Cement and Concrete Research 39 (2009) 30–35

Contents lists available at ScienceDirect

Cement and Concrete Research

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

Contribution of granular interactions to self compacting concrete stability: Development of a new device

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ARTICLE INFO

Article history:
Received 8 April 2008
Accepted 30 October 2008

Keywords:
Rheology
Cement paste
Aggregate
Concrete
Self Compacting Concrete (SCC)

ABSTRACT

Understanding the SCC behaviour is essential for resolving placement and consolidation problems in the field. As far as segregation is concerned, one of the main remaining obstacles is the design of a concrete mixture suitable for given casting conditions. Physical approaches which consist in studying the sedimentation of a single particle in a yield stress fluid failed to describe SCC static segregation. Segregation is a more complex phenomenon and the interactions between coarse aggregates have to be taken into account. They contribute to the stability of fresh SCC and this contribution should only depend on the solid fraction of the granular skeleton. A new experimental device has been developed in order to highlight and quantify the combined effects of coarse aggregates. This device allows studying lattices of particles. These latter are organised according to a cubic centred pattern and are immersed in a yield stress fluid. The experimental device and the test procedure are described in this paper. The validity of measurements has been demonstrated by performing a first series of tests and numerical simulations. Repeatability is quite satisfactory and "wall effects" can be limited.

1. Introduction

In comparison to conventional concrete, Self-Compacting Concrete (SCC) usually exhibits very low shear yield stress and a fairly wide range of viscosities. A sophisticated mix design leads to specific rheological behaviours and thus to innovative concretes. These latter enable casting and repairing complex structures without any vibration. However, problems met on building sites, like bleeding and segregation, have emphasized the need for a better understanding of fresh SCC behaviour and for an adequate control of the concrete before placing. As far as segregation is concerned, one of the main remaining obstacles is the design of a concrete mixture suitable for given casting conditions.

Segregation corresponds to the loss of homogeneity between both the granular and the suspending phases. Segregation is said to be "static" when it occurs after fresh concrete has been poured into formworks and "dynamic" when it occurs during placing. Several tests have been proposed to characterize the flow-ability of SCC, but very few tests enable to estimate the segregation risk of SCC. The French Association of Civil Engineering (AFGC) has advised the sieve stability test both in its provisional recommendations published in 2000 [1] and more recently in its new recommendations published in January 2008 [2]. Besides, the cylinder and the column tests, together with the sieve stability test, have been evaluated within the framework of a European project [3,4]. It is clear that such empirical tests are not representative of all actual placing conditions. However, it should be possible to associate acceptable ranges of experimental results with both given placing conditions and standard applications [2].

A study dealing with the initiation of static segregation is presented in this paper. It has been done at the LCPC in the framework of a PhD thesis [5]. Fresh concrete is assumed to be made of two phases: the granular skeleton and the suspending medium. Cement paste is usually taken as the suspending medium. However, if we consider the continuity of the granular skeleton, the definition of the boundary between both phases is not so obvious.

In the general case of one particle immersed in a yield stress fluid, the existence of a stability criterion based on the diameter of the particle, the yield stress of the fluid and the difference between their specific weights can be demonstrated [6]. This physical approach has been illustrated by the authors in a previous study carried out on cement pastes [7]. However, it is not sufficient to reflect the reality which is more complex. Coming back to the physical point of view, several elements can be emphasized. Whereas high values of the yield

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doi:10.1016/j.cemconres.2008.10.007

stress of the suspending medium prevent coarse aggregates from segregating, high viscosities and thixotropy can reduce the speed of sedimentation and then the extent of segregation. However, due to the high fluidity of the concrete itself, the rheological parameters of most of the cement pastes are very low. What is even more surprising is that most concretes are stable despite the low values of the rheological parameters of their cement pastes. Hence, the following conclusion can be drawn:

- SCC cement paste can not be considered as the actual suspending medium and interactions between particles have also to be accounted for in the description of segregation phenomena.

Hence, a new approach and a new experimental device have been developed and are presented in this paper. The idea consists in taking into account the granular skeleton parameters in the definition of the stability criterion. Cement pastes characterized by their shear yield stress, as could be any other fluid, are used as suspending phases. However, the suspending phase composition has still to be defined. As regards the new experimental device, it has been designed to quantify the interactions between aggregates. It allows measuring the force applied to a granular lattice or to an isolated particle, to move in a yield stress fluid. By comparing the force applied to one particle with that applied to the same particle included into a lattice, group effects can be highlighted and quantified.

This paper focuses on the description of the new experimental device and shows the relevance of measurements. A future study will bring to the fore combined effects by analysing results on several suspending media and lattices of particles. The former will differ in their yield stress and the latter in both their arrangement and solid fraction.

2. Background

In the case of a single particle immersed in a yield stress fluid, the existence of a stability criterion can be demonstrated [6,7]. This was illustrated on cement pastes in reference [7]. The main useful elements are reminded below.

A single sphere immersed in a yield stress fluid is submitted to forces: a motion force f_m and a resisting force f_{res}. The latter is a function of the rheological characteristics of the fluid. In the case of a static approach, these forces can be expressed as follows [7,8]:

$$\begin{cases} f_m = \dfrac{\Delta\rho g\pi D^3}{6} \\ f_{res} = K\pi D^2\tau_0 \end{cases} \quad (1)$$

Where D is the particle diameter, K a constant, τ_0 the yield stress of the fluid, $\Delta\rho$ the balance between the particle and the fluid densities, and g the gravitational acceleration.

The balance between the motion force and the resisting force leads to a stability criterion:

$$D<D_c = 6K\frac{\tau_0}{\Delta\rho g} \quad (2)$$

Where D_c is the critical diameter, i.e. the diameter beyond which the particle is liable to segregate. The stability constant K_0 (with K_0=6 K) is also often used in the expression of Eq. (2).

Experimental results obtained on a spherical particle immersed in cement pastes and data found in the literature have led to different values of the stability constant K_0 [7]. This is due to the chosen approach or to the type of fluid. K_0-values are ranging from 10 to 30 (i.e. K-values are ranging from 1.67 to 5). Even if most of the K_0-values seem to be very close to 15 or 20, they do not lead to a stability criterion precise enough. For a given shear yield stress: 6 Pa for example, the critical diameter D_c would be ranging from 15 to 20 mm (with $\Delta\rho\approx600$ kg m^{-3}).

As stated before, a sufficiently high yield stress could reduce the risk of sedimentation of coarse aggregates. However, SCC yield stress has also to be low enough to ensure a sufficient fluidity.

To improve the description of SCC stability, all the parameters have to be taken into account and particularly the combined effect of aggregates. Several authors have already mentioned this phenomenon without quantifying it [9–11].

In the case of one particle included in a lattice, the problem has a supplementary parameter a: the spacing between particles. A supplementary dimensionless variable is then involved D/a: the diameter to spacing ratio. It is equivalent to consider the solid fraction φ. Finally, the stability criterion will take the same form as Eq. (2) with a constant value: K becoming a function of this variable $K_{lattice}(\varphi)$. In the case of one particle included in a lattice whose solid fraction is φ, the resisting force takes the following form:

$$f_{res-lattice} = K_{lattice}(\varphi)\pi D^2\tau_0 = \frac{K_{0,lattice}(\varphi)}{6}\pi D^2\tau_0 \quad (3)$$

$K_{lattice}$ (or $K_{0,lattice}$) will be higher than K (or K_0) in case of positive group effects, i.e. if interactions between aggregates contribute to the stability of SCC, and lower in the opposite case.

A new experimental device has been developed to highlight and quantify the group effects, i.e. to precisely determine both $K_{lattice}$ and K and to compare them.

3. Experimental device

3.1. General description

The original feature of the device is to allow the study of a lattice of particles placed into a yield stress fluid. With this device, it is possible to measure the maximum force exerted on a granular lattice while immersed in a moving fluid. The lattice is composed of marbles of the same diameter organized according a cubic-centred pattern. The parameters that must be controlled during the test are essentially the dimensional stability of the lattice (i.e. spacing between particles) and the motion of the container. The technical solutions chosen to ensure relevant experimental conditions are detailed below. The main elements of the device are presented in Fig. 1.

A mobile rig slides on four guiding rods until upper stop blocks by means of a linear bearing which limits friction. A sensor enables to

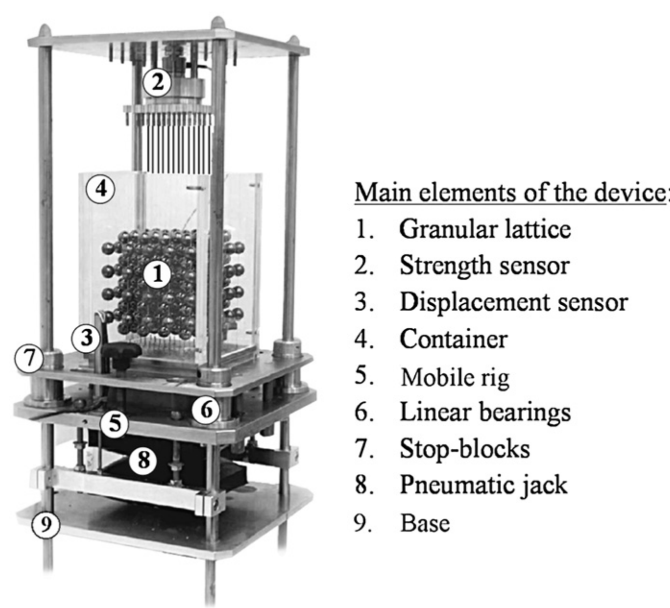

Fig. 1. New experimental device.

measure the displacement of the mobile rig during the test (i.e. the displacement of the container). The mobile rig is supported by a pneumatic jack placed on the base. An air leak has been fitted to allow both the generation of a regular deflation and a suitable test duration. The mobile rig is composed of a primary plate covered by a back plate whose position is displaceable (cf. Fig. 2(a) and Section 3.2. for further explanations). The central and prominent part of the back plate is the bottom of the container (cf. Fig. 2(b)). Two pieces made of plexiglass

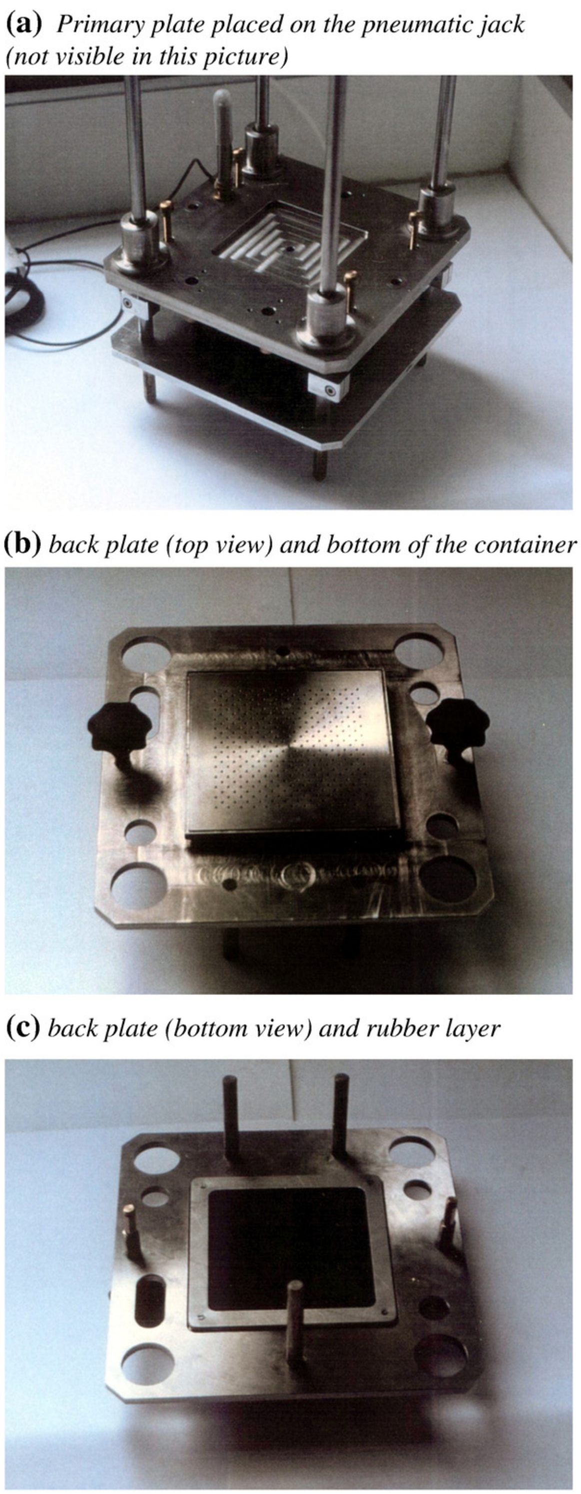

Fig. 2. Mobile rig: primary plate and back plate.

Fig. 3. Container: U-shaped side walls and front panel.

form the side walls of the container: a U-shaped one and a front panel (cf. Fig. 3). This enables placing the granular lattice before both the container and the fluid. The lattice is composed of spherical particles connected to a force sensor placed just under the upper support. The design of lattices and their specific placing are described in the following paragraph.

Tests can also be performed with the same device on a single particle. In this case, a suitable force sensor is used (cf. Fig. 4). The comparison of the results with the theoretical expression (Eq. (2)) would provide elements to validate the relevance of this new experimental device.

3.2. Granular lattice

The granular lattice is motionless. It is composed of marbles of the same diameter arranged according to a cubic-centred pattern. Marbles are made of hematite whose high specific gravity contributes to maintain the geometrical features of the lattice during the test. Marbles are threaded into strings and then bonded to the nylon wires (cf. Fig. 5(a)). Two types of vertical marbles strings can be distinguished:

- marble strings connected to the force sensor,
- marble strings fixed directly to the upper support.

The latter are placed around the central lattice to avoid any wall effects by acting as a “guard ring” (cf Fig. 5(b)). They were expected to enable the simulation of an infinite medium. This hypothesis will be more detailed in the Section 4.2.

Let us underline that the high specific gravity of hematite is in any way involved in measurements. More over, the section of nylon wires was selected to ensure no deformation of the string under expected forces. When placing the lattice, the lower end of all marble strings is temporarily fixed to a rubber layer underlying the perforated back plate by using hollow needles (cf. Fig. 2(c)). This ensures the marble strings verticality during the filling of the container (cf. Fig. 5(c)). Finally, needles are released by lowering the back plate onto the primary plate just before the beginning of the test.

The combination of various marble diameters: D and various reticular distances: a, enables to obtain a wide range of solid fractions. Some of them are obtained by means of different configurations

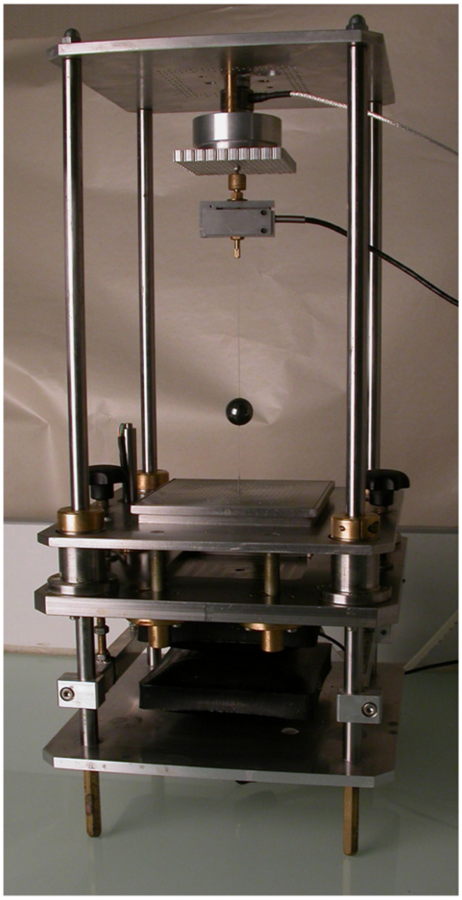

Fig. 4. Device and force sensor in the case of one isolated marble (The container has not been placed around the marble).

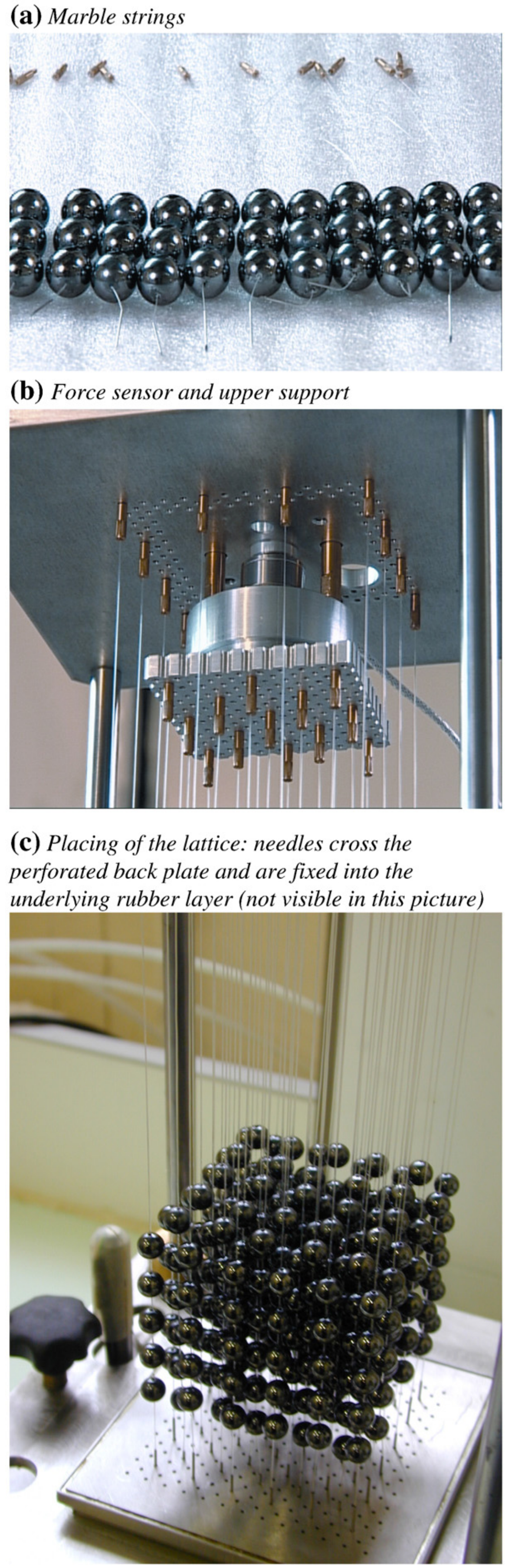

Fig. 5. Marble strings and their connection: (a) upper end and (b) lower end.

(distinct particle diameters and distinct reticular distances). Table 1 shows the different solid fractions which were tested and the number of marbles connected to the sensor. The marbles belonging to the "guard ring" are not taken into account. For instance, three different configurations lead to the solid fraction 0.21. This solid fraction can be obtained with marbles whose diameter is 14, 10.5 or 7 mm and whose spacing is 24, 18 or 12 mm, respectively. The studied solid fractions are ranging from "0" (case of a single particule) to values of the same order of magnitude as solid fractions of coarse aggregates generally encountered in SCC (i.e. about 0.30).

3.3. Experimental procedure

The pneumatic jack is pressurized which places the mobile rig at the upper stop-block. The marble strings are suspended from the upper support or from the force sensor. The needles are simultaneously fixed into the rubber layer through the back plate. When the placing of the lattice is finished, the U-shaped part of the container is placed around it and closed by the front panel. The container is then filled with the fluid: cement paste, fine mortar or "model" fluid. A sample of the fluid is also taken to perform rheological measurements.

As expected, different steps have been identified during test. These steps are shown in Fig. 6 and are described below:

- Phase I: a short and constant time is required since the filling of the container to the beginning of the test. During this phase, the black plate is lowered, the force sensor is released, the acquisition of data is started and finally the calibrated air leak is created.

Table 1
Solid fraction of granular lattices

a (mm)	*D* (mm)								Number of marbles
	16	15	14	12	11.3	10.5	8	7	
24	0.31	0.26	0.21	–	0.11	–	0.04	0.03	48
18	–	–	–	0.31	0.26	0.21	–	–	116
12	–	–	–	–	–	–	0.31	0.21	230

- Phase II: During this phase, the pressure is progressively and rapidly released in the pneumatic jack. The decrease in the force exerted by the pneumatic jack on the mobile rig is first offset by the reduction of stresses in stop-blocks. After their cancellation, the force exerted on the lattice increases. This is due to the bond between the lattice and the fluid sample. No significant displacement is observed except the elastic one. The maximum value of the force is reached when this bond breaks down (end of phase II).
- Phase III: After the peak of force, the lattice is moving and progressively extracted from the fluid. Significant displacements are measured during this phase.

Using a pneumatic jack and a calibrated air leak have enabled to control the test and to shorten its duration in compararison to the structuration time of the fluid (in case of cementitious materials). Hence, an actual “breakdown” test has been designed.

4. Validation of measurements

4.1. Repeatability

A first series of tests has been performed to study the repeatability of measurements. As a result of changes in the rheology of cement paste over time (structuration and ageing), the lattice test can not be repeated on the same sample of fluid. A new sample has to be prepared for each lattice test. The yield stress of each sample of paste is measured at the beginning of the lattice test, by using a Vane test. A mould is filled with paste and a Vane (the mobile tool) rotates at a constant and extremely small speed. The generated torque evolution is measured and can be related to the shear stress. The maximum value of the shear stress corresponds to the shear yield stress. The relevance and the accuracy of this kind of rheological measurements are described in reference [12]. Variations in yield stress can be observed. They are essentially due to the repeatability of the mixing procedure itself and to the accuracy of dosages.

Three tests were carried out with a given lattice (φ=0.31 and D=16 mm) and with a given cement paste. The results of the measurements are presented in Fig. 7. As far as measurements are operating only until the peak of force, the repeatability is quite satisfactory. However, a slight discrepancy is observed in the value of the peak between the first test and the other two. This can be attributed to a higher yield stress of the cement paste (9 Pa for the first test against 7.9 and 7.5 Pa for the other two).

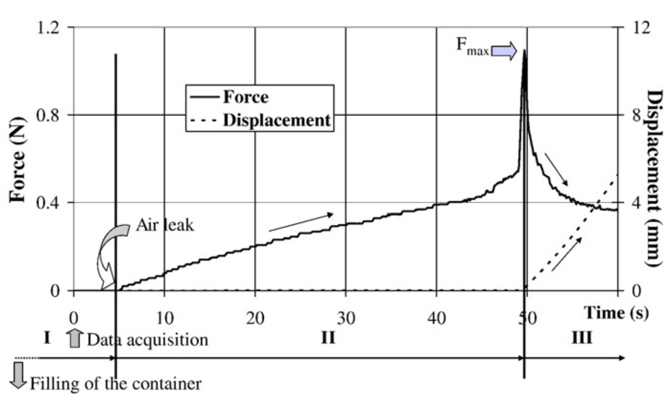

Fig. 6. Steps observed when performing test on lattice.

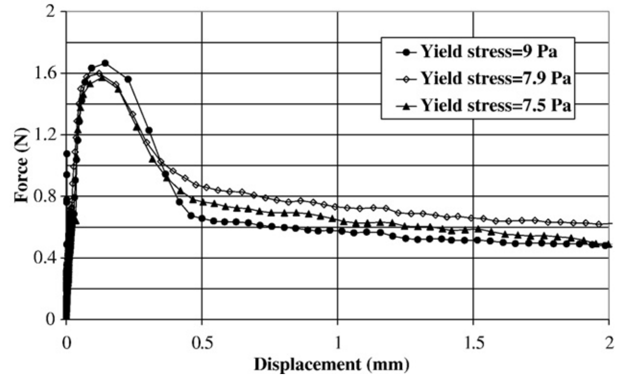

Fig. 7. Repeatability of measurements — lattice features: solid fraction φ=0.31 and marble diameter D=16 mm.

Thus, this first series of tests has shown the quite satisfactory repeatability of measurements and has pointed out the benefit to measure the yield stress of each cement paste. This has enabled to free from any hypothesis on variations in rheological characteristics and to be more accurate and hence relevant, in the analysis of lattice results. Other supplementary tests have been carried out to complete the validation. They are not presented here for the sake of lisibility. See reference [13] for more details.

4.2. Simulations of wall effects

2D Numerical simulations were done with the Finite Elements Program CESAR-LCPC [14]. The main aim of these simulations was to show the role of the “guard ring” and to verify the influence of the wall effects.

Rigid particules are immersed in a von Mises elasto-plastic medium. Simulations are done in plane strains. The specific test procedure led to define a load which is here an imposed displacement to the elasto-plastic medium on the bottom and on the side walls considered as rigid surfaces. A given configuration of the lattice was chosen for the simulations: φ=0.31 and D=16 mm. The diameter of each cylindrical particule (2D calculations) was corrected to keep the solid fraction and the spacing between particules (a=24 mm) as

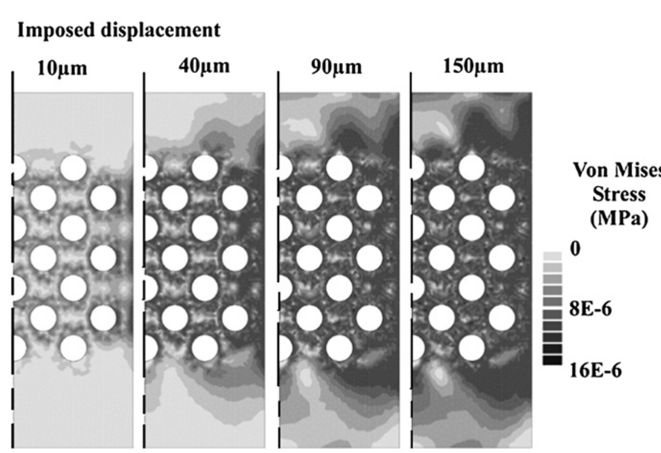

Fig. 8. Results of 2D numerical simulations in terms of von Mises stress for increasing imposed displacements (solid fraction of the lattice: φ=0.31).

constants. In this case, the equivalent diameter of the cylinders is: $D_e = 10.5$ mm.

The other data required for the simulations are listed below:

- Elasto-plastic and incompressible medium: Young's modulus $E_m = 3000$ Pa, Poisson's ratio $\nu_m \approx 0.5$ and shear yield stress $\tau_0 = 10$ Pa
- Rigid particules: $E_p = 10^5$ Pa and $\nu_p = 0.3$

It must be underlined that the elastic modulus of different cement pastes have been measured in dynamic mode. The real part G' of the complex modulus G^* corresponds to the elastic modulus of the material [15]. Hence, the Young's modulus value used for the simulations corresponds to the real part of the modulus G^* of a cement paste whose shear yield stress is about 10 Pa.

The results of numerical simulations are shown in Fig. 8 for several displacement values. Within the "guard ring", it can be reasonably assumed that the same pattern of stress state is repeated around each inclusion. The "guard ring" fully plays its role. However, the maximum value of the stress is first obtained beyond the "guard ring", i.e. in the area between the "guard ring" and the wall of the container. Thus, if the adhesion between the suspending medium and the wall of the container is weak, the flow will occur there rather than inside the lattice. In that case, the peak force will be underestimated.

Subsequent experimental results have shown that cement pastes exhibiting shear yield stress greater than 10 to 15 Pa should better not be taken into account in the analysis of results. Given that these cement pastes represent the suspending phase of SCC which are themselves very fluid, this constraint is not really a disadvantage.

5. Conclusion

According to the literature, the stability of a single sphere immersed in a yield stress fluid depends on the diameter of the particle, on the yield stress of the suspending medium and on the difference between their specific weights. A constant also intervenes in the expression of the stability criterion. This constant is referred to as "stability constant" and its value was so far not precisely determined. This basic description of sedimentation is not sufficient to reflect the reality, i.e. the segregation of SCC composed of a continuous and wide granular skeleton and a fluid phase. Hence, the approach adopted in this study consists in taking into account the combined effects of aggregates. The same form of the stability criterion is assumed for both an isolated particle and a particle included into a lattice. The comparison of the stability constants would lead to show the positive combined effects which should only depend on the solid fraction of the granular skeleton. A new experimental device has been developed in order to highlight and quantify the interactions between coarse aggregates.

In this paper, the experimental device and the test procedure have been described. The validity of measurements has been demonstrated by performing a first series of tests and numerical simulations. The repeatability of measurements has revealed itself quite satisfactory. More over, the relevance of the analysis of experimental results is improved by measuring the yield stress of each cement paste at the beginning of the test on lattice. Numerical simulations have enabled to show the role of the "guard ring" in limiting wall effects. Besides, the conditions of adhesion between the fluid and the walls of the container have led to limit the yield stress of cement pastes to 10 Pa.

In a future paper, several experimental results will be presented. They have enabled to bring to the fore and to quantify the positive combined effects of coarse aggregates.

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