Cement and Concrete Research 39 (2009) 227–232

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Passing ability of fresh concrete: A probabilistic approach

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ARTICLE INFO

Article history:
Received 29 November 2007
Accepted 28 November 2008

Keywords:
Rheology
Casting
Aggregates
Blocking

ABSTRACT

In the present paper, it is first reminded that the probability of granular blocking of a suspension crossing a flow contraction increases with the number of particles crossing the obstacles, their volume fraction and the ratio between the diameter of the particles and the contraction gap. It is moreover reminded that this phenomenon can be described using a simple dimensionless geometric parameter as this phenomenon only slightly depends on the rheology of the suspending fluid. An adaptation of this dimensionless parameter to the specific case of concrete is proposed and compared to experimental results. Finally, an application to the prediction of the passing ability of Ordinary Rheology Concrete (ORC) and Self Compacting Concrete (SCC) is proposed and compared to the European technical recommendations.

1. Introduction

Although the yield stress of a given concrete could allow for the filling of formworks with complex shapes [1], it should not be forgotten that this concrete contains coarse particles that could get jammed in the most reinforced zones during the casting process (See Fig. 1). When concrete flows through an obstacle such as steel bars, several phenomena occur between which a distinction should be made.

First, the fact that fresh concrete displays a yield stress has a direct consequence on the shape of the mixture at stoppage in the vicinity of the obstacle [1–3]. If we consider, for instance, the crossing of an obstacle by a purely viscous fluid, the material would self level under the effect of gravity. Gravity would indeed induce a pressure gradient in the fluid if the upper surface of the material is not horizontal. This pressure gradient would generate a shear stress in the material that would create a shear rate and force the material to flow until the upper surface becomes horizontal and the pressure gradient at the origin of the flow has disappeared. The viscosity of the material would only play a role on the time needed to obtain a horizontal surface. In the case of a yield stress fluid such as concrete, gravity and pressure gradient also generate a shear stress. However, if this shear stress, which is a complex function of the obstacle geometry, becomes lower than the yield stress of the concrete, flow stops before the concrete self levels. This effect has been quantified in the case of the L-Box test with and without steel bars [4] and it was demonstrated that the thickness variation (h_1–h_2) between the case with bars and without bars is of the order of $3\tau_0/\rho g$ where τ_0 and ρ are respectively the yield stress and the density of the tested SCC. For traditional SCC, the yield stress of which is of the order of 100 Pa, this variation is therefore of the order of 1 cm. This value was validated by testing stable limestone filler suspensions, which did display a yield stress of the same order as SCC, but the constitutive particles of which were too small to create a granular blocking in the vicinity of the obstacle. This also explains why there exists, even for stable concretes which do not display any granular blocking, a systematic difference between slump flow and J-Ring test [5,6]. It is interesting to note here that, in [5], all the measurements and conclusions may be explained by the yield stress variation between the various tested concretes and that there is no granular blocking at all.

Moreover, it has to be kept in mind that the coarsest particles in concrete are submitted to gravity and are immersed in a fluid with a lower density, and of viscosity possibly too low to prevent them from settling or segregating within the flow duration. If concrete is at rest, it has been demonstrated that it is the yield stress of the cement paste that may prevent these coarse particles from settling [7]. When concrete is flowing, the drag force exerted by the suspending fluid (mortar or cement paste depending on the multi-scales frame chosen [8]) on each particle has to be high enough to "carry" the particles. If the studied concrete is not stable, then the presence of the obstacle could increase segregation effects. Indeed, it is a known feature of suspensions that particles migrate from high shear rates zones to lower shear rates zones [9]. The flow perturbations induced by steel bars locally increase these shear rate gradients and can thus increase shear induced segregation. It can be noted that, up to the knowledge of the present authors, this phenomenon has still not been modelled and properly measured from a practical point of view in the case of concrete. Although the above phenomena do not lead directly and systematically to granular blocking, they can strongly affect the coarsest particles configuration and volume fraction at the vicinity of the obstacle.

Finally, if the characteristic size of the obstacles (*e.g.* the gap between the bars) is not far from the size of the coarsest particles,

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0008-8846/$ – see front matter
doi:10.1016/j.cemconres.2008.11.009

Fig. 1. Granular blocking during a L-Box test on SCC (from [4]).

proper granular blocking may occur and granular arches may appear, stable enough to resist the flow. This is this last aspect that is studied in this paper. At the origin of the formation of these granular arches is granular clogging, jamming or blocking, namely the fact that the suspended particles at some time jam somewhere in the obstacles formed by the steel reinforcements. It can be noted that granular blocking may occur for particles with a diameter smaller than the gap between obstacles and that it is thus essentially a collective effect. It has however to be kept in mind that segregation induced by flow or gravity and described above may lead to an increase in the local volume fraction of coarse aggregates which could itself locally increase the risk of granular blocking. In order to separate the problems, in this paper we will focus on granular blocking in the case of stable and non segregating SCC. This means that the local volume fraction of coarse aggregates taken into account in the prediction of the blocking phenomenon will be equal to the coarse aggregates volume fraction calculated from mix proportions.

In the first part of this paper, the main results from literature dealing with the granular blocking of suspensions of particles in different model fluids are presented. It is reminded that granular blocking is basically a matter of probability, *i.e.* a sufficient number of particles must be present at the same time at the right place. This process may be described with the help of a simple dimensionless parameter which very well captures the experimental data. In a second part, this parameter is adapted to the specific case of concrete. Finally, this concept is applied to experimental results obtained on concretes and to experimental results from literature and the predictions of the model are compared with technical recommendations from the Eurocode II [10].

2. Granular blocking in literature and expected consequences on concrete casting

A suspension in a liquid with a solid fraction of particles ϕ of uniform diameter d is considered. N is the total number of particles in a volume of material Ω crossing the obstacle. The obstacle is made of parallel cylindrical bars, where δ is the free spacing. The residue R is the value of the solid fraction being jammed behind the bars. The residue varies between 0 (no particles are stopped by the obstacle) and 1 (all particles in the suspension are stopped by the obstacle).

The following striking points about granular blocking of a suspension can then be gathered from [11]:

- The granular blocking phenomenon has a probabilistic nature: for a given experiment, the measured residues vary significantly according to the specific, initial distribution of particles in the fluid, which cannot be controlled; this emphasizes that, at a local scale, the granular blocking is related to the probability of presence of particles. As a consequence, it should not be possible to completely suppress the risk of granular blocking in a given concrete casting process but only to reduce it below an acceptable level.
- There exists a transition around a critical ratio $(\delta/d)_c$ higher than 1 between a regime in which all the particles in the suspension are stopped by the obstacles and a regime in which all particles cross the obstacles. As a consequence, this means that, as it could have been expected intuitively, the coarsest particles in a given concrete may be stopped even when they are significantly smaller than the gap between the steel bars.
- From a probabilistic point of view, a granular blocking event requires that the particles be sufficiently close to each other, and thus is more probable for large particles volume fraction. This result in particular means that it should be possible to improve casting process by adjusting the coarsest inclusions volume fraction and not only the diameter of the coarsest particles. This might be handier on a given building site than having to use two types of gravel (a small one for the most reinforced zones and a normal one for the standard zones). This means additionally that, as SCC contains less coarse inclusions than ORC [12], its probability of granular blocking (or passing ability) should be lower (higher) than ORC.
- The number of granular blocking events increases with the number of attempts (drawings, in probabilistic terms), which implies that, even if the probability of granular blocking is low, the residue will increase with the crossing volume for a given particle volume fraction. From a practical point of view, this means that the volume of fresh concrete that has to cross the obstacle should play a strong role on the probability of blocking.
- The rheological behavior of the suspending fluid does not seem to play any role in the blocking phenomenon. As a consequence, this means that granular blocking during concrete casting should only depend on the number and size of the coarsest particles crossing the obstacle, their volume fraction and the free spacing between the bars but not on the rheological behavior of the constitutive cement paste. This, of course, stays true only if the cement paste is viscous enough to prevent any dynamic segregation of the concrete which could locally increase the volume fraction of the particles (see Introduction).

From the above considerations, it is possible to extract from [11] a “blocking parameter” P equal to:

$$P = 6\Omega/\pi d^3 \phi^{0.85\delta^2/d^2} \quad (1)$$

As long as P is small compared to 1, it is equal to the probability of the formation of a granular arch between two parallel cylindrical bars when a volume Ω of a suspension containing a volume fraction ϕ of particles of uniform diameter d flows through the gap of width δ between the bars. As an illustration, the residue R is plotted in Fig. 2 as a function of P in the case of visco-plastic gels containing glass beads flowing through parallel bars [11,13]. It can be seen that, in this particular case, as long as P stayed lower than 0.1 (dashed line in Fig. 2), no blocking was measured.

3. Specific aspects of concrete

The experimental results described above in the general case of model fluids show that the probability of granular blocking during casting of concrete should increase with the volume fraction of coarse particles, the ratio between the diameter of the coarse particles and the free spacing between the steel bars and the volume of concrete that has to flow through the obstacle. However, contrary to the case of the model fluids described above, in the case of concrete, the particle size distribution in the suspension is not uniform and particles are not spherical.