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Yielding and flow of foamed metakaolin pastes

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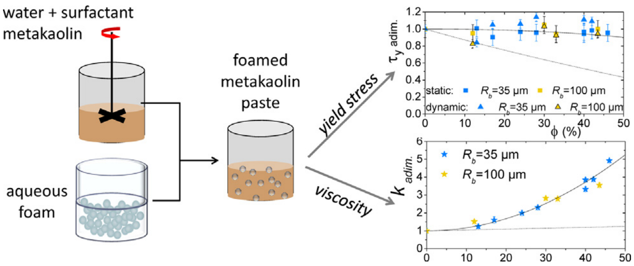
HIGHLIGHTS

- The rheology of foamed (0–50% gas) non-reactive metakaolin pastes is measured.
- The yield stress of the foamed samples is the same as that of the paste.
- The viscosity, however, increases with the gas volume fraction.
- Those results are in agreement with previous studies on model materials.

GRAPHICAL ABSTRACT



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ABSTRACT

We perform an experimental study of the rheology of a foamed non-reactive particulate paste. The paste is a concentrated suspension of metakaolin, a material commonly used in the production of ceramics and in the construction industry. Most manufacturing processes of porous ceramics or foamed building materials require the preparation and handling of a foamed slurry. The slurry is a concentrated particulate paste, which has a non-Newtonian rheology. In particular, a minimum stress is necessary to make it flow: it is a yield stress fluid. We systematically investigate the influence of bubble addition on the workability of our metakaolin slurry by dispersing bubbles of known radius at a chosen volume fraction in the surfactant-laden metakaolin paste. We perform rheometry measurements to characterize the minimum stress required for the foamed materials to flow (yield stress), and the dissipation occurring during flow. We show that the yield stress of the foamed samples is equal to that of the metakaolin paste, and that dissipation during flow increases quadratically with the bubble volume fraction. We show that this behaviour can be well understood from the recent results of Ducloué et al. [7]. This agreement suggests that the results we present here on foamed metakaolin samples may apply to a broader class of foamed particulate pastes.

1. Introduction

Foams from concentrated suspensions of particles are produced in many industrial processes: aeration of dense suspensions of ground ore allows for effective mineral extraction through the production of a mineral-rich foam in the froth flotation process [1]; the purposeful addition of bubbles in fresh concrete or plaster slurries enables the design of versatile light-weight materials with good insulating properties and controlled strength [2]. The bubble size, gas volume fraction and material homogeneity play a key role in achieving the desired properties of a foamed construction material, and are mostly determined during the processing stage of the fresh material. The industrial need to control the structure of those foamed concentrated suspensions has motivated studies of the equilibrium structure of liquid foams with added rigid particles in their continuous phase. They highlighted the importance of the

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interaction between the rigid particles and the soft porous network formed by the bubbles in determining the overall particle distribution in the foam [3]. The stability at rest of such particulate foams has also been tackled from the point of view of drainage (or equivalently bubble rise) under gravity, which is detrimental in foamed construction materials because it leads to heterogeneous samples. It has in particular been shown that drainage can be completely suppressed in foamed concentrated suspensions if the minimum stress required to make the suspension flow is large enough [4]. The presence of particles in the continuous phase of a liquid foam can also prevent foam drainage via contact between the particles, which build up into a rigid stabilising skeleton [5].

Little is known about the flow properties of foamed particulate pastes. Yet, the incorporation and the preservation of the gas bubbles in the slurry when elaborating a foamed construction material is essential. From a rheological point of view, the particulate paste is a complex fluid, which only flows if the stress applied to it is larger than a critical value: the yield stress of the paste. Above that yield stress, the paste flows with a viscosity that depends on its flow rate. The interplay of the complex rheology of the paste with the bubbles' physical properties (radius, surface tension) will determine the stability of the bubbles entrapped in the paste, but also the rheology of the foamed material. Understanding this behaviour is necessary to elaborate optimized processes and materials.

A few studies focused on the mixing and casting properties of foamed concrete from a practical point of view, addressing the workability of a given formulation (see e.g. Ramamurthy et al. [6] for a review). While of undeniable practical interest, those studies raise the question of the specificity of the chosen formulation, and the generality of the established results. At the other extreme, all material details have been deliberately ignored in a recent model approach characterizing the flow behaviour of foamed model yield stress fluid [7]. Monodisperse bubbles were mixed in model yield stress fluids made of monodisperse isotropic constituents (micron-size oil droplets), which have a time-independent rheological behaviour. The use of such model materials allowed for scale separation between the droplets and the bubbles, and the description of the fluid as a continuous medium embedding the bubbles, an approach that was validated by the good agreement found between the experimental results and micro-mechanical estimates. While the results of such model studies can potentially be adapted for any foamed yield stress fluid of known rheology, the simplifying assumptions underlying them may break down when considering industrial materials in which the paste will typically contain particles of various sizes and shapes, and a range of bubble sizes. The aim of the present study is to relax some of the constraints imposed in the study of model foamed yield stress fluids and take a step towards industrial foamed particulate pastes, by investigating the rheological behaviour of a concentrated metakaolin paste containing monodisperse air bubbles. Metakaolin is commonly used in the production of foamed clay pastes, which can be sintered to produce porous ceramics used as thermal insulators but also filters or catalysts [8], or alkali activated to produce foamed geopolymer concrete [9,6]. It is also commonly used in the construction industry as a partial replacement for Portland cement [10]. We work with a concentrated non-reactive metakaolin paste containing surfactant to stabilize mechanically added air bubbles, and focus on how the rheological behaviour of the paste is modified by the addition of bubbles of known radius at a given volume fraction in the range 0–50%. In doing so, we aim at asserting the validity of the approach previously developed for model systems, particularly the description of the paste as a continuous medium, for our foamed metakaolin pastes.

The first section of this paper describes our experimental system and the rheometry procedure used to characterize it. The following section presents the results we obtained for two rheological properties relevant for bubble stability and material workability: the minimal stress required to induce flow and the dissipation during flow of the foamed metakaolin pastes. In the third and last section, we evaluate the practical applicability of the results obtained on model foamed yield stress fluid by discussing our results in the light of the experiments and micro-mechanical estimates developed for those model systems.

2. Experimental procedure

We prepared model samples of foamed metakaolin pastes by dispersing bubbles of well defined radius at a chosen volume fraction in a concentrated metakaolin paste. To achieve the required level of control on our systems, we prepared a very concentrated bubble-free metakaolin paste, which we then mixed with a separately produced monodisperse aqueous foam. This procedure, which is presented below after the details of the materials used, allowed us to control the bubble size and the gas volume fraction of the foamed metakaolin samples throughout the process of mixing and characterization. The volume fraction of entrapped air, ϕ, was varied in the range 0–50%, which is the void volume fraction commonly found for instance in the production of foamed geopolymer concrete by mechanical agitation or mixing with a foam [11]. Sample preparation and characterization was done at 25 °C.

2.1. Metakaolin paste

The metakaolin paste that was mixed with the foam ("stock paste") was a suspension of a fine metakaolin (Argical M1200-S, AGS minéraux – Imerys group) powder dispersed at 46.4 wt% in an aqueous solution containing 10 wt% of a non-ionic surfactant (Tween 20®, Fisher Chemicals) in deionized water. The presence of this surfactant at the same concentration in the stock paste and in the aqueous foam ensured that the bubbles' surface was not deprived of surfactants once the foam was mixed with the paste, keeping the bubbles stable to coalescence in the resulting foamed sample. The constant surfactant concentration throughout the process also prevented the potential migration of surfactants adsorbed at the surface of the metakaolin particles, which would alter the rheology of the paste. A micrograph of a dilute suspension of the metakaolin powder in water is shown in Fig. 1. The grains are anisotropic (lamellar) and polydisperse, but small enough that no sedimentation nor creaming of the metakaolin suspended in water was observed at the concentrations we used for the pastes.

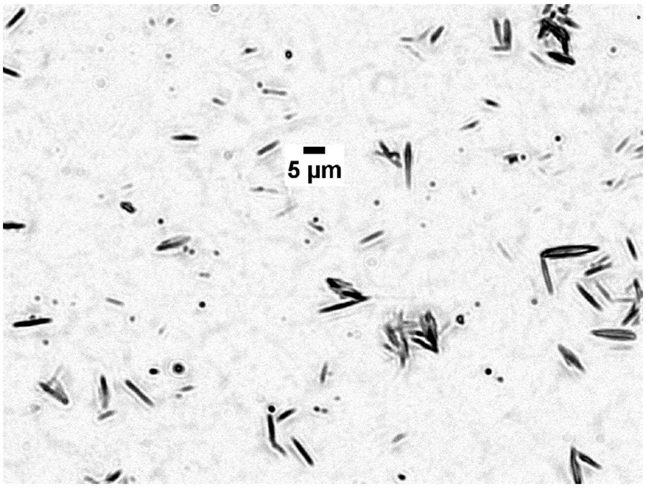

Fig. 1. Micrograph of a dilute suspension of M1200S in water. A drop of the suspension has been deposited on a glass slide.