OPTIMIZATION OF SELF COMPACTING CONCRETE THANKS TO PACKING MODEL

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Abstract

Self Compacting Concrete (SCC) technology is spreading worldwide since the last years. A number of practical methods have been proposed to design such concrete but they generally require a great number of laboratory trials or do not permit a rapid and precise concrete optimization. Yet, such an optimization is necessary to limit the paste volume in order to restrain the cost and the amount of delayed strains of the concrete.

The aim of this paper is then to present a theoretical approach of the behavior of Self Compacted Concrete at fresh state, that can be used to build a mix-design software. This approach is based on a mathematical model developed at LCPC and called the Compressible Packing Model. This model allows to optimize the granular skeleton of concrete.

The paper explains first how fresh SCC is characterized at LCPC. Then, after a brief presentation of the packing model, it shows how the flowing properties in unconfined conditions (namely yield stress, viscosity, slump flow and flow time) can be calculated from the properties of the constituents. In a second part, it describes how the model has been adapted to calculate the filling ability of a concrete for a given confinement and its proneness to segregation. Finally, a rational mix design process for SCC without viscosity agent is proposed based on these predictive models, which needs further validation.

Keywords

self compacting concrete, rheology, yield stress, plastic viscosity, slump flow, L box, blocking, segregation, mix design

1. Introduction

Self Compacting Concrete (SCC) are spreading worldwide because of their very attractive properties at the fresh state. However, this kind of concrete is certainly one of the most difficult to design due to the necessity of finding an equilibrium between its different properties which depend on distinct mechanisms: in fact, fresh SCC must have a great flowability, a high stability at rest after casting and, generally, a great filling ability through narrow reinforcements. Moreover, workability requirements lead to high volume of paste which can promote a too high shrinkage and creep. On the other hand, the mixture-proportioning process is complicated by the multiplication of the constituents available on the market: rounded or crushed aggregates with different mineral natures, pure Portland or blended cements, a variety of mineral admixtures, different types of superplasticizers, and sometimes other chemical admixtures, like viscosity agent. In that context, a rational optimization process for SCC is obviously needed to deal with all these properties and constituents.

A first mix-proportioning system has been proposed by Okamura and Ozawa [1] and Ouchi and al. [2] from the University of Tokyo. In this method, the coarse aggregate volume is fixed at 50% of its packing density and the sand volume (particles coarser than 90 µm) at 40 % of the mortar one. The powders, water and superplasticizer contents are adjusted at the mortar level in order to provide a sufficient viscosity (measured by the flowing time in a V funnel) and a high flowing ability (measured by a slump flow). Because this method is general and very simple to proceed, it must be safe versus blocking risks. Then, it generally leads to concrete with higher paste volume than required in the optimum mix. This may be particularly the case with coarse aggregate with a small maximum size or with river sand. The induced overcost may be unacceptable in countries were the material cost is submitted to a hard competition. A second method has been proposed by Pertersson and al. [3] based on work done by Tangtermsirikul and Van [4]. In this method, the minimum paste volume necessary to reach a good filling ability in an L box, with a given clear space between reinforcements, is calculated for each gravel to sand ratio thanks a reference curve, established by trials for each nature of aggregate. The minimum paste volume to reach the target slump flow is roughly estimated on the basis of the packing density of dry mixes of gravel and sand. The final gravel to sand ratio is the one which gives the same minimum paste volume for both properties. The powders, water and superplasticizer contents are then adjusted to reach the compressive strength and to obtain a sufficient viscosity and a small yield stress (measured in a coaxial viscometer) for the mortar containing the particles finer than 250µm. The rheological approach replaces here the devices used in the Japanese one. This method proposes a better optimization of the skeleton but the reference curve for blocking criterion is not general and is cumbersome to obtain for each nature of aggregate. Moreover, the relationship between slump flow and packing density of the skeleton is not clearly established and needs a lot of trials.

For all these reasons, we have tried to develop at LCPC a more efficient (which means accurate and rapid) mix design system for SCC [5]. The following sections presents the different steps of this development; first of all, it was necessary to completely characterize the concrete at the fresh state.

2. Characterization of fresh SCC

2.1. Flow behavior

The flow behavior in unconfined conditions of the concrete was characterized with a concrete rheometer called BTRHEOM developed at LCPC and extensively validated [6-8]. It has been recently demonstrated by de Larrard and al. [9] that concrete is a Herschel-Bulkley fluid but the same authors propose a method to keep a simpler Bingham model (see fig. 1) according to the following equation:

$$\tau = \tau_0' + \mu' \dot{\gamma} \qquad (1)$$

where $\dot{\gamma}$ is the strain rate (in 1/s), τ the shear stress (in Pa)

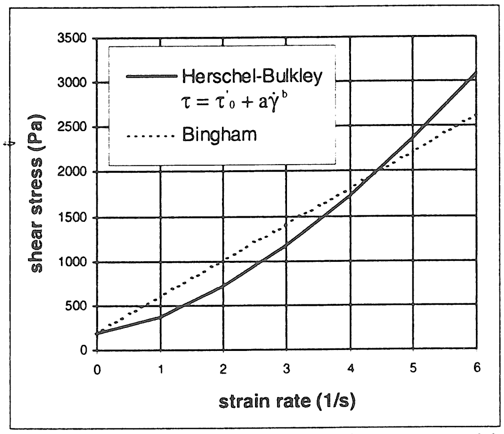

Fig1: Approximation of the rheological behavior of concrete with a Bingham model.

The shear yield stress τ_0' (in Pa) and the plastic viscosity μ' (in Pa s) are intrinsic properties of concrete and can be used in finite element calculations to predict any flow of the concrete [10]. In a recent study, Sedran [5] has confirmed that, for SCC, these two properties could be roughly estimated with the Abrams cone (fig. 2). In fact, the slump flow given by the mean of two perpendicular diameters of the final spread can be connected to the shear yield stress with the following empirical equation:

$$\tau_0' = (808 - Sl)\frac{Mg}{11740} \text{ (mean error 95 Pa)} \qquad (2)$$

where Sl is the slump flow in mm, g the gravity acceleration and M the density in kg/m^3. Moreover, thanks to a dimensional analysis it has been shown that the time to reach a 500 mm diameter spread is related to the plastic viscosity by:

$$\mu' = \frac{Mg}{10000}(0.026Sl - 2.39)\, t_{500} \text{ (mean error 35 Pa.s)} \qquad (3)$$

where t_{500} is the spreading time in s.

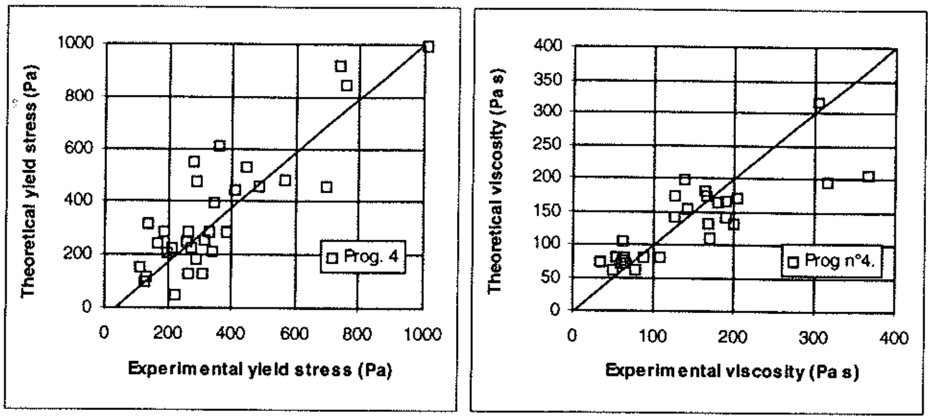

Fig.2: Prediction of rheological parameters with equ. 2 and 3 [5].

For practical purposes, a small value of the shear yield stress guarantees a good spreading ability of the concrete, while a small viscosity allows a rapid casting and facilitate the pumping of the concrete [6].

2.2. Filling ability

SCC are designed to flow through narrow spaces between reinforcements under their own weight. Various devices have been proposed in the literature to evaluate this filling ability: the U box [11], the box with pipes [12] or the V funnel [13], etc.... At LCPC, we have adapted the L box test described in [3] which presents the following advantages: it needs less than 12 liters of concrete, it is easy to carry out, the flow through reinforcements seems similar to that in real structure and blocking is easily visible.

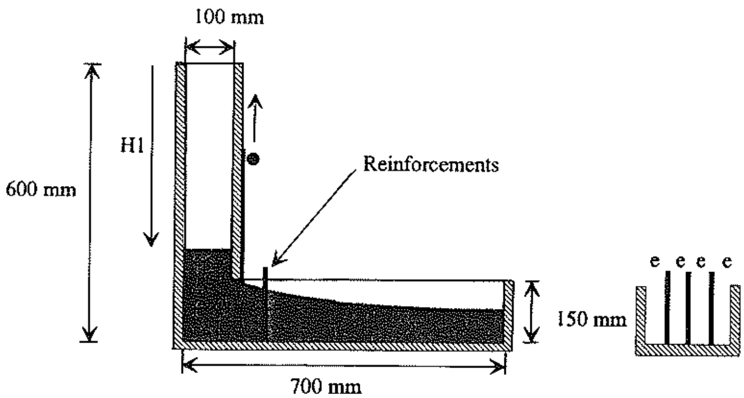

Fig.3: dimensions of L box used at LCPC

The apparatus is made of water resistant plywood and its dimensions are shown on the figure 3. The clear spaces between bars on one hand, and between a bar and a wall on the other hand, are the same. Because all bar diameters are equal to Ø14 mm, the width of the box must be adjusted when the clear space is changed. The concrete is filled in one shot in the vertical part of the L box thanks to a bucket and let at rest for one minute to include potential segregation of coarse aggregate. The gate is then open and we measure the height H_1 finally reached by the concrete. A high value of H_1 (maximum 510 mm) means a good filling ability.

2.3. Segregation of aggregates

Even if a concrete has a good filling ability, its coarse aggregates may segregate at rest. Yet, it is necessary that the concrete remains stable after casting and before hardening, to have homogeneous mechanical properties in the final structure. So, we had to select a specific test for that property. The segregation proneness of a concrete was then described by the mean sinking height of the two higher aggregates (with a diameter more than 8 mm) measured on a half Ø16x32 cm cylinder splitted in a splitting tensile test after hardening (fig. 4). The cylinder was cast without any rodding nor vibration.

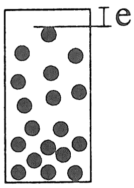

Fig. 4: measurement of the sinking depth (e) of coarse aggregate.

A first idea was to measure the thickness of the halo of mortar around the final spread in the slump flow test. But we observed in laboratory (fig. 5) that a homogeneous spread is not a sufficient condition to avoid segregation in cylinders. This was confirmed by observation in formworks on site.

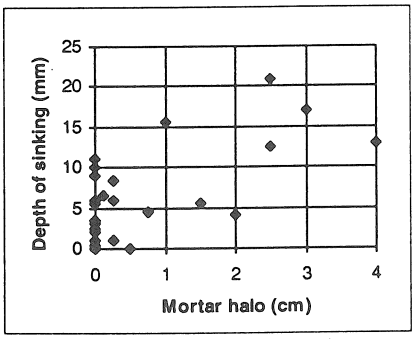

Fig. 5: strong segregation on Ø16x32 cm cylinder (depth>5 mm) may occur even if there is no mortar halo around the spread in the slump flow test.

3. The Compressible Packing Model (CPM)

The results of the tests made with the previous set of devices, were analyzed within the theoretical frame of a packing model developed at LCPC: the Compressible Packing

Model. This model is entirely described in [14] and [5] and is an evolution of the Solid Suspension Model already presented in [15] and [16]. The following sections summarize the main principles of this model.

Let consider a set of n monosized granular classes with a mean diameter of d_i where $d_1 \geq d_2 \geq ... \geq d_n$. A class is defined by two consecutive sieves in the standardized series ($d_{max}/d_{min} = \sqrt[10]{10}$ according to the French standard). The virtual packing density γ of any mix of these classes is given by

$$\gamma = \inf_i(\gamma_i) \tag{4}$$

where

$$\gamma = \gamma_i = \frac{\beta_i}{1 - \sum_{j=1}^{i-1} y_j \left(1 - \beta_i + b_{i,j}\beta_i\left(1 - \frac{1}{\beta_j}\right)\right) - \sum_{j=i+1}^{n} y_j\left(1 - a_{i,j}\frac{\beta_i}{\beta_j}\right)}$$

$$a_{i,j} = \sqrt{1 - \left(1 - d_j / d_i\right)^{1,02}}$$

$$b_{i,j} = 1 - \left(1 - d_i / d_j\right)^{1,5}$$

The virtual packing density is the maximum packing density attainable with the material considered with an infinite amount of compaction energy.
$a_{i,j}$ describes the loosening effect exerted by the class j on the class i (if $d_i \geq d_j$ which means $i \leq j$) and $b_{i,j}$ the wall effect exerted by the class j on the class i (if $d_j \geq d_i$ which means $j \leq i$). The y_i value is the volume content of class i (in proportion of the total volume of the dry skeleton). For concrete, these values are simply calculated from the proportions and the size distribution of each constituent (powders, sand, gravel). The β_i value represents the virtual packing density of the class i. These values are not measured for each class (which would be cumbersome!) but simply deducted from the packing density of each constituent. This packing density is measured on dry material for sand and gravel, and in presence of water and eventually of superplasticizer for powders (d_i<80 μm). The model can thus be applied very easily to concrete granular optimization.

A concrete can be considered as suspension of a solid skeleton (from fine powders to coarse gravel) in water. By analogy with some viscosity models, we have defined a compaction index K' which conventionally describes the degree of compaction of the suspension: the more dilute the suspension, the lower the compaction index. K' is given by:

$$K' = \sum_{i=1}^{n} K'_i = \sum_{i=1}^{n} \left(\frac{\frac{y_i}{\beta_i}}{\frac{1}{\Phi} - \frac{1}{\gamma_i}} \right) \tag{5}$$

where Φ is the solid content of the concrete (that is the complement to 1 of the water content). As shown in equation 5, the compaction index K' of the concrete is the sum of partial indexes K'_i which express the participation of the class i to the compaction of the suspension.

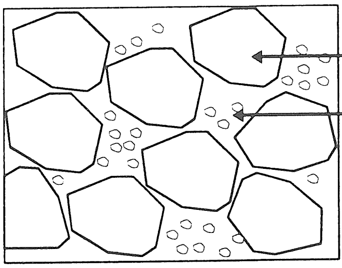

Fig. 6: A simplified representation of a concrete

This notion is more clearly explained on the figure 6, where the concrete is almost saturated with coarse aggregates (it is difficult to add one more in the given volume). So the coarse class heavily participates to the blocking and its partial index is high. On the contrary, it appears quite easy to add small aggregates and the partial index of the small class is low.

4. Predictive models for fresh concrete

4.1. Flow behavior

A review of the technical literature [14] has shown that the viscosity of a suspension should only be related to the ratio ϕ/ϕ^* where ϕ is the solid content and ϕ^* is the packing density of the skeleton. Within the scope of the CPM, ϕ^* has been defined by the solid content which gives a compaction index of 9 in equation 5. This approach applied to the results obtained in [5] gave the following relationship independent of the constituents nature and the superplasticizer content:

$$\mu' = \exp\left(45.88\left(\frac{\Phi}{\Phi^*} - 0.8512\right)\right) \quad \text{(mean error 46 Pa.s)} \qquad (6)$$

It should be noted that in another study, Ferraris and de Larrard [17] have found a slightly different equation but more research is needed to explain this difference.

$$\mu' = \exp\left(26.75\left(\frac{\Phi}{\Phi^*} - 0.7448\right)\right) \text{(mean error 61 Pa.s)} \qquad (7)$$

On the basis of the two same studies, the following model was proposed for the shear yield stress with a mean error around 100 Pa.

$$\tau'_0 = \exp\left(a_0 + \left(a + b\left(1 - \frac{Sp}{Sp^*}\right)^m\right)\sum_{powders} K'_i + \sum_{aggregates}\left(0{,}736 - 0{,}216\log(d_i)\right)K'_i\right) \qquad (8)$$

where a_0, a, b and m are positive constants depending on the nature of the superplasticizer, Sp the dosage of superplasticizer and Sp* the saturation amount of superplasticizer as defined in the AFREM method [18]. Powders are fines particles having a size less than 80 µm.

This equation was validated for Sp/Sp*≥0.5, on concrete containing pure Portland cements, different kind of aggregates and possibly fine sand particles and a calcareous filler. It describes three phenomena:

- the more a granular class i saturates the suspension, the more it participates to the shear yield stress (terms K'_i);
- concerning aggregates: for the same solid content, a small aggregate leads to more intergranular contacts than a coarser one due to its higher specific surface. Considering that these contacts increase the yield stress, it explains why the coefficients associated to K'_i decrease when the diameter increases. These coefficients appear to be independent of the nature of the aggregate;
- an increase of superplasticizer decreases the yield stress by two mecanisms:
    - the powders are deflocculated and their packing densitity is increased so K'_i is lessen;
    - the superplasticizer lubricates the powders (the multiplicative coefficient associated to K'_i is lessen).

4.2. Filling ability

Near a container boundary, the packing of a granular class with a mean diameter equals to d is loosen when the distance from the container is less than d/2. The CPM accounts for this effect by replacing β_i in equation 4 and 5 by:

$$\bar{\beta}_i = \left(1 - \frac{v}{V}\right)\beta_i + \frac{v}{V} k \beta_i \qquad (9)$$

where V is the volume of the container, v the volume of the disturbed zone (fig. 7) and k a constant fitted to 0.87 for rounded aggregate and 0.73 for crushed aggregate [14].

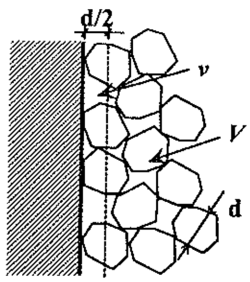

Fig. 7: Boundary wall effect

In the L box test, the effect of two bars, with a clear space equals to e, on the concrete blocking is supposed to be the same as two parallel plans separated by the same space. So the confining effect of the bars is included in the CPM through the following ratio

$$\frac{v}{V} = \frac{d_i}{e} \qquad (10)$$

Coarse gravel play a particular role in blocking because they tend to form arches when the concrete flows though reinforcement. If we group the granular classes four by four in clusters, we have a discontinuous representation of the granular skeleton of the concrete in which a cluster i-1 has a mean diameter 2.5 times ($10^{0.4}$) less than the cluster i. De Larrard has shown in [14] that, in this condition, all clusters smaller than a given cluster may percolate through it. Let consider now the concrete as a diphasic material containing on one hand the gravel with a diameter coarser than $d^{90}/2.5$ (d^{90} is the sieve diameter for which 90% of the skeleton is passing) and on the other hand a micro-concrete made of the finer classes. Blocking will occurs if the coarse gravel almost saturate the concrete whatever the nature of the micro-concrete which will tend to flow through it, by definition. As explained in §3, the saturation of the concrete by the coarse gravel can be expressed by the sum of the terms K'i for $d_i \geq d^{90}/2.5$. This sum called K'_{cg} is calculated while accounting for the confinement exerted by the bars in the L box thanks the equation 5. The figure 8 clearly shows (except for one point) that K'_{cg} is effectively a good index to evaluate the risk of blocking of a concrete. Below 1.4, the concrete will have a good filling ability (great values of H_l). This limit should be independent of the nature, size and shape of the aggregates because these properties are taken into account in the calculation of K'_i.

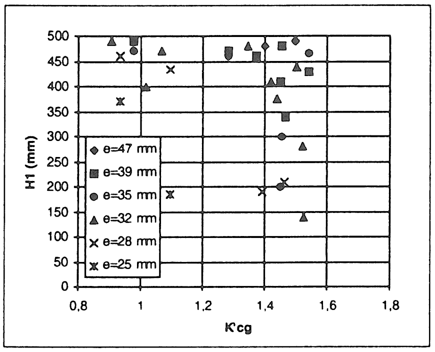

Fig. 8: relationship between H_l value and K'_{cg} for different concretes and several clear spaces (e) in the L box [5].

4.3. Segregation of aggregates

Let now consider the concrete as a diphasic material made of aggregate on one hand and a paste on the other hand. It is intuitive to think that the segregation of aggregates will be controlled by the viscosity of the paste and then, by the saturation of the concrete by the powders. So, on a first set of concretes, containing a pure Portland cement, crushed aggregate with fines particles in the sand and different amounts of superplasticizer, we have tried to connect the depth of segregation to the term K'_p, sum of the partial index K'i for di≤80µm. The figure 9 shows that there is a quite good linear relationship between these two values for a given dosage of superplasticizer. By fixing an acceptable upper limit to the segregation (e=5 mm for example), it is then possible to determine for each dosage of superplasticizer, the minimum acceptable value $K'_p{}^{min}$. These values appear to depend only on the superplasticizer nature.

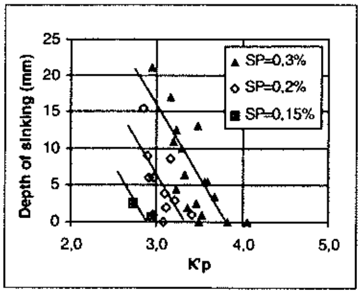

Fig. 9 Relationship between the depth of sinking and the K'_p term for different dosages of superplasticizer.

5. Mix design of-self compacting concrete

With a given set of constituents, it is then easy to write a rational and quantified set of requirements at the fresh state to produce a self compacting concrete, as shown in the table 1. All these requirements can be implemented in a software to optimize the mixes in terms of properties and economy. The required input data are the size distribution, the density, the packing density of the constituents and the saturation amount of superplasticizer which can easily be measured in laboratory. As we have seen previously, the constants a_0, a, b and m in the yield stress model and the $K'_p{}^{min}$ values depend on the superplasticizer nature. Nevertheless, these parameters can be rapidly calibrated by making a rheological test and a segregation test on some concretes (around 10) containing different amounts of this superplasticizer and water but with the same skeleton. Finally, the table 1 must be completed by requirements on hardened concrete, at least the compressive strength. For this latter property, we can used the modified Feret's law [14] which accounts for the binding effect of calcareous fillers and pozzolans.

Comment	Property	Equation
High flowability	$\tau'_0 \leq 400$ Pa	8
Good pumpability	$\mu' \leq 200$ Pa.s	6
Good filling ability	$K'_{cg} \leq 1.4$	5 & 10
No segregation	$K'_p \geq K'_p{}^{min}$	5 & 10

Table1: Set of requirements for a fresh SCC.

Numerical optimization gives a first theoretical recipe of SCC which must then be tested and adjusted if needed thanks to laboratory trials.

6. Conclusion

A set of general equations has been proposed to describe the rheology, the filling ability and the segregation proneness of fresh SCC without viscosity agent based on the

Compressible Packing Model. These equations provide a first rational mix design process to produce optimized self compacting concrete with good stability, low cost and limited shrinkage and creep risks, which are the necessary conditions for a sustainable development of this material. Nevertheless, although the models have been built on the basis of several tests, we have to validate them more widely for concretes containing different mineral admixtures (fly ashes, filler, slag ...). Moreover research is needed to clarify the influence of the nature of the superplasticizer on yield stress and segregation and to account for viscosity agents.

7. Acknowledgement

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8. References

[1] H. OKAMURA and K. OZAWA: "Mix design for Self-Compacting Concrete", Concrete Library of JSCE, No. 25, June, 1995.
[2] M. OUCHI, M. HIBINO and H. OKAMURA: "Effect of Superplasticizer on self Compactability of Fresh Concrete", Transportation Research Board, 76th Annual Meeting, Washington D.C., 12-16 January, 1997.
[3] O. PETERSSON, P. BILLBERG and B. K. VAN: "A Model for Self-Compacting Concrete", RILEM International Conference on Production Methods and Workability of Concrete, RILEM Proceedings 32, pp 483-492, Glasgow, Scotland, 3-5 June, 1996.
[4] S. TANGTERMSIRIKUL and B.K. VAN: "Blocking criteria for Aggregate Phase of Self-compacting High Performance Concrete", Proceedings of Regional Symposium on Infrastructures Development in Civil Engineering, SC-4, pp 58-69, 19-20, December, 1995.
[5] T. SEDRAN: "Rheologie et rhéométrie des bétons. Application aux bétons autonivelants. (Rheology and Rheometry of concrete. Application to SCC"), Doctoral Thesis of Ecole Nationale des Ponts et Chaussées, March 1999.
[6] F. DE LARRARD, C. HU, T. SEDRAN, J.C. SZITKAR, M. JOLY, F. CLAUX and F. DERKX: "A New Rheometer for Soft-to-Fluid Fresh Concrete", ACI Materials Journal, Vol. 94, No. 3, May/June, 1997.
[7] F. DE LARRARD, T. SEDRAN, C.HU, J.C. SZITKAR, M. JOLY, F. DERKX: "Evolution of the Workability of Superplasticized Concretes: assessment with BTRHEOM Rheometer", RILEM International Conference on Production Methods and Workability of Concrete, pp 377-388, Glasgow, Scotland, 3-5 June, 1996.

[8] C. HU, F. DE LARRARD, T. SEDRAN , C. BOULAY, F. BOSC and F. DEFLORENNE: "Validation of BTRHEOM, the new rheometer for soft-to fluid concrete", RILEM, Materials and Structures, Vol. 29, No. 192, pp 620-631, October, 1996.
[9] F. DE LARRARD,C. F. FERRARIS and T. SEDRAN: "Fresh Concrete: a Herschel-Bulkley Material", Technical note, Materials and Structures, Vol. 31, pp494-498, August-September, 1998.
[10] Y TANIGAWA and H. MORI: "Analyticial Study on Deformation of Fresh Concrete", Journal of Engineering Mechanics, Vol. 115, No 103, pp 493-508, March, 1989.
[11] M. HAYAKAWA, Y. MATSUOKA and T. SHINDOH: "Development and Application of Super Workable Concrete", RILEM Proceeding 24. Special Concretes: Workability and Mixing, pp 183-190, 1994.
[12] M. YURUGI, N. SAKATA, M. IWAI and G. SAKAI: "Mix Proportion for Highly Workable Concrete", Conference Concrete 2000, Dundee, 7-9 September, 1993.
[13] K. OZAWA, N. SAKATA and H. OKAMURA: "Evaluation of Self Compactibility of Fresh Concrete using the Funnel Test", Concrete Library of JSCE, n°25, June, 1995.
[14] F. de LARRARD: "Concrete Mixture-Proportioning: a scientific approach Modern Concrete Technology series No. 9, A. Bentur and S. Mindness editors, E & FN SPON, 1999.
[15] T. SEDRAN and F. DE LARRARD: "René-LCPC: a Software to Optimize the Mix Design of High Performance Concrete", BHP 96, Fourth International Symposium on the Utilization of High Strength/High Performance Concrete, Vol.2, pp 169-178, Paris, 29-31may, 1996.
[16] F. DE LARRARD, C. HU and T. SEDRAN: "Best Packing and Specified Rheology: Two Key Concepts in High-Performance Concrete Mix-Design", Adam Neville Symposium, Advances in Concrete Technology, Las Vegas, June, 1995.
[17] C. F. FERRARIS and F. DE LARRARD: "Testing and Modeling of Fresh Concrete Rheology", NIST Report NISTIR 6094, Gaithersburg, Maryland 20899, February, 1998.
[18] F. de LARRARD, F. BOSC, C. CATHERINE and F de FLORENNE: "The AFREM Method for the Mix Design of HPC", Materials and Structures Vol. 30, No 201, pp 439-446, August- September, 1997.