts an against force F_A that is used to balance the weight of the lid and other parts connected to it in order to be able to obtain low normal stresses [13].

To run a shear test, the shear cell is filled with the sample and rotates at a constant rotational velocity ω of 2.3 mrad/s. The bottom of the trough and the lower side of the lid are rough due to the presence of the teeth which prevent wall slippage. The shear plane occurs below the teeth of the lid, therefore the weight of the particles between the teeth is taken into consideration when calculating the normal stress σ acting on the sheared surface. We used:

$$\sigma = \frac{Mg}{A} + \rho g h_t, \tag{2}$$

where M is the normal loading weight, g is the gravitational constant, A is the area of the lid and $h_t = 4$ mm is the height of the teeth. The value