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Passing ability of fresh concrete: A probabilistic approach

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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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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.

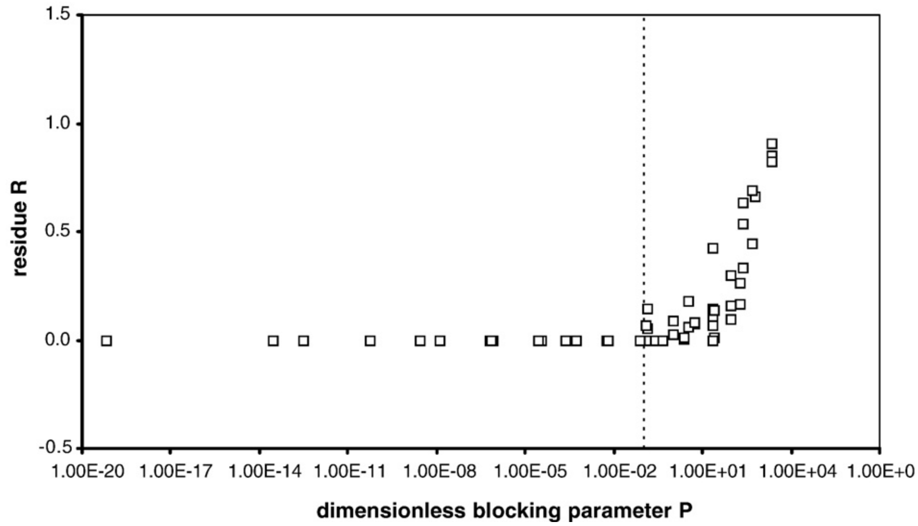

Fig. 2. Residue as a function of the blocking parameter P for visco-plastic gels containing glass beads flowing through parallel bars (from [11]).

3.1. Effect of grading

As a first step, let us consider a suspension containing two types of grains. The coarsest grains shall have a diameter d whereas the smallest shall have a diameter $d/2$. Both grains shall have the same particle volume fraction in the suspension ($\phi \ll 1$). The granular arches at the origin of the blocking phenomenon may then be formed either from a single type of particles or from a combination of the two types of particles. Using Eq. (1), the ratio between the probability of forming a granular arch with the coarsest particles and the probability of forming a granular arch with the smallest particles writes $8\phi^{-2.55\delta^2/d^2}$ and, for $\phi \ll 1$, is always far higher than 1 meaning that the contribution of the smallest particles to the blocking phenomenon may be neglected.

However, in the case of concrete, the grading of the particles is continuous and the question of the size of particles which play a determining role in the blocking phenomenon has to be dealt with.

Let us now consider the case of a concrete with typical grain size distribution as shown in Fig. 3. It can be seen that, in the case of real concrete, all particles do not have the same volume fraction. It can then be noted that, although it is easier for smaller particles to pass through obstacles, their high numbers could strongly increase their probability of blocking.

Using Eq. (1), we compute and plot in Fig. 4 the relative contribution to the blocking probability of a class of particles (probability of blocking of this class of particles divided by the probability of blocking of the coarsest particles class) as a function of the relative diameter of the particles (diameter of the particles divided by the diameter of the coarsest particles). It can be seen that only the particles larger than 80% of the coarsest particle diameter play a role in the blocking phenomenon. The relative contribution of the particles smaller than this limit is indeed lower than 1% and can therefore be neglected in the prediction of the blocking phenomenon. The volume fraction of the particles larger than 80% of the diameter of the coarsest particles in the mixture corresponds for standard granular distribution to the 10% coarsest particles. The average diameter of these particles (which are the only ones playing a role in the blocking phenomenon) is of the order of $0.9D_{max}$. It has however to be kept in mind that these values could of course vary in the case of non standard granular skeleton. It

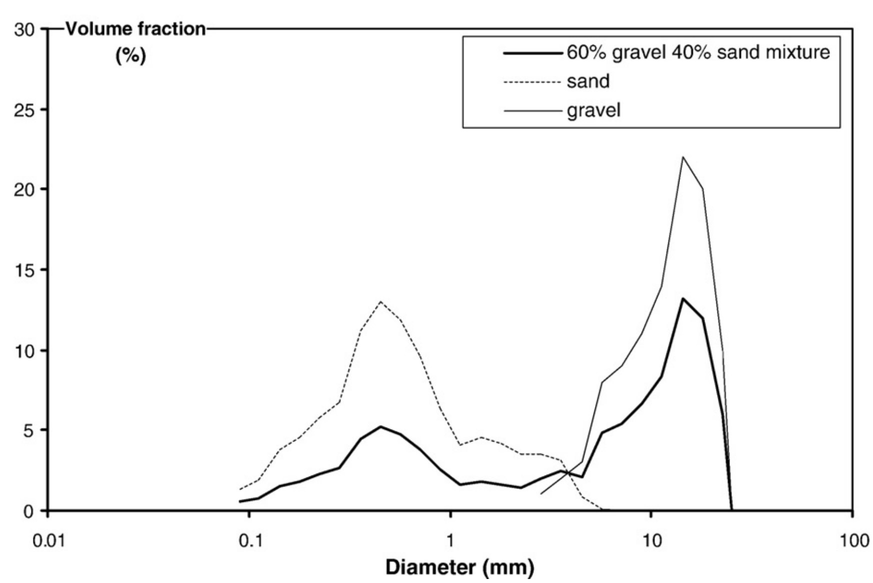

Fig. 3. Example of a concrete granular skeleton grading curve.

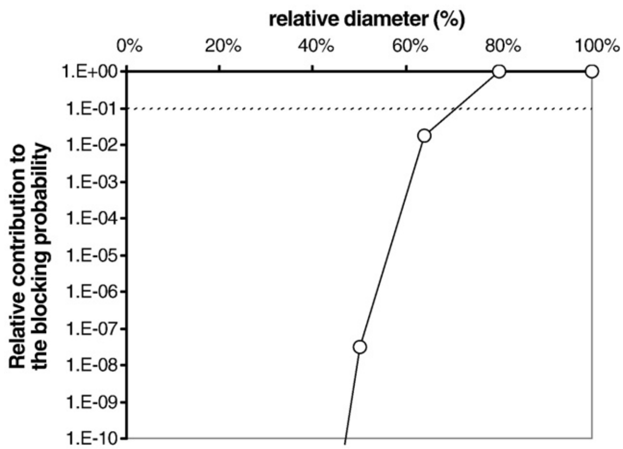

Fig. 4. Relative contribution of each class of particles (probability of blocking of this class of particles divided by the probability of blocking of the coarsest particles class) in a real concrete to the blocking probability in terms of the relative diameter of the particles (diameter of the particles divided by the diameter of the coarsest particles).

may then be useful to define a blocking parameter under the following form:

$$P = \left(2.6\Omega/D_{\max}^{3}\right)\left(0.1\phi_G\right)^{0.85\delta^2/0.81D_{\max}^2} \quad (2)$$

where $D_{\max}$ is the diameter of the coarsest particle in the concrete and ϕ_G is the volume fraction of the aggregate particles (*i.e.* sand and gravel).

3.2. Effect of particles shape

Whereas the inclusions tested in the model fluids in [11] were perfectly spherical, the coarsest particles in concrete may be rounded, and therefore closed to the spherical inclusions of the model fluids, or crushed, displaying far more irregular shapes (Fig. 5). As a consequence, crushed gravels should be more prone to form stable granular arches than rounded ones. In order to take into account this specific aspect of concrete, it is possible to introduce an effective diameter of the particles equal to $\beta D_{\max}$, with β larger than 1. The blocking parameter may then be rewritten under the following form:

$$P = \left(2.6\Omega/D_{\max}^{3}\right)\left(0.1\phi_G\right)^{0.85\delta^2/0.81(\beta D_{\max})^2} \quad (3)$$

where $D_{\max}$ is the diameter of the coarsest particle in the concrete, ϕ_G is the volume fraction of the aggregate particles (*i.e.* sand and gravel)

Table 1
Mix proportions of the studied SCC

Constituent	SCC N°1 (kg/m^3)	SCC N°2 (kg/m^3)	SCC N°3 (kg/m^3)
Cement CEM I 52.5	350	350	350
Limestone filler	130	130	130
Rounded sand 0/4	742	705	710
Rounded gravel 6.3/12.5	857		
Crushed gravel 6.3/20		892	
Crushed gravel 4/16			871
Cimfluid adagio 2019	4	4	4
Collaxim L4	0.5	0.5	0.5
Water	185	185	185

and β a coefficient equal to 1 for rounded gravels and higher than 1 for crushed gravels.

4. Experimental results

4.1. Materials and procedures

We carried out experiments on various fluid concretes prepared with rounded and crushed gravels with the coarsest gravel diameter equal to 12.5 mm, 16 mm or 20 mm. Parallel bars obstacles specifically built for these experiments with 3 mm metal bars with clear spacing varying between 19 and 41 mm were studied and a 9 l volume of concrete was poured in an inclined channel in the middle of which the parallel bars were fixed (see Fig. 3). After the end of the flow, the mass (m) of particles remaining above the steel bars was washed and weighed, which provided the *residue R*, equal to m/M, in which M was the mass of the 10% coarsest particles initially in concrete (see Fig. 2). The volume fraction of coarse aggregates (sand and gravel) in the mixture was varied around the reference mix proportions (±15% every 5%) keeping the ratio between sand and gravel constant. The reference mix designs of the tested SCC are given in Table 1.

4.2. Analysis

The experimental results obtained in this paper are plotted in Fig. 6 as a function of the blocking parameter P. It can be seen that this blocking parameter seems to capture the transition between blocking and passing for the concretes prepared with rounded gravels. Moreover, for these particular experiments, no blocking was measured for P lower than 0.1.

In the case of the concretes tested in this paper and prepared with crushed gravels, the value of β was fitted so that no blocking appears for P lower than 0.1 (β = 1.8). Experimental results obtained in [6,15] were also used to fit the values of the parameter β. In [6], granular

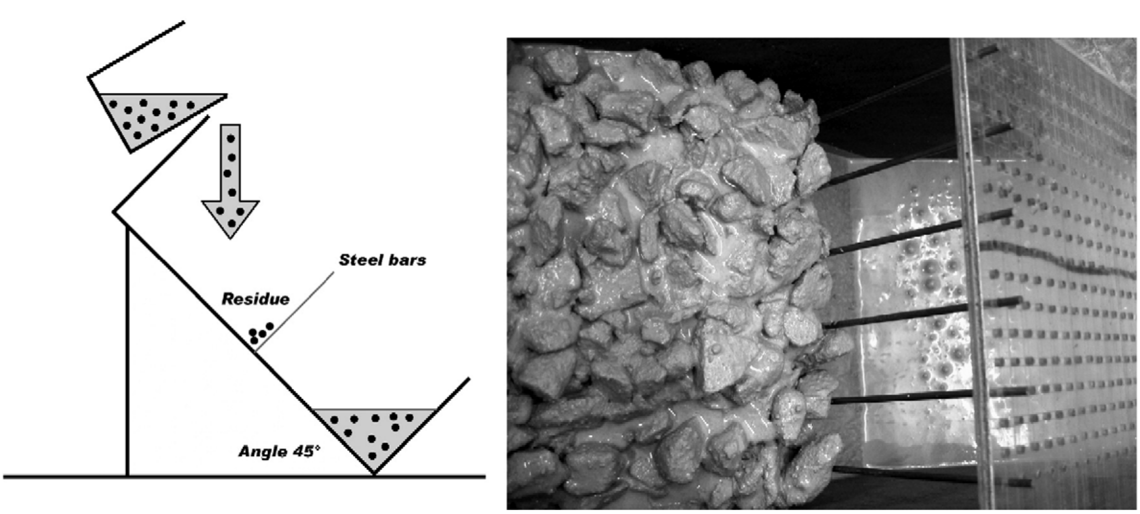

Fig. 5. Measurement method of the residue using an inclined channel. (Photo) test result for a SCC.

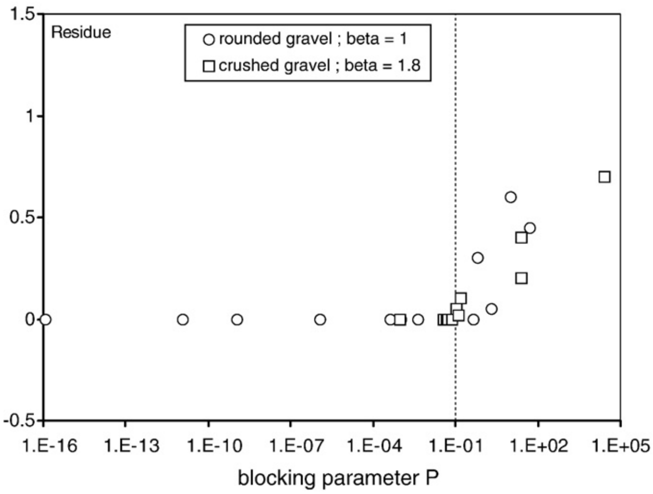

Fig. 6. Residue as a function of the blocking parameter *P* for the concretes tested in this paper.

blocking is deduced from the difference between slump flow and J-ring test whereas in [15], it is deduced from L-Box test. As described in the Introduction of this paper, it is however necessary to distinguish among the blocking results the ones which are due to segregation under gravity or to proper granular blocking. The unstable concretes (*i.e.* sieve segregation test result higher than 15% or visual spotting) tested in [6,15] are therefore not included here and only results obtained for stable concretes are considered. If the values of β are fitted so that no blocking appears for *P* lower than 0.1, β ranges from 1.4 to 2.2. This correction is equivalent to considering that the coarsest crushed particles in all the tested concretes have an effective diameter comprised between $1.4D_{max}$ and $2.2D_{max}$, which seems in agreement with the aspect ratio of this type of granular material [14].

4.3. Extrapolation of a design criterion

The above results show that the proposed blocking parameter *P* seems able to capture the occurrence of blocking during flow of concrete through an obstacle. A further approximation in order to get closer to a practical simple relation could consist in considering that the order of magnitude of ϕ_G is 0.8 for ORC and 0.6 for SCC [16]. Eq. (3) becomes then:

$$P = \left(2.6\Omega/D_{\max}^3\right)(0.08)^{\alpha\delta^2/0.81(\beta D_{\max})^2} \text{ for ORC} \quad (4a)$$

$$P = \left(2.6\Omega/D_{\max}^3\right)(0.06)^{\alpha\beta\delta^2/0.81(\beta D_{\max})^2} \text{ for SCC} \quad (4b)$$

From an industrial point of view, *P* should be limited to acceptable values according to an acceptable degree of risk. It is not the object of this paper to state on an acceptable upper limit of *P*. However, as a first approximation, it can be assumed that, if less than 10% of the particles are stopped by the steel bars ($P<0.1$), the casting process could be considered as efficient. It is then of interest to compare criteria (4a) and (4b) to the technical recommendations that can be found in Eurocode II [10]. These recommendations state that:

> "The clear distance (horizontal and vertical) between individual parallel bars or horizontal layers of parallel bars should be not less than the maximum of k_1.bar diameter, ($D_{max}+k_2$) mm or 20 mm where the maximum size of aggregate is."

> *Note: The value of k_1 and k_2 for use in a Country may be found in its National Annex. The recommended values are 1 and 5 mm respectively.*

First, it can be noted that these recommendations do not take into account the volume of concrete which has to cross the obstacle and the nature of the aggregates (rounded or crushed). In the following, we consider concretes prepared with rounded gravels with D_{max} equal to 16 mm which is to be cast between steel bars with 20 mm diameters with a clear distance between bars δ equal to 20 mm as recommended by the above text. We moreover assume that blocking phenomena will be acceptable as long as the blocking parameter *P* stays lower than 0.1. This is the case as long as the volume of ORC crossing the obstacle is lower than 300 l (equivalent to a 30 cm layer of concrete behind a square meter of parallel steel bars) or as long as the volume of SCC is lower than 1800 l (equivalent to a 1.8 m layer of concrete behind a square meter of parallel steel bars). These volumes are, still in theory, respectively reduced to 20 and 80 l (2 and 8 cm layers) in the case of crushed gravels with β= 1.1. This means that EC II recommendations seem to only guarantee an efficient casting of the material if the casting point is often displaced during the casting process so that the volume which has to cross the obstacle stays lower than the above values. In the case of less traditional casting processes, during which a large quantity of concrete has to cross a given obstacle, the present authors consider that the criteria (4a) and (4b) could be more suitable and may even prove very useful in order to choose either the clear spacing between steel bars or the diameter of the coarsest particles of the concrete to be cast.

Finally, it may be useful to discuss here the fact that the rheology of the cement paste should not affect the granular blocking phenomenon. It is indeed natural to imagine that a low viscosity cement paste and thus a very fluid SCC would be more prone to have its coarsest particles blocked in highly reinforced zones. However, as stated in the Introduction, the fact that the material is too fluid to carry its own particles during flow is not directly at the origin of the granular blocking. The consequence of this high fluidity is that the material is not stable and that the local coarse particles volume fraction may increase above the volume fraction deduced from mix proportions as shown in Fig. 7.

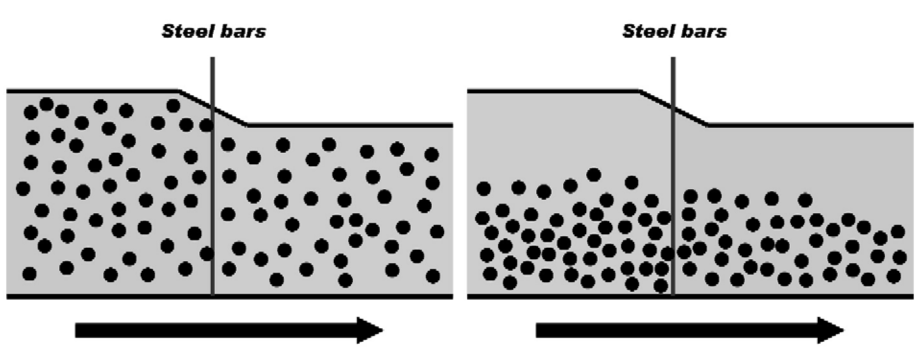

Fig. 7. Local increase of the aggregate volume fraction due to dynamic segregation. A low viscosity cement paste could increase the risk of blocking by allowing for a strong segregation within the material.

This increased volume fraction due to segregation may thus be sufficient to create granular blocking although the volume fraction deduced from mix proportions was not. The above criteria are thus to be applied to concretes which stay homogeneous during flow. In the case of gravity or shear induced segregation, it could however be very interested in the future to simulate the local coarse particles volume fraction and to use this calculated value in the criteria defined in this paper in order to describe the industrial situations in which segregation leads to local coarse particles volume fraction sufficiently high to create some granular blockings.

5. Conclusion

In the first part of this paper, the main results from literature dealing with the granular blocking of suspensions of particles in various model fluids were presented. It was 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 was adapted to the specific case of concrete. Finally, we have applied this concept to experimental results obtained on concretes and to experimental results from the literature and compare the predictions of the model with technical recommendations from Eurocode II.

It was found that, in specific casting processes, during which a volume of concrete higher than several tens of litres has to cross an obstacle, the criteria proposed in this paper could allow for the choosing of either the clear spacing between steel bars or the diameter of the coarsest particles in the concrete to be cast in order to prevent any granular blocking during casting.

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