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REOLOGYCAL BEHAVIOR OF FRESH CONCRETE

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ABSTRACT

This paper presents the results of an experimental program dealing with the rheology of fresh concrete. In the following section a brief review of recent developments in the characterization of the rheological properties of concrete is presented.

1. Introduction

Studies on the rheology of fresh concrete, from a materials science approach, are just beginning to appear. In fact, the concretes that are easier to describe by such an approach, i.e., concretes that are sufficiently fluid, have only been commercially used recently. Previously, it was considered adequate to use an engineering approach for characterizing rheological properties, consisting of subjecting a concrete sample to a more-or-less controlled loading and deriving an index (slump, flow time, compacting density, etc.) to classify the mixtures in terms of workability. This approach is limited as the classifications obtained by using different tests vary substantially.

First, it is necessary to understand how the processing parameters are linked to the rheological behavior of the concrete. For example, it seems that concrete pumpability is controlled by plastic viscosity .Also, it would be interesting to determine if the stability of fresh concrete placed at an angle (or on a slope) is controlled by the yield stress .One could establish requirements for concrete rheological characteristics that would make it possible to empty a concrete bucket within a given time based on finite element calculations of the same type as those used by Tanigawa et al.

Second, efforts must be made to *link the rheology of the concrete to its composition*. When this objective is reached, the engineer will be able, at the mixture design stage, to optimize the mixture proportions taking into account placing methods and structure types.

2. Experimental studies

The experimental plan consisted of systematically characterizing a reasonable range of the mixtures that could be made from the three basic materials: coarse aggregates, combined sand (a mixture of alluvial sand and fine silica sand in fixed proportions) and cement.The composition of the central mixture was designed to obtain the maximum dry packing density, but with a slight excess of cement in order to minimize the bleeding in all of the mixtures under-dosed with sand. It was the optimization of the packing density at a fixed cement content that led to adopting the proportion of fine sand to alluvial sand of 30% by mass, a value that was maintained throughout the series. The other dry mixtures were generated on the basis of the *central* mixture by changing one or both of the following two parameters: the volumetric proportion of cement and the volumetric ratio of sand to total aggregate. It should be noted that the latter ratio was 100% for three dry combinations that were mortars. For these mixtures, to avoid the bleeding that was produced with a cement dosage equivalent to those for the concretes, the proportion of cement by volume was increased. Finally, the combination corresponding to the lowest dosage of cement and the highest dosage of gravel was not made because of the segregation problems, i.e., sedimentation and bleeding, that would have unavoidably occurred.

3. A physical interpretation of the Bingham model

Fresh concrete is analyzed as a granular mixture in a water suspension. In this analysis, the content of entrapped air will be ignored. The minimum volume of water is that which corresponds to the porosity of the dry system. A concrete with zero workability is therefore, by definition, a packing in which the porosity is just saturated with water (Figure 1).

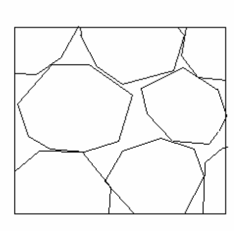

Figure 1. Suspension with minimum water content. No shearing movement is possible without localized rupture of the particle structure

3.1. The case of a mixture with single-size particles, i.e.,. with one granularclass

An increase in the water content, beyond the minimum to fill the pores makes possible a water-filled spacing between the particles in the mixture, and, consequently, sliding between particles can be initiated (see Figure 4). If the shearing of the system is confined, a deformation will appear if this applied shear stress is sufficient to counteract the friction forces between the solid particles. Thus, the yield stress will be governed not by the liquid phase, the only role of which in the material is to define the average distance between particles, but by the number and nature of the contacts between particles. Hence, for a mixture with a single size class of particles, there will be a relationship between yield stress and packing of the following form:

$$\tau_0 = f\left(\frac{\Phi}{\Phi^*}\right) \quad (1)$$

where Φ is the volumetric fraction of solid material (with respect to a total volume of one), * is the maximum value of for close packing (or packing density of the dry mixture) and f is an increasing function. The ratio /* is an expression of the relative concentration of solids, compared to the maximum packing. The function f increases with /*, because the yield stress increases with increasing values of /*
To investigate the microstructure of the flowing material, we will assume that the speed of each particle is equal to the macroscopic speed of the homogeneized fluid, i.e., fresh concrete.
Thus, in the classic form of the Bingham model:

$$\tau = \tau_0 + \mu \dot{\gamma} \quad (2)$$

the term $_0$ is the contribution of the skeleton and the term $\mu\dot{\gamma}$ is the contribution of the suspending liquid. Based on the preceding analysis, a general form for the plastic viscosity, μ , can be deduced:

$$\mu = \mu_0 g\left(\frac{\Phi}{\Phi^*}\right) \quad (3)$$

where μ_0 is the plastic viscosity of the suspending fluid and g is an increasing function of /*.
The function g is increasing because the plastic viscosity increases with the increase of /*.

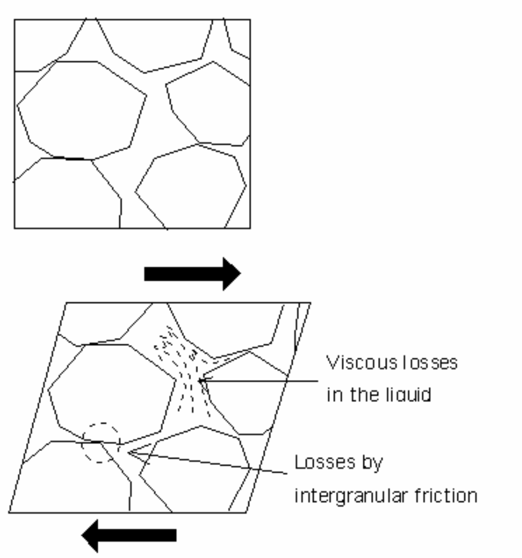

Figure 2. Suspension containing an excess of liquid compared with the minimum content

3.2. Mixtures with several classes of particles

In the case of particles of several sizes, the value of the function f should depend on all the contributions of the various size classes of particles. Therefore the yield stress is as follows:

$$\tau_0 = f\left(\frac{\Phi_1}{\Phi_1^*}, \frac{\Phi_2}{\Phi_2^*}, \dots, \frac{\Phi_n}{\Phi_n^*}\right) \quad (4)$$

where $_i$ is the volume fraction of granular size class i and $_i$* is its maximum value for close packing, all of the other $_j$ (j i) being constant. When the size and surface roughness of the particles change, the number of contacts between particles and the roughness of the particles change.It is therefore to be expected that the contribution of each size class to the yield stress includes size and roughness parameters relative to the particle fraction.As to the plastic viscosity, it is already known, in the case of suspensions of single-size spheres, that the plastic viscosity does not depend on the size of the particles. For binary systems of spheres, it appears that the parameter /* continues to control the apparent viscosity, the influence of the size distribution being contained in the packing density term * . Clearly, it would be desirable if this assertion were to remain valid for particle systems with a large range of sizes in which the particles are not spherical.

Thus, as a first step, an attempt was made to verify this assumption for the mortars and concretes that were tested. The basic assumption that permits us to explain the Bingham model physically, i.e., the plastic viscosity does not depend on the shear strain rate, is probably true only for a narrow range of shear strain rates. Flocculation of particles, or the appearance of local turbulence, probably modify the flow conditions of the liquid phase in the interstices of the granular phase

4. Calculation of the packing density of the mixtures tested.

It follows from the previous considerations that the calculation (or measurement) of the packing density of the dry mixtures, defined as the maximum concentration (by volume) that the "dried out" suspension could attain, constitutes an essential preliminary step to modeling the rheological properties. A recent model developed for mathematically describing compaction of powders is described in the following section.

4.1.The compressible packing model

The essential innovation in this second model consisted in distinguishing the *actual packing density* of a mixture, which was attained by using a given placement and compaction procedure, from the *virtual packing density*, the maximum packing density that could be attained only by putting the particles in place one by one.

4.2. Validation for several dry mixtures in the present program

Until now, attempts at direct validation of packing density models have only concerned granular materials of a smaller range of particle size than that of concrete. It was, therefore, hoped that the applicability of the new model to cement-and-aggregate mixtures could be verified. We first measured the dry packing density of the cement, using the same procedure as used for the aggregates. Given the compacting process and the compaction index associated with it, the value of the virtual packing density is less than that of the cement in the presence of water (0.61 instead of 0.64). This shows that the forces of interaction between particles and the friction forces they generate are more significant in air than in water, despite the formation of hydrates, which occurs from the first contact between the water and the anhydrous cement. In other words, if the fresh concrete were dried out, e.g. by using a drained vibro-compaction procedure to squeeze out the maximum amount of the interstitial water, one would expect a higher packing density than for the dry mixture. It was also anticipated that the model would be equally suitable for predicting the plastic viscosity of the concentrated suspensions

4.2.3 Calculating the packing density of the wet mixture

The effect of the presence of water on the virtual packing density of the cement shows that the parameters $_i$ needs to be calculated from measurements made on the binders in the presence of water. Recall that $_i$ is the virtual packing density of a single-size fraction.

4.3. Modeling the rheological parameters

4.3.1. Review of the existing models of plastic viscosity

Hu examined the literature concerning rheological models linking mixture composition and viscosity of suspensions. He found that most authors analyzed fresh concrete as a paste/aggregate composite and tried to deduce the plastic viscosity of the concrete from the plastic viscosity of the paste by multiplying it by a function that took into account the volume and nature of the granular phase. Some authors even extended this analysis to the cement paste, using the Farris approach. In order to calculate the plastic viscosity of the multi-modal suspensions they performed an iterative calculation, the whole being made up of the suspending fluid and the finest classes being dealt with homogeneously at the scale of a given class As elegant as they might be, these models suffer from not taking into consideration the inter-particle interactions. In fact, most concrete mixtures have a more or less continuous size distribution, so that the division into a number of discrete classes is arbitrary. Even the distinction between cement paste and aggregate, which is pertinent in the case of hardened concrete, is difficult to justify for fresh concrete. The large particles of cement are of comparable size comparable to the finest sand particles and their respective contributions to the rheology of the whole are not of a different One way of attempting to link the rheology of the neat cement paste with that of concrete was to introduce another factor, i.e., the gap existing between the aggregates. However, this approach requires measuring the rheological behavior of the paste through independent means, which was not done in the present study.

4.3.2. A simple model of plastic viscosity applicable to the six families of mixtures

The model described herein is based on the work of Chang and Powell, in which the relative concentrations of the suspensions were treated as controlling their plastic viscosity. When the experimental plastic viscosity μ' measured in this study is plotted as a function of the ratio between solid volume fraction and packing density, the plot in figure 3 is obtained. The solid volume fraction that is used that of the "de-aired" mixture, which means that the quantity of air has been disregarded (see Figure 3)

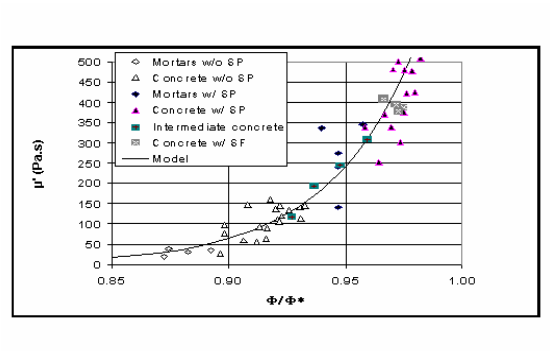

Figure 3. Plastic viscosity (μ') of the mortars and concretes as a function of their relative solid concentrations.

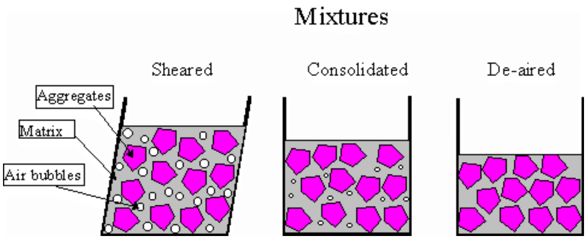

Figure 4. Different states of compaction of a wet mixture.

5. Conclusions

The proposed models need to be validated using a larger pool of constituent materials. If and when validated, they can be easily integrated into a computerized system for mixture proportioning. The plastic viscosity can be estimated from measurements of the size distribution and packing density of the materials. The model for estimating yield stress needs to be further validated to determine whether the values of the parameters apply to a whole family of materials or, must be modified when the components are changed.

Finally, a modification of the standard slump test intended to make it possible to evaluate for fresh concretes the two parameters in the Bingham equation is presented.

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