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Effect of particle morphological parameters on sand grains packing properties and rheology of model mortars

H. Hafid [a,b], G. Ovarlez [b,c], F. Toussaint [d], P.H. Jezequel [d], N. Roussel [a,*]

[a] Université Paris Est, IFSTTAR, Cité Descartes, 14-20 Boulevard Newton, Champs sur Marne, Marne la Vallée Cedex 2, F-77447 Paris, France
[b] Université Paris Est, Laboratoire Navier (CNRS–IFSTTAR–ENPC), Champs sur Marne, France
[c] CNRS, LOF, UMR 5258, F-33600 Pessac, France
[d] Lafarge Centre de Recherche, Saint Quentin Fallavier, France

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ABSTRACT

In this paper, we study the rheological behavior of mixtures of various sand particles suspended in model laboratory yield stress fluids. Using image analysis, we assess the morphology of the studied sand particles. We then measure the packing properties of these particles and show that, as a first approximation, the overall shape of the particles (*i.e.* the aspect ratio) is the dominant morphological parameter conditioning packing. We finally use magnetic resonance imaging (MRI) to assess the rheological behavior of suspensions of these sands in a water-in-oil emulsion and show that both the yield stress and consistency diverge for the same critical volume fraction, which seems to be fully correlated to both the random dense packing fraction and loose packing fraction of the grains. We finally suggest that there exists a correlation between a variation in yield stress and a variation in viscosity due to a change in the particle morphology.

1. Introduction

In many places around Europe, availability of natural rounded aggregates for the production of concrete has become a crucial question and has led to increased market shares for crushed stone aggregates. In parallel, environmental concern about concrete wastes obtained by concrete crushing after demolition suggests that incorporation of recycled concrete aggregates (RCA) in new concrete is upon the construction industry. These two trends suggest that crushed particles with non-spherical shapes shall form the majority of rigid inclusions in fresh concrete or mortar.

This evolution has major consequences on the rheological properties of these materials. It can be expected from literature that consistency (*i.e.* both yield stress and viscosity) shall increase as the particle shape gets further from the spherical shape [1]. However, in order to set some target requirement for particle shapes, fix some limit values on the morphology of aggregates allowing for the production of concrete or even improve current crushing technologies, it is necessary to get a better quantitative understanding of the influence of particle morphology on the rheological properties of fresh mortars or concretes.

In this paper, we therefore study the rheological behavior of mixtures of various real sand particles suspended in model laboratory yield stress fluids. Using image analysis, we assess quantitatively the morphology of the studied sand particles. We moreover measure their packing properties. We finally use magnetic resonance imaging (MRI) to assess the rheological behavior of suspensions of these sands in a water-in-oil emulsion. We then study the correlations between morphology, granular packing and flow behavior. We finally suggest that there exists a correlation between a variation in yield stress and a variation in viscosity due to a difference in the particle morphology. This correlation allows for the prediction of variations of viscosity from the simple measurement of a variation in yield stress.

2. Materials and procedures

2.1. Model yield stress fluid

We study here the rheological behavior of mixtures of real sand particles suspended in model laboratory yield stress fluids. The behavior of such materials was investigated in detail in [2] and it was shown that suspensions of aggregates in cement pastes behave like suspensions of particles in any other yield stress fluid [3] from a purely rheological point of view. That is why we choose here to suspend our particles in water-in-oil emulsions, which have been shown to be simple yield stress fluids [4]. This choice allows us to avoid all the experimental and analytical complexities linked to non reversible and reversible evolutions of cement paste rheology while allowing for a proper measurement of the variations of the rheological properties of model mortars as a function of the sand particle volume fraction [3]. It moreover greatly simplifies all MRI measurements carried in this work as, compared to cement, these systems do not contain *Fe* paramagnetic oxides, which

* Corresponding author. Tel.: +33 180668605.
E-mail address: nicolas.roussel@ifsttar.fr (N. Roussel).

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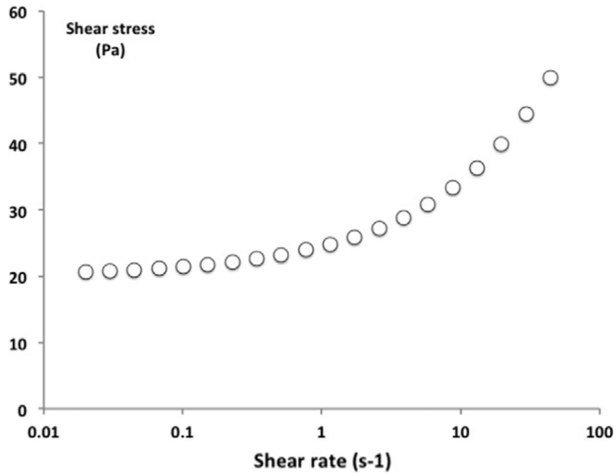

Fig. 1. Flow curve of the water-in-oil emulsion studied in this paper.

enhance the relaxation kinetic, thus leading to very poor signal to noise ratio. The rheological behavior of the emulsion can be described using a Herschel Buckley model with an exponent 1/2 relating the shear stress τ with the shear rate $\dot{\gamma}$ following $\tau = \tau_0 + K\dot{\gamma}^{\frac{1}{2}}$, where the yield stress τ_0 and the consistency K were respectively around 20 Pa and 4.5 Pa.s$^{1/2}$ as shown in Fig. 1.

2.2. Sands and beads

Four real sands were studied (Cf. Fig. 2). The first sand is a naturally rounded river-sand (S_1 0/4 mm) whereas the three other sands S_2 (0/4 mm), S_3 (0/1 mm) and S_4 (0/4 mm) are produced from crushed rocks. In order to get rid of the effect of the initial differing particle size distribution, we sieved the tested sands and isolated three grain fractions shown in Fig. 3 (160–200 μm, 315–400 μm and 800–1000 μm). We also chose as a reference material some dense polystyrene beads of diameter 315 μm (size dispersity < 5%) and density 1.05.

2.3. Morphology measurements

Each sand sample was first embedded in an epoxy resin. The resulting samples were sawn and polished before being imaged using optical microscopy. The resulting images were then treated and analyzed using the freeware ImageJ©. The chosen resolution was selected in order to have all studied particles in a 1000 × 1000 pixel square. For each sand and sand fraction tested, three morphological parameters were assessed on 120 randomly selected particles.

The morphological parameters are defined using the notations in Fig. 4, where D_{max} is the largest dimension of the projected particle whereas D_{min} is the smallest one. The aspect ratio is computed as D_{max}/D_{min}. Circularity (also called high sensitivity or HS circularity) is defined as $4\pi S/P^2$ and convexity is computed as the ratio between the Hull perimeter defined in Fig. 4 and P. The Hull perimeter is further defined as the smallest perimeter of a polygon capturing the projected particle. Examples of geometrical 2D shapes and their associated morphological parameters are given as illustrations in Table 1.

It is interesting to note that aspect ratio is supposed to capture the overall shape of the particle whereas circularity captures the deviation from the perfect circle. Finally, convexity is supposed to capture the surface rugosity or roughness of the particle. Whereas convexity and aspect ratio are supposed to be uncorrelated, circularity varies with both overall shape and surface roughness.

2.4. Packing measurements

We measure here two specific packing fractions for our sands in order to further characterize their properties: the random loose packing fraction (RLP fraction), which is theoretically defined as the loosest packing that can be obtained by pouring grains, and the random dense packing fraction, which is an empiricallly defined value that depends on the specific amount of energy brought to the system to be packed [1]. It can be kept in mind that the RLP fraction for spheres is around 0.55 whereas the so-called random dense packing fraction is considered to be around 0.64 [5] although, as stated above, higher values can be reached by bringing additonal compacting energy to the system under scope. From a practical point of view and in terms of concrete mix design, it was shown [6] that, for an aggregate volume fraction below the RLP fraction, the rheological behavior of the fresh concrete is dictated by the behavior of the paste, whereas, for increasing aggregate volume fractions above the RLP fraction, the rheological behavior progressively finds its origin in the nature and number of direct frictional contacts between aggregates.

We measure the RLP fraction of our sands through the pouring and slow settling of the studied grains in a viscous Newtonian liquid in a glass tube of diameter 42 mm. The idea behind such a protocol is to measure the thickness of the resulting packed bed of grains while dampening the inertia of the settling grains in order to allow for the grains to reach the RLP fraction without any kinetic energy. The RLP results obtained with this procedure should not be affected by the value of the viscosity, which we checked by varying the composition of the suspending fluid. The liquid chosen here is a mixture of glycerol and water with a Newtonian viscosity between 80 mPa s and 5 Pa s depending on the proportions between the water and pure glycerol. Our preliminary tests showed that, for the particle size and density tested here, a viscosity around 1 Pa s was an acceptable compromise value. Below this value, the diameter of the particles and therefore their inertia had an obvious influence on the measured RLP fraction although the morphological parameters, as discussed further, do not depend on the sand fraction. Above this value, some entrained air bubbles were trapped within the packed bed of grains affecting the measured RLP fraction. We will however show further that the RLP fractions measured for the 800–1000 μm sand grains are systematically higher than the ones measured for smaller particle fractions suggesting that this viscosity value is still too low to fully dissipate the kinetic energy of the settling coarsest grains. Finally, it can be noted that each RLP fraction measured in this paper results from the average of 20 measurements for each sand and sand fraction. We moreover checked that, using the above protocol, we measure a value of 0.557 ± 0.005 for the RLP fraction

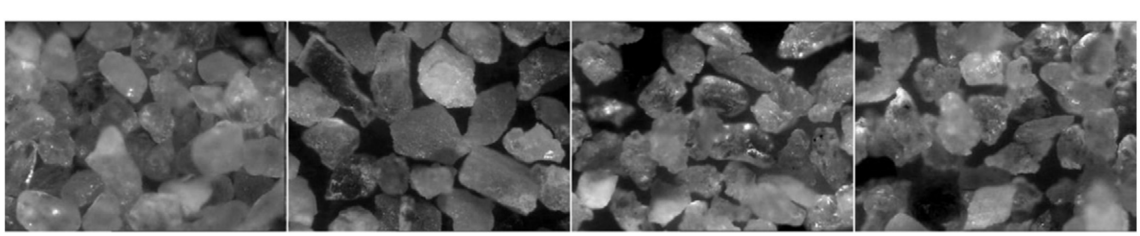

Fig. 2. The four sands studied in this paper.