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From ordinary rhelogy concrete to self compacting concrete: A transition between frictional and hydrodynamic interactions

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ABSTRACT

This paper focuses on the physical phenomena involved in the transition between ordinary fluidity concrete and high fluidity concrete according to the aggregate content of the mixture. It is shown that there exists a strong transition in the rheological behavior of concrete between a regime dominated by the friction between aggregate particles and a regime dominated by hydrodynamic interactions far less dissipative. It is also demonstrated that it is possible to define a transition criterion between these two regimes. Finally, the consequences of these changes in mix design on the mechanical strengths of the concretes are studied showing that a small decrease in granular skeleton volume fraction, which may generate a decrease in yield stress of almost two orders of magnitude, only reduces the mechanical strength of a few percents.

1. Introduction

High Performance Concretes (HPC) display high mechanical strengths due to a reduced water to cement ratio and an optimized granular skeleton [1]. The low porosity of this type of concrete also guarantees that they have a low permeability to aggressive external ions [2]. They do however also display ordinary fluidity although their use is most of the time associated to dense steel bars reinforcements. Therefore, from an empirical point of view, their slump value is most of the time of the order of 10–15 cm. This corresponds, from a physical point of view, to yield stresses between 1500 and 2000 Pa [3]. This is the value of the stress that has to be applied to the material to initiate or to maintain flow. It can be noted that, in most industrial castings, the applied stress is generated by a pressure gradient in the material due to gravity only as concrete is very rarely injected under pressure into formworks.

Self Compacting Concretes (SCC) on the other hand may display very variable mechanical strengths according to their mix design but have in common a very high fluidity, which eases their placement in complex or very reinforced formworks. Although their plastic viscosity is, as many concretes, between 50 and 200 Pa s, their yield stress is most of the time lower than a couple hundreds Pa [4]. Therefore, the stress generated by gravity in the flowing SCC always stays higher than the yield stress during casting thus ensuring the almost complete filling of traditional formworks.

These modern concretes mix designs have two aspects in common:

A highly adjuvanted cement paste. In the case of HPC, the objective is to reduce the Water to Cement ratio in order to increase the mechanical strength of the cement paste. In the case of SCC, the objective is to increase the fluidity of the cement paste and thus the fluidity of the concrete itself. It is known that, up to a saturation amount [5], the yield stress of the cement paste and therefore of the concrete itself will decrease when the High Range Water Reducer Admixture (HRWRA) dosage is increased.

A lower content of agregates. In the case of HPC, the objective is to get as close as possible to the perfect granular distribution from the micrometer scale (silica fume) to the centimeter scale (gravel) [1]. This imposes the choice of a higher powder content and inversely a lower content of aggregates. In the case of SCC, the objective is to increase the fluidity of the mixture. Okamura and Masahiro [6] have indeed explained that, when the aggregate particles volume fraction decreases, "the frequency of collision and contacts between aggregate particles can increase as the relative distance

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Fig. 1. The Millau viaduct, during the building of which 53,000 m^3 of the concrete used as a reference concrete in this paper were cast.

between the particle decreases" and that limiting the coarse aggregate content, the energy dissipation of which during flow is particularly high, allows for the mix design of fluid concretes.

Although the physical and chemical phenomena involved in the action mechanisms of HRWRA start to be well understood [7], the effect of the aggregate particles volume fraction on the rheological behavior of concrete is still very unclear from a quantitative point of view.

The objective of this paper is therefore to provide a better understanding of the physical phenomena involved in the transition between ordinary fluidity concrete and high fluidity concrete according to the aggregate content of the mixture. As concrete rheometers do not yet give any absolute value of the rheological parameters such as yield stress [8,9], we will use here simple empirical tests along with their analytical correlation with yield stress. These test only give access to the value of the yield stress of the studied materials; but, as stated above, it is the most important rheological parameter from a casting point of view [10].

In the first part of this paper, the materials studied and the rheological measurements procedures used will be described. In a second part, the obtained results will be analyzed and the existence of a strong transition between two types of rheological behavior according to the aggregate content will be shown. Finally, the consequences of these changes in mix design on the mechanical strengths of the concretes will be studied.

2. Materials

The reference concrete in this work is a famous one. It is the concrete that was cast during the building of the Millau Viaduct (see Fig. 1). This viaduct is a large road-bridge that spans the valley of the River Tarn near Millau in southern France. Designed by English architect Norman Foster and French bridge engineer Michel Virlogeux and built by Eiffage Travaux Publics, it is the tallest vehicular bridge in the world, with one pier's summit at 343 m (1125 ft)—slightly taller than the Eiffel Tower and only 38 m (125 ft) shorter than the Empire State Building. The mix proportioning of the concrete used to cast the viaduct piles is given in Table 1.

An initial objective of the work presented here was to study *a posteriori* the changes in mix design that would have been necessary to transform this HPC into SCC in order to ease the placement of the concrete in the viaduct zones where the steel bars reinforcements were very dense.

The maximum packing fraction of the granular skeleton with the proportions given in Table 1 was calculated using the free software RENE LCPC [11] and was equal to 84%.

3. Rheological measurements

Although values of the yield stress instead of empirical measurements such as slump or slump flow will be studied in this paper, we chose however to use simple test and to deduce from these measurements the value of the yield stress of the concrete.

Typically, in a slump test, a mould of a given conical shape is filled with the tested material. The mould is lifted and flow occurs. If inertia effects can be neglected [12], it is generally admitted that the flow stops when the shear stress in the tested sample becomes equal to or smaller than the yield stress [13]. Consequently, the shape when flow stops in the yielding region is directly linked to the material yield stress. From a practical point of view, in civil engineering, two geometrical quantities may be measured, the "slump" or the "spread" (called slump flow). The slump is the difference between the height of the mould at the beginning of the test and when flow stop. The spread is the final diameter of the collapsed sample. In most of the applications of the ASTM Abrams cone [14], the initial height of which is 30 cm, the slump is measured if it is smaller than 25 cm, otherwise the spread is measured (slump flow test for SCC).

Several attempts to relate slump to yield stress can be found in literature. They generally assume that the cone can be divided into

Table 1
Mix proportioning of the Millau viaduct HPC

Component	Content (kg/m^3)	Volume proportion
Cement CEM I 52.5	420	48% of the cement paste
Water	140.9	50% of the cement paste
Super Plasticizer Optima 175®	5.88	2% of the cement paste
Rounded sand 0/2 mm	312	17% of the aggregates volume
Crushed sand 0/4 mm	468	25% of the aggregates volume
Crushed gravel 4/6 mm	362	19% of the aggregates volume
Crushed gravel 6/14 mm	711	38% of the aggregates volume

two parts: above a critical height, the shear stress remains smaller than the yield stress and no flow occurs; below this critical height, the shear stress induced by the pressure due to the mass of material situated above is larger than the yield stress. In the latter region, each layer of material widens until the pressure reaches a critical value for which the shear stress is equal to the yield stress. Following this approach, Murata [15] wrote a relation between the final total height of the cone and the yield stress that does not depend on the mould geometry. Subsequent works established analogous relationships either for conical [13] or cylindrical moulds [16] according to the same assumptions. These results were successfully validated by Clayton et al. [17] and Saak et al. [18] in the case of cylindrical moulds. However, in the case of some conical moulds or in the case of high yield stress values (*i.e.* low slumps) with cylindrical moulds, a discrepancy between predicted and measured slumps was systematically obtained.

For large slumps, the spread is a more relevant parameter to estimate the material yield stress [19,20] but the above approach likely does not apply since there is in general no undeformed region. Coussot et al. [19], extending a two-dimensional solution of Liu and Mei [21], wrote a solution for this spreading problem for a yield stress fluid. This approach is based on the assumption that the depth of the fluid layer is much smaller than the characteristic length of the solid–liquid interface [22].

Roussel and Coussot [12] showed recently that two very different regimes may be identified and that, in order to obtain a correct quantitative correlation between the test result and yield stress, the incipient or stop flow conditions should be described with a proper three dimensional yielding criterion. They obtained two analytical solutions suitable for asymptotic regimes, namely large height to diameter ratio or large diameter to height ratio [12]. Numerical simulations of the slump test were also carried out for two classical conical geometries, the ASTM Abrams cone and a mini cone for cement pastes [23]. An excellent agreement between the predicted and measured slumps over a wide range of dimensionless yield stress was then written. The following correlation was obtained:

$$S = 25.5 - 17.6\frac{\tau_0}{\rho} \qquad (1)$$

where τ_0 is the yield stress, S is the measured slump and ρ is the density of the tested concrete. This correlation is valid for slumps between 5 and 25 cm.

Moreover, it was demonstrated that the slump flow test cannot be universally correlated to the rheological parameters of the SCC tested [24]. Indeed, although most of the conditions for the correlation to be valid (negligible surface tension effects and inertia effects) are fulfilled, the thickness of the sample when flow stops is of the same order as the largest particles. This prevents from considering the concrete as an homogeneous fluid and from deriving any continuous fluid mechanics equations. This does not mean however that the slump flow cannot be used as an acceptance test. For a given SCC with a given granular skeleton, the spread value measurement is indeed a handy tool to spot, for example, a water amount variation during production. But the measured spread (or slump flow value) cannot be directly and universally correlated to the yield stress of the tested SCC.

An alternative test method was recently proposed for concretes displaying a slump higher than 25 cm: the “LCPC BOX”. It requires the same amount of concrete as the slump flow test but fulfils the minimum thickness condition allowing for an analytical relation between the test result and the yield stress of the tested material.

This test is inspired by the fact that, in an axi-symmetrical test, the information on the shape of the sample when flow stops is redundant. Indeed, on each diameter, from a theoretical point of view, if the testing surface is horizontal, the same spread is measured. It is thus in theory, sufficient to measure only one of these diameters by studying a 2D channel flow (Cf. Fig. 2). The width of the channel is l_0=20 cm. Its length is 120 cm. The studied volume of SCC is the same as the one used in the slump flow (6 L) as it is sufficient to be representative of the tested concrete. As the flow is nearly unidirectional, the thickness of the sample when flow stops for the same sample volume is greater than in the slump flow test. Moreover, it was checked that emptying a 6 L bucket is generating a flow slow enough for any inertia effects to be negligible. As a consequence, the final shape does not depend on the pouring speed of the concrete to be tested.

The analysis of this flow and its stop can be found in [24,25]. The analysis takes into account the shear stress at the lateral walls and at the bottom wall to predict the shape when flow stops of a given volume of a yield stress fluid flowing slowly enough for any inertia effects to be negligible. The excellent agreement of this method with other experimental measurements was demonstrated in the case of limestone powder suspensions [24].

This new test is a cheap and easy way to measure the yield stress of fluid concretes when trying to reach the optimum mix design or to compare the rheology of various SCC. Unlike the slump flow test, the measured spread length is correlated to the yield stress of the material via a unique law (Cf. Fig. 2 (right)). As an intermediary conclusion, it can be kept in mind that the above two tests and the associated correlation between the geometrical measurement (*i.e.* slump or spread length) and the yield stress allow for the measurement of this physical parameter for any concrete without the use of a rheometer.

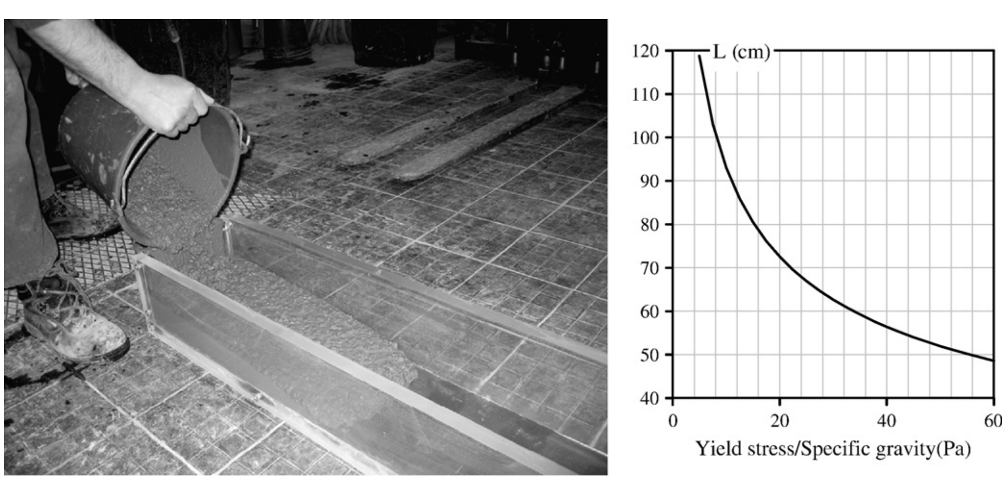

Fig. 2. LCPC BOX test on a SCC. (Left) The concrete is slowly poured at one end of the box; (Right) Correlation between measured spread length in the box and yield stress of the tested material.

4. Experimental results

The paste mix proportioning given in Table 1 was kept constant and the water to cement ratio was thus kept equal to 0.33. The mix proportioning of the granular skeleton indicated in Table 1 was also kept constant meaning that the granular skeleton was always closed to the optimal packing. The proportions between the four classes were kept constant. The only variable parameter was therefore the volume fraction of the aggregates in the mixture (or inversely the volume fraction of the cement paste) and 21 concretes were prepared and tested.

The obtained experimental results (slump, slump flow and LCPC Box spread length) are gathered in Fig. 3. The yield stresses calculated from slump and LCPC Box spread length are shown in Fig. 4. It can first be noted that the continuous transition between the yield stress calculated from LCPC Box spread length and from slump confirm the validity of the correlation between yield stress and empirical measurement used here. Moreover, it is possible to distinct three zones in Fig. 4. For $\Phi>70\%$, the yield stress of the concrete is of the order of a couple thousands Pa and the rheology is the one of a traditional concrete (slump lower than 15 cm). For $\Phi<60\%$ the yield stress of the concrete is of the order of several tens of Pa and the rheology is the one of a SCC. For $60\%<\Phi<70\%$, the striking point is that, over a variation of 10% of the aggregates volume fraction, there is a variation of almost two orders of magnitude of the yield stress of the concrete. This strong transition only appears when studying the value of the physical parameter that is yield stress and is hidden when only studying results of empirical test. Finally, it can be noted that, for $\Phi<65\%$, the concrete tested here becomes self compacting (slump flow higher than 600 mm and yield stress lower than 200 Pa).

5. Analysis

5.1. Multi-scales approach

Concrete components range from micrometric cement particles to centimetric aggregate particles. In order to overcome this difficulty in the study of the relation between mix design and rheological properties, multi-scales approaches seem very promising [7,26]. The simplest multi-scales approach only involves two scales and it is therefore often considered that concrete is a suspension of aggregate particles (sand and gravel) in a suspending fluid (cement paste). It can then be expected, as a first approximation, that, as for many suspension in nature or industry, the yield stress of the suspensions (*i.e.* the concrete) is proportional to the yield stress of its suspending fluid (*i.e.* the constitutive cement paste).

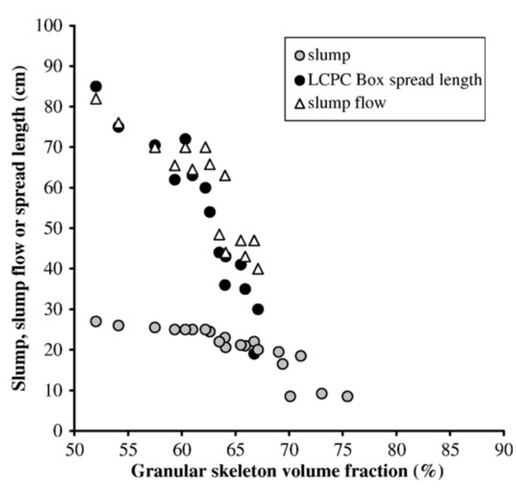

Fig. 3. Empirical test results as a function of the aggregates volume fraction. Both slump, slump flow and LCPC box spread length are plotted.

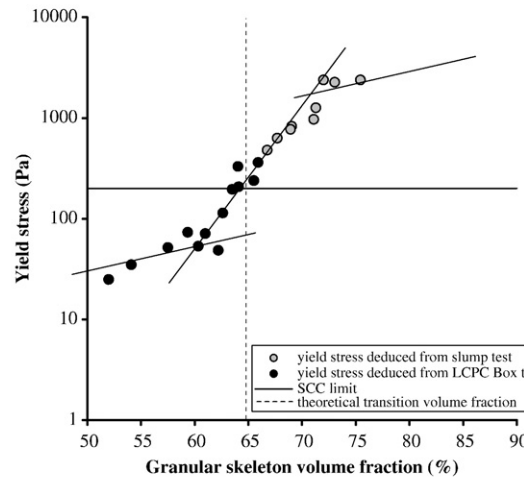

Fig. 4. Concrete yield stress as a function of the aggregates volume faction. The yield stress is either extrapolated from slump or LCPC Box measurement according to the concrete fluidity.

This statement can be extrapolated from general relations similar to Krieger–Dougherty relation [27,28] for apparent viscosity, which relate the rheological properties of the suspending fluid and the volume fraction Φ of the particles to the rheological properties of the mixture. The general form of these relations is:

$$\tau_0^{\mathrm{Conc}} \approx \tau_0^{\mathrm{cp}} f(\Phi/\Phi_{\mathrm{m}}) \tag{2}$$

where τ_0^{Conc} and τ_0^{cp} are respectively the yield stresses of the concrete and of the cement paste. Φ_{m} is the maximum packing volume fraction.

It must not be forgotten that this type of phenomenological relation have been historically established for purely hydrodynamic interactions between the suspending fluid and the particles and thus apply for moderate inclusions volume fraction.

It is of great interest to study the relative yield stress of the concrete (*i.e.* the ratio between the yield stress of the concrete and the yield stress of the cement paste) as it allows theoretically to focus on the effect of the granular inclusions content (*i.e.* $f(\Phi/\Phi_{\mathrm{m}})$) independently of the cement paste mix design.

However, the above approach could be subject to debate as there does not exist any reason to consider that the cement paste is the suspending fluid more than water or mortar. Let us describe the consequences of the three types of approaches which can be found in the literature on the modeling of the behavior of the mixture.

1) Water may be considered as the suspending fluid and all particles in the mixture are considered as inclusions and participate to the total solid content of the mixture [1]. This is the most rigorous approach from a theoretical point of view. However, difficulties come from the fact that all the types of inter-particles interactions from frictional interactions between the largest grains to the highly complex colloidal interactions occurring at the cement paste scale are to be taken into account in order to describe the system and the knowledge of the total solid content is not sufficient to know which type(s) of inter-particles interactions will dominate. As each type of interaction is more or less associated to a particle size [7], any quantitative predictions can only come from a distinction between the various species in the mixture.
2) The natural answer to this difficulty consists in considering, as described above, that concrete is a suspension of aggregate particles (sand and gravel) in a suspending fluid (cement paste). Two granular species are thus considered: more or less colloidal particles and non-colloidal particles. One has then to assume that the

ratio between the aggregate particles diameter and the cement particles diameter is far higher than 1. If the diameters of the largest particles are considered (*i.e.* 100 μm for the cement particles and around 10 mm for the coarse particles), cement paste can thus be considered as a continuum medium and therefore as the suspending fluid at the scale of the sand and gravel particles. However, sands and gravels also contain small amount of fine particles, the diameter of which is of the order of the largest cement particles. Choosing this approach thus needs to neglect this overlap in species diameter. Moreover, it has been shown recently that aggregate particles (probably the finest with the largest specific surface) may adsorb a non negligible part of the HRWRA [29]. This means that the independently measured cement paste yield stress is systematically lower than its yield stress once inside concrete and that the calculated relative yield stress will be a strong approximation of the real relative yield stress of the material studied.

3) The last type of approach that can be found in the literature consists in considering that the inclusions are the aggregate particles larger than a given separation size. The question that arises is then "which size ?". Several values can be found in the literature between 0.125 mm and 1 mm [26,30]. This approach is of course more rigorous from a theoretical point of view as all the potentially colloidal particles can be studied together but it is also more complicated from a practical point of view as it requires to isolate the finest sand particles and add them to the cement paste to be studied.

5.2. Existing theoretical frames

5.2.1. Excess thickness theory

The concept of a layer of cement paste surrounding all sand and gravel particles with varying thickness according to the granular content is often used to explain the influence of coarse aggregate content on workability. This layer is said to lubricate the grains relative movement and increase the flowability of the mixture. This concept however is far from what can be found in more fundamental research areas, in which solid or inclusions volume fraction Φ is the only parameter used to describe the system jamming state and thus its ability to deform [31]. The concept of thickness layer has proved its efficiency in explaining many observed phenomena [32,33]. It can however be noted that paste excess thickness is in fact another way to express the average distance b between the granular inclusions which writes:

$$b = -d\left(1 - (\Phi/\Phi_m)^{-1/3}\right) \tag{3}$$

It can be noted that Eq. (3) is only a very rough approximation of an average inter-particles distance. For a more realistic calculation of a distribution of inter-particles distance, one should read [34].

The fact that a correlation between the excess paste layer thickness calculated from Eq. (3) and the rheological properties of the concrete is obtained can therefore be explained by the fact that there exists a relation between rheological properties and jamming of the system. This jamming is correlated to the inclusions volume fraction. Moreover, there exists a direct relation between volume fraction and average distance between aggregate inclusions. Finally, this average distance is equal to two times the cement paste excess layer (see Fig. 5).

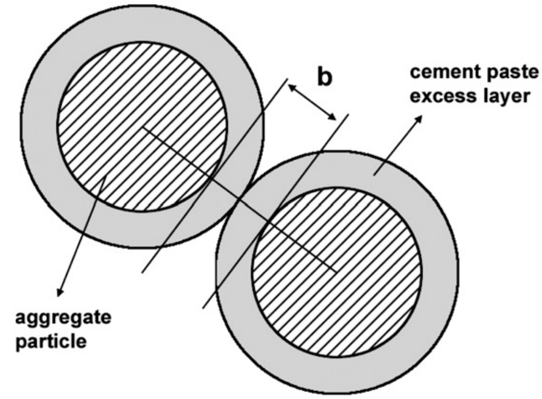

Fig. 5. Cement paste excess layer and average distance between particles.

5.2.2. Physical approach

When particles (sand and gravel) are mixed in a fluid (cement paste), the type of particle/particle or fluid/particle interactions may vary according to the packing of the particles in the system. At low volume fractions, these interactions can be hydrodynamic. The relative motions of particles such as sand grains or gravels in a cement paste implies some flow of the cement paste. If the concrete is flowing, some analogous effect occurs that induces additional energy dissipations so that the apparent viscosity of the cement paste plus the grains is greater than that of the cement paste alone. Thus the apparent viscosity of a concrete increases with the volume fraction of inclusions.

At higher volume fractions, direct contacts may occur between aggregate particles. It is in fact rather difficult to define the exact form that such a process should take. Indeed, because of particle interactions, particles roughness, and hydrodynamic effects, a "true" direct contact can hardly occur over a large surface. A possible way of defining direct contact without dwelling on details is to consider it from its effects on particle dynamics rather than through its mechanisms. Thereby, it is usual to distinguish between collisional (brief duration) and frictional (sustained) contacts. The predominance of contacts in the physical behavior necessarily results from the existence of a considerable amount of contacts throughout the suspension, so that we conclude that this situation can be associated with the existence of a continuous network of particles in contacts. Since this phenomenon is associated with a percolation process, it occurs when the solid fraction is larger than a critical one (Φ_c). Current knowledge in this field does not make it possible to specify to what extent Φ_c depends on flow and suspension characteristics. However, experimental and numerical results indicate that, for uniform spheres (Φ_m=0.64), Φ_c should be situated around 0.5 [35]. However, Φ_c should be increased in the case of poly-disperse particles such as sand and gravel as the average distance between particles scales with $(\Phi/\Phi_m)^{-1/3}$ and thus increases when Φ_m increases. It may thus be of interest to deal with the value of the relative solid volume fraction Φ/Φ_m that can be compared to the critical value deduced from the mono-sized spheres case Φ/Φ_m=0.79 instead of dealing with the value of the volume fraction itself.

We can then apply these concepts to the experimental results obtained here. As the maximum packing of the granular skeleton used in this paper is equal to 84%, the transition volume fraction is therefore of the order of 65%. This value is plotted in Fig. 4 and it can be seen that it is indeed around this transition value that the variation of two orders of magnitude of the yield stress occurs. This means that, below this transition value, more or less direct contacts between the inclusions can be neglected. As there are no colloidal interactions between the coarse inclusions, this means that, in this regime, the consequences of the presence of the aggregate particles on the rheological behavior of the mixture are thus purely hydrodynamic. Inversely, above this transition value, direct frictional contacts between particles start to dominate the rheological behavior. Their highly dissipative nature strongly increase the yield stress of the concrete.

It has to be noted that the contribution of the granular skeleton content cannot turn alone any ordinary rheology concrete into a SCC. Indeed, the fact that the granular content is below the transition between frictional regime and hydrodynamic regime only guarantees that the contribution of the aggregates to the yield stress of the mixture will be low. It has to be kept in mind that the yield stress of the concrete will never be lower than the yield stress of its constitutive cement paste as adding aggregates in the mixture can only increase the capacity of the system to dissipate energy. It has also to be kept in mind that, in the hydrodynamic regime, the yield stress of the concrete is more or less proportional to the yield stress of the cement paste (see Eq. (2) in Section 5.1). As a consequence, in order to mix design SCC, one has to ensure that the aggregate volume fraction is lower that the transition value and, moreover, that the yield stress of the cement paste is low (but sufficient to ensure the stability of the coarsest particles [36]).

It can be interesting to apply this concept to other results from the literature. As the maximum packing fraction of the granular skeleton used in those papers is not always specified, we shall use in the following, as a first approximation, the semi-empirical relation proposed by Hu and de Larrard [37] which quantitatively predicts Φ_m:

$$\Phi_m = 1 - 0.45(d_{min}/d_{max})^{0.19} \quad (4)$$

where d_{min} and d_{max} are respectively the smallest and the largest grains diameter in the granular skeleton considered.

Relative yield stresses measured using a BML-viscometer by Pedersen and Smeplass [30] are plotted in Fig. 6 as a function of the volume fraction of the aggregates larger than 0.125 mm. Although the multi-scales approach chosen in that work (*i.e.* the suspending fluid is made of water and all the grains smaller than 0.125 mm, the inclusions are made of all the grains larger than 0.125 mm) is not the same as in the one chosen in this paper, the transition value between hydrodynamic and frictional regimes also seems to be applied.

Measured values of mortar yield stresses are also plotted in Fig. 7 as a function of the total solid volume fraction (sand + cement) [38]. As for the experimental results presented above, the values of the yield stress are either extrapolated from mini slump or mini slump flow measurement according to the mortar fluidity. It can be noted that, in this case, the consequences of the presence of the particles below the transition value are not purely hydrodynamic but are of course strongly colloidal. However, once again, the predicted transition value is in agreement with the experimental measurements.

It can therefore be kept in mind that, on the particular aspect of the transition between frictional and hydrodynamic regimes, the question of the suspending fluid discussed in Section 5.1. does not seem to be relevant. The same transition concept can be applied with the same transition value. Indeed, let us consider, as an example, a stable concrete (*i.e.* no segregation of the components) containing, in volume proportions, 40% of gravel, 30% of sand, 10% of cement and 20% of water. If we consider that sand and gravel particles are the inclusions with a maximum packing volume fraction of 0.8 and that the cement paste is the suspending fluid, then the value of Φ/Φ_m will be equal to

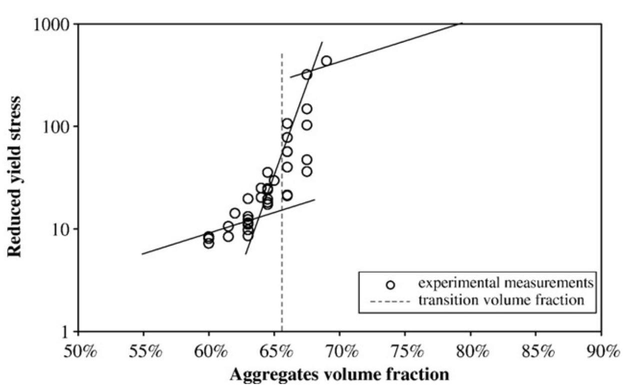

Fig. 6. Concrete reduced yield stress (ratio between concrete yield stress and cement paste yield stress) as a function of the volume fraction of aggregates larger than 0.125 mm. The yield stress is measured using a concrete rheometer [30].

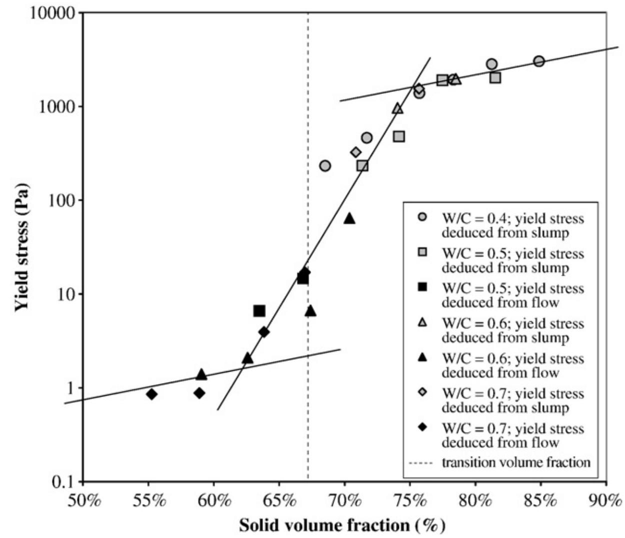

Fig. 7. Mortar yield stress as a function of the total solid volume fraction. The yield stress is either extrapolated from the measurements of slump or slump flow measurement carried out in [37].

0.7/0.8 = 0.88 > 0.79 and it will be possible to predict that the behavior will be dominated by the friction between the aggregates (*i.e.* ordinary rheology concrete). If we consider now the total solid volume fraction *b* (cement, sand and gravel), this solid skeleton will have, because of its higher poly-dispersity, a higher maximum packing volume fraction (0.9 as a first approximation) and the value of Φ/Φ_m will be equal to 0.8/0.9 = 0.89. The same conclusion will be reached. As the volume fraction and the maximum packing fraction of the solid content considered will vary inversely, the transition volume fraction between the frictional and hydrodynamic regime will still mean something no matter the type of multi-scales approach chosen to describe the system.

6. Mechanical strengths

It has been demonstrated here that it is possible to greatly affect and therefore control the rheology of a given concrete by varying the aggregates content of the mixture. However, this knowledge is useless if we do not know the consequences of these changes on the mechanical strength of the hardened concrete. Simple compression mechanical tests were thus carried out on all the concretes prepared. The mechanical strengths were measured at 28 days on three cylindrical samples for each batch (diameter 11 cm, height 22 cm).

As shown above, in the particular case of the concrete of the Millau Viaduct studied here, decreasing the aggregates volume fraction from 72% to 65% was sufficient to transform this ordinary rheology HPC into a SCC. It can be seen in Fig. 8, in which the ratio between the measured mechanical strength and the mechanical strength of the reference concrete is plotted as a function of the granular skeleton volume fraction, that a decrease in mechanical strength is very difficult to spot in this range. We tried to apply to our results the packing model developed by de Larrard [1] which predicts that the mechanical strength f_c is proportional to:

$$f_c \approx \left(1 - (\Phi/\Phi_m)^{-1/3}\right)^{-r} \quad (5)$$

with *r* between 0.13 and 0.16. The predictions of this model when taking as a reference the Millau viaduct concrete are plotted in Fig. 8. It can be seen that, for a 7% decrease in granular skeleton volume fraction that generates a decrease in yield stress of almost two orders of magnitude, only a decrease of less than 10% of the mechanical strength is to be feared. It has however to be kept in mind that other problems such as higher shrinkage, higher heat flux during setting

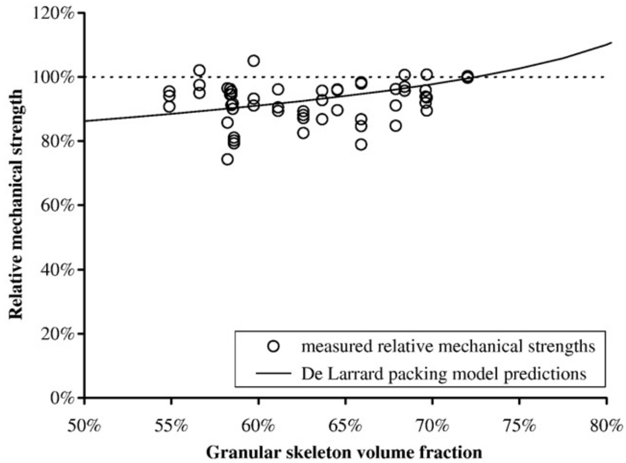

Fig. 8. Relative mechanical strength (ratio between mechanical strength and mechanical strength of the reference concrete) as a function of the aggregates volume fraction.

and higher cost because of the higher amount of cement in the mixture have to be taken into account. By substituting a fraction of the cement by alternative powders such as limestone fillers or fly ashes, these problems can however be solved. The mix design, which will then be obtained, is the one of a standard SCC.

7. Conclusions

This paper has focused on the physical phenomena involved in the transition between ordinary fluidity concrete and high fluidity concrete.

In the first part of this paper, the materials studied and the rheological measurements procedures used were described. One original aspect of the work presented here is that, although physical parameters such as yield stress were studied to quantify the workability of the concretes tested, no concrete rheometer was used. Simple analytical correlations from the literature between empirical measurements such as slump, slump flow or LCPC box spread length and yield stress allowed for the identification of this physical parameter.

It was therefore shown that, although it cannot be spotted when only considering results of empirical test, there exists a strong transition in the rheological behavior of concrete between a regime dominated by the friction between aggregate particles and a regime dominated by hydrodynamic interactions far less dissipative.

It was also demonstrated that it is possible to define a transition value between these two regimes that seem to apply no matter the multi-scales approach chosen. This is very useful from a mix design point of view as it allows for the civil engineer to ensure that the contribution of the granular skeleton to the consistency of the concrete will be as low as possible.

Finally, the consequences of these changes in mix design on the mechanical strengths of the concretes were studied showing that a small decrease in granular skeleton volume fraction that may generate a decrease in yield stress of almost two orders of magnitude, only reduces the mechanical strength of less than 10%. This has allowed us to transform a HPC into a SCC with high mechanical strength. The questions of the delayed deformations and of the effects of the cement substitution by an alternative powder will be the subject of future complementary studies.

References

[1] F. de Larrard, Concrete Mixture Proportioning, E & FN Spon, London, 1999.
[2] Y. Malier, Bétons à Hautes Performances, Presse de l'Ecole Nationale des Ponts et Chaussées, 1991.
[3] N. Roussel, Correlation between yield stress and slump: comparison between numerical simulations and concrete rheometers results, Mat. Struct. 39 (4) (2006) 501–509.
[4] O. Wallevik, Rheology — a scientific approach to develop self-compacting concrete, Proceedings of the 3rd International RILEM Symposium on Self-Compacting Concrete, Reykjavik, Iceland, 2003, pp. 23–31, (RILEM PRO33.
[5] A.M. Kjeldsen, R. Flatt, L. Bergström, Relating the molecular structure of comb-type superplasticizers to the compression rheology of MgO suspensions, Cem. Concr. Res. 36 (2006) 1231–1239.
[6] H. Okamura, O. Masahiro, Self compacting concrete, J. Adv. Concr. Technol. 1 (1) (2003) 5–15.
[7] R. Flatt, Towards a prediction of superplasticized concrete rheology, Mat. Struct. 27 (269) (2004) 289–300.
[8] Comparison of concrete rheometers: international tests at LCPC (Nantes, France) in October 2000, in: C.F. Ferraris, L.E. Brower (Eds.), National Institute of Standards and Technology Interagency Report (NISTIR), 6819, 2001.
[9] Comparison of concrete rheometers: International tests at MB (Cleveland OH, USA) in May 2003, in: C.F. Ferraris, L.E. Brower (Eds.), National Institute of Standards and Technology Interagency Report (NISTIR), 7154, 2004.
[10] N. Roussel, S. Staquet, L. D'Aloia Schwarzentruber, R. Le Roy, F. Toutlemonde, SCC casting prediction for the realization of prototype VHPC-precambered composite beams, Mat. Struct. 40 (9) (2007) 877–887.
[11] T. Sedran, F. de Larrard, RENÉ-LCPC — Un logiciel pour optimiser la granularité des matériaux de génie civil, Note technique, Bull. Liaison Lab. Ponts Chaussées 194 (Novembre-Décembre, 1994) (in French). Download the free RENE LCPC software at http://www.lcpc.fr/fr/produits/index.dml#software.
[12] N. Roussel, P. Coussot, "Fifty-cent rheometer" for yield stress measurements: from slump to spreading flow, J. Rheol. 49 (3) (2005) 705–718.
[13] W.R. Schowalter, G. Christensen, Toward a rationalization of the slump test for fresh concrete: comparisons of calculations and experiments, J. Rheol. 42 (4) (1998) 865–870.
[14] ASTM Designation C-143-90, Standard test method for slump of hydraulic cement concrete. Annual Book of ASTM Standards, 04.01, Am. Soc. Test. Mat., Easton, MD, 1996, pp. 85–87.
[15] J. Murata, Flow and deformation of fresh concrete, Mat. Struct. 98 (1984) 117–129.
[16] N. Pashias, D.V. Boger, J. Summers, D.J. Glenister, A fifty cent rheometer for yield stress measurements, J. Rheol. 40 (6) (1996) 1179–1189.
[17] S. Clayton, T.G. Grice, D.V. Boger, Analysis of the slump test for on-site yield stress mèeasurement of mineral suspensions, Int. J. Miner. Process. 70 (2003) 3–21.
[18] A.W. Saak, H.M. Jennings, S.P. Shah, A generalized approach for the determination of yield stress by slump and slump flow, Cem. Concr. Res. 34 (2004) 363–371.
[19] P. Coussot, S. Proust, C. Ancey, Rheological interpretation of deposits of yield stress fluids, J. Non-Newton. Fluid Mech. 66 (1996) 55–70.
[20] P. Domone, The slump flow test for high-workability concrete, Cem. Concr. Res. 28 (1998) 177–182.
[21] F.K. Liu, C.C. Mei, Slow spreading of a Bingham fluid on an inclined plane, J. Fluid Mech. 207 (1989) 505–529.
[22] N. Roussel, C. Stefani, R. Le Roy, From mini cone test to Abrams cone test: measurement of cement based materials yield stress using slump tests, Cem. Concr. Res. 35 (5) (2005) 817–822.
[23] N. Roussel, Correlation between yield stress and slump: comparison between numerical simulations and concrete rheometers results, Mat. Struct. 39 (4) (2006) 501–509.
[24] N. Roussel, The LCPC BOX: a cheap and simple technique for yield stress measurements of SCC, Mat. Struct. 40 (9) (2007) 889–896.
[25] T.L.H. Nguyen, N. Roussel, P. Coussot, Correlation between L-box test and rheological parameters of an homogeneous yield stress fluid, Cem. Concr. Res. 36 (10) (2006) 1789–1796.
[26] Z. Toutou, N. Roussel, Multi scale experimental study of concrete rheology: from water scale to gravel scale, Mat. Struct. 39 (2) (2006) 189–199.
[27] I.M. Krieger, T.J. Dougherty, A mechanism for non-Newtonian flow in suspensions of rigid spheres, Trans. Soc. Rheol. 3 (1959) 137–152.
[28] M.R. Geiker, M. Brandl, L.N. Thrane, L.F. Nielsen, On the effect of coarse aggregates fraction and shape on the rheological properties of self compacting concrete, Cem., Concr. Aggreg. 24 (1) (2002) 3–6.
[29] E. Maruya, M. Osaki, H. Igarashi, Relationship between rheological constant of cement paste and fluidity of high-fluidity concrete, J. Adv. Concr. Technol. 4 (2) (2006) 251–257.
[30] B. Perdersen, S. Smeplass, The relationship between the rheological properties of SCC and the corresponding matrix phase, Proceedings of the 3rd International RILEM Symposium on Self-Compacting Concrete, Reykjavik, Iceland, 2003, pp. 23–31, RILEM PRO33.
[31] P. Coussot, C. Ancey, Rheophysical classification of concentrated suspensions and granular pastes, Phys. Rev. E 59 (4) (1999).
[32] A. Denis, A. Attar, D. Breysse, J.J. Chauvin, Effect of coarse aggregate on the workability of sandcrete, Cem. Concr. Res. 32 (5) (2002) 701–706.
[33] G. Chanvillard, O. Basuyaux, Une méthode de formulation des bétons de sable à maniabilité et résistance fixées, Bull. Liaison Lab. Ponts Chaussées 205 (1996) 49–63.
[34] E.J. Garboczi, D.P. Bentz, Analytical formulas for interfacial transition zone properties, Adv. Cem. Based Mater. 6 (1997) 99–108.
[35] G.Y. Onoda, E. Liniger, Random loose packings of uniform spheres and the dilatancy onset, Phys. Rev. Lett. 64 (1990) 2727–2730.
[36] N. Roussel, A theoretical frame to study stability of fresh concrete, Mat. Struct. 39 (2006) 81–91.
[37] C. Hu, F. de Larrard, The rheology of fresh high performance concrete, Cem. Concr. Res. 26 (2) (1996) 283–294.
[38] J.I. Miyake, H. Matsushita, Evaluation method for consistencies of mortars with various mixture proportions, J. Adv. Concr. Technol. 5 (1) (2007) 87–97.