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High strength self-compacting concrete
Original solutions associating organic and inorganic admixtures

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Abstract

Self-compacting concrete (SCC) is today a pretty well-known technology. It has been established by several authors, on the basis of numerous engineering achievements, that the main benefit that can be expected from this kind of material is the high speed of casting. Furthermore, the concrete's transportation and placing down are greatly facilitated by the use of pumps; the extreme fluidity allows the realization of complex pieces and enables the access to difficult casting zones, which leads to an improvement of the structure's durability. However, the concrete's formulation remains difficult and sensitive; still too often, in their first approach, some formulators simply increase the water-to-cement ratio or only adjust the dosage of superplasticizer, which generates some poor-quality concrete. In this paper, we present a new method based on the use of two admixtures : a nanometric, amorphous, silica SiO_2 (for its reactivity with the cement paste), combined with a specific polysaccharide (for its suspending ability), both of them used under a liquid form. We show that one can formulate, at a reasonable cost, a highly fluid concrete, without bleeding or segregation. The setting kinetic is improved, which allows the reduction of the demoulding time; the surface of the hardened concrete is smooth and homogeneous; and the final strengths values achieved are in line with those attained with high strength concrete.

Keywords: Concrete; High performance concrete; Workability; Silica fume; Bleeding

Thanks to gradual improvements in concrete mix design, materials quality control, and the mechanization of mixing and placing techniques, plain concrete structures have displayed steady esthetic and durability gains over recent years. Concrete mix design, however, remains a sensitive issue: still too often, the suboptimal rheology of a high strength mix makes its casting difficult. Ill-mastered use of vibration systems (e.g., vibrating needles and forms) can generate various disorders, such as poor coating of rebars, segregation, bleeding, voids, and gravel clusters.

Highly flowable mix designs have been introduced for some years now. They allow for substantial savings in terms of labor and concrete placing time, doing away with vibrating operations, reduced work hardship and noise, a decrease in the number of heavy handling equipment (cranes, etc.) on the job site, easier concreting in hardly accessible areas, and an improved aspect of finished parts.

But users of such high performance concrete (which was successfully implemented, for instance, on the Arche de la Défense job site, in Paris, with concrete being pumped to the top of the building, and on the Montparnasse Tower job site, where concrete was pumped over 200 m) have sometimes gone through disillusions. Simply increasing water or superplasticizer proportions falls short of being effective; such a crude approach usually leads to a level of bleeding detrimental to the esthetics of the work, as well as substantial segregation (with its typical effects on surface aspect, strength and durability); an overly late set (with its characteristic effects on concrete drying shrinkage/cracking and on forms immobilization with the related slow down of works in process, etc.); and a strength loss.

Some new rheology control admixtures, such as modern superplasticizers, allow for definite performance improvements: The user can combine high flowability and reduced water proportions, which helps increasing strength. However, the use of those admixtures alone does not provide an effective solution to all of the above-mentioned issues. Most of the high water-reducing agents available (polynaphthalenes, carboxylates, sulfonates, and their derivatives) generate significant set delays, which are detrimental to early strength and therefore induce demoulding delays. Moreover, even a slight variation in the water/cement ratio will

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produce bleeding. In a concrete plant, even a limited failure in the aggregate humidity measurement system will typically generate a 10–20 L excess dose of water per m^3 of concrete, which is enough to cause the above-mentioned disorders. Therefore, some authors have recommended the use of polysaccharide (modified sugar) type water retention agents (high molecular weight, water-soluble organic polymers), but this generally results into various drawbacks:

- The powder-form presentation of such products makes them difficult to dose (at generally very low rates) and disperse into the concrete mix.
- The preparation of a mother solution can be contemplated only in as far as the solution is used within a period of time short enough to eliminate risks of bacterial attacks (knowing that temperature rises substantially increases that risk).
- Despite the use of such products, concrete performance remains fairly sensitive to variations in water proportions, especially in case of poor granular design.
- Some of the cellulose derivatives (normally used with melamine-based water reducers) have shown incompatibilities with special types of naphthalene-based high range water reducers [1]. They may lead to an abnormal increase in viscosity when added with a poly-alkylaryl sulfonate water-reducer admixture in aqueous solution [2].

An innovative solution is presented here. It is based upon two key concepts:

- Enriching the granular skeleton of the mix with ultrafine elements (fillers < 80 μm) by using a precipitated silica slurry [totally amorphous nanometric SiO_2 (see Fig. 1; this aims at improving granular capacity (see Fig. 5), therefore improving materials capacity.
- Keeping aggregates well suspended (Figs. 4 and 5), by using a liquid-form polysaccharide (the organic compound is predispersed in vegetal oil, which ensures its conservation and allows for a faster swelling); this is meant to provide the concrete mix with thixotropic properties.

One can observe that, compared with silica fume (Fig. 2), precipitated silica displays an extreme fineness and is

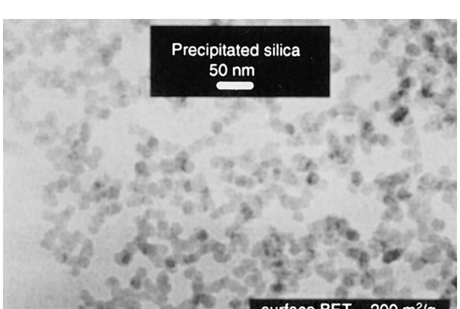

Fig. 1. View of the precipitated silica.

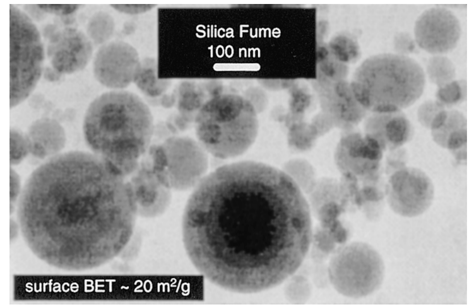

Fig. 2. View of silica fume.

free of organic compounds (unburned coal fines, etc.) and of any other, more or less crystallized, inorganic impurities (quartz grains). Those reasons account for its being fully reactive.

1. Materials

The polysaccharide we used was of the polysuccinoglycane type (see Fig. 3). Issued from the industrial biotechnology, it is characterized by a high molecular mass (6,000,000) and a remarkable stability in various conditions. Fast hydration in high pH media (with a good stability in a wide range of salts concentration) and highly pseudoplastic behavior (Fig. 4) are two of this polysaccharide's remarkable properties. Furthermore, it is effective at very low dose rates (0.1–0.3% of the hydrocolloids suspension, by cement mass).

The use of the hydrocolloid's suspension has no purpose other than keeping aggregates suspended because its structure, in the shape of dispersed, substantial size "needles," actually accounts for limited water-retention capabilities. Therefore its only critical function in the system is to generate the desired mechanical effects (suspending ability).

On the basis of those two admixtures, we performed both the in-lab study then the on-site testing of a high strength self-compacting concrete (with characteristic strength between 60 and 100 MPa) mix design. The imposed specifications included the following rheological and mechanical characteristics:

- homogeneous concrete mix, without bleeding nor segregation

(GLU-GLU-GALAC-GLU)
GLU-GLU (Succinic acid *)
GLU (Pyruvic acid **)

Fig. 3. Molecular structure of the polysaccharide used. GLU: glucose; GAL: galactose. * CH_2COOH_2. ** CH_3COCO_2H. Hydrocolloid suspension in vegetal oil (active ingredient content = 5%); $\rho \sim 0.9$; suspension viscosity <500 mPa.s at 20°C.

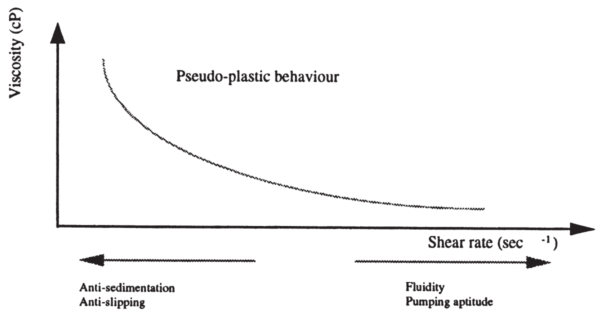

Fig. 4. Rheological behavior under shear of the special polysaccharide used for its suspending ability.

- Abrams cone-measured slump equal or superior to 18 cm after an hour
- flow slump of at least 600 mm after an hour
- concrete pumpability; placing done without any vibration
- demoulding ability within 16 to 20 hours (minimum strength required: 5 MPa)
- 28-day strength required: 60 MPa

Once the laboratory tests were finalized, an on-site trial was performed (Crozet Viaduct at Vif, on the A51 freeway between Grenoble and Sisteron, in the French Alps). It consisted in casting an experimental 11 m^3 thrust block (heavily steel reinforced), subdivided into two compartments: the first one, with a volume of 6 m^3, was dedicated to the concrete's mix design described in this study; the second one was dedicated to the testing of a rival self-compacting mix design.

Based on 1 m^3 of concrete, the mix design under study included 400-kg ordinary portland cement (CEM I 52.5, sulphate-resistant) and some 30-kg densified silica fume (Condensil). The granular skeleton used a mix of rolled aggregates: 0/5-mm sand, 5/12-mm gravel, and 12/20-mm gravel. The gravel/sand ratio was 1.35 (it is well known that the internal friction coefficient, which influences fresh concrete workability and therefore its self-compacting ability, rises with the proportion of large aggregates, especially in the case of crushed gravel): relatively low gravel/sand ratios are recommended if self-compaction is desired. A commercial superplasticizer was used at a 2.75% by weight of binder (ordinary portland cement + silica fume) dose rate. In addition, a set retarder was incorporated at a 0.2% (by weight of binder) dose rate to ensure enough rheology control at a temperature ranging between 23 and 28°C. The precipitated silica slurry was dosed at 2% by weight of cement. As for the hydrocolloid under liquid presentation, it was incorporated at a 0.15% dose rate (by weight of cement). The hydration water volume was 172 L for 1 m^3 of concrete, which corresponds to a water/binder (binder is cement and silica fume) ratio of 0.40 and to a water/cement ratio of 0.43.

Given the fact that maximal dimension of aggregates is 20 mm (standard concrete), the proportion of fine elements (<0,15 mm, including cement) is effectively in line with the recommendations of the International Concrete Committee (400–500 kg/m^3). It is actually necessary to incorporate enough fine and ultra-fine elements between the sand grains and the gravels, which must have a rounded shape, in order to facilitate self-compaction so as to ensure better compaction and to decrease the volume of voids (the same volume would otherwise be occupied by water during the concrete plastic phase, thus generating risks of bleeding, sedimentation, and plastic shrinkage, as well as a strength decrease). It is obvious that in order to improve capacity, the primary solution consists in filling the voids existing in a stack of similar-size grains with grains of smaller size (see Fig. 5). According to Caquot, cited by Guyon and Troadec [3], if one uses a grain diameter ranging from a smallest value d_1 to a largest d_2, the porosity is in the order of

$$\sqrt[5]{\left(\frac{d_1}{d_2}\right)}$$

To increase concrete mechanical strength properties, one has to reduce porosity. To that purpose, a diversity of grain size can be used, the granulometrics of which ranges from 1 cm for the largest gravels down to a few micrometers for the very fine-powder additions (silica fine particles). That way, one can reduce to a few percent only the fraction of volume occupied by voids [3].

Here, the amorphous precipitated silica slurry performs two key functions:

1. Its fineness ($d_{90} < 12$ μm) allows for substantial enriching in fine particles, even while using low-dose rates of the product. Hence, the user can design mixes with relatively low cement contents, which proves beneficial not only in economic terms but also from a technical standpoint, due to the heat of hydration being reduced, with positive impact on shrinkage and cracking limitation.
2. Due to their amorphous nature, the nanometric SiO_2 particles perform the function of nucleation sites for hydrates such as calcium silicate hydrates (C-S-H).

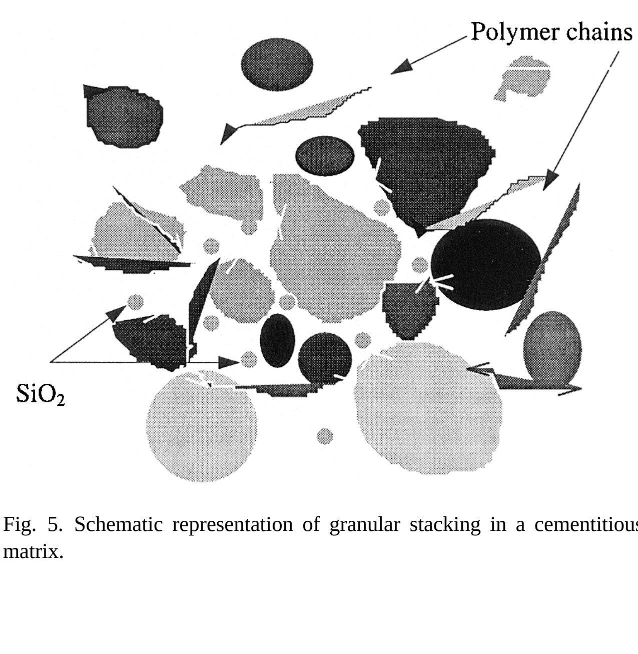

Fig. 5. Schematic representation of granular stacking in a cementitious matrix.

This accounts for the creation of an additional quantity of the crystallites that initiate the setting process. That phenomenon partially offsets the delay caused by the superplasticizer, therefore speeding up early strength acquisition and shortening demoulding time.

Furthermore, again due to its amorphous nature, precipitated silica (SiO_2) reacts with portlandite [$Ca(OH)_2$] through the mechanism described in Eq. (1):

$$SiO_2 + Ca(OH)_2 \rightarrow CSH \quad (1)$$

Effectively, during its hydration [4], cement will progressively release calcium hydroxide $Ca(OH)_2$, as shown in Eq. (2):

$$3CaO \cdot SiO_2 + water \rightarrow Ca(OH)_2 + xCaO \cdot ySiO_2 \cdot aq \quad (2)$$

that are more generally expressed as shown in Eq. (3):

$$C_3S + (2.5 + n)H \rightarrow C_{1.5+m}SH_{1+m+n} + (1.5 - m)CH \quad (3)$$

C_2S hydration also leads to the release of lime [$Ca(OH)_2$], according to Eq. (4):

$$2(2CaO \cdot SiO_2) + 4H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2 \quad (4)$$

that is, Eq. (5):

$$C_2S + (1.5 + n)H \rightarrow C_{1.5+m}SH_{1+m+n} + (0.5 - m)CH \quad (5)$$

This lime will progressively combine with amorphous silica; this will take place all the more rapidly as precipitated silica's large specific surface area (~160–200 m^2/g) accounts for high reaction kinetics. As a result, the formation of Taylor type C-S-H_I is increased; hence the contribution to early mechanical strength development.

As for the hydrocolloid, its incorporation ensures aggregates suspendability, even in the case of a relatively low fine-particle proportion: It makes up for the deficit in ultrafine particles via a slight viscosation of the mix. One knows the viscosity of an inorganic particle suspension initially grows linearly with the volumic concentration. When the concentration is such that all rigid particles are in contact with one another and cluttering becomes too high for the grains to be able to move away from one another, the system gets locked; viscosity has become infinite [3]. One therefore realizes that solutions such as those consisting in only adding fillers such as fly ash have their limitations, due to the fact that a deficit will generate bleeding and an excess will result into a viscosity level detrimental to the flowability. The combined use of the silica slurry and of the hydrocolloid therefore brings a response to this twofold, apparently antinomic, requirements: achieving a compact enough stacking while allowing relative moving of the grains.

Finally, concerning the incorporation of silica fume (Condensil) into the mix, the main purpose is durability (i.e., taking advantage of its pozzolanic properties). Whereas optimal proportion from the standpoint of mechanical strength contribution ranges from 20–25%, we chose a dose rate of: SF/(C + SF) ~ 7%.

It has been established [5] that incorporating 5% of silica fume into a concrete mix in which the superplasticizer dose rate is kept constant does not cause any increase in the water demand; the water/cement ratio remains stable for silica fume proportions between 5 and 20%, with a cost-effectiveness optimum around 10% [6]. Typically, one must seek a trade-off between the minimum water proportion required to achieve binders full hydration and the higher proportion required to maximize flowability: water/cement ratios below 0.42 never allow cement pastes full hydration; only above this 0.42 threshold can total hydration be achieved [7]. We therefore chose a water/cement ratio slightly above that limit in order to promote strength development over an extended period of time. The water volume indicated above (172 L) does, of course, take into account the water carried by the aggregates (measured in situ via the frying pan method, the water content of the aggregates is: $\omega_S = 5.2\%$, $\omega_{Gv} = 2.0\%$, $\omega_{Gr} = 0.4\%$) and by the silica slurry (20% dry matter).

Flowability was checked through flow slump tests, using an Abrams cone (as defined by French Standard NF P. 18-451; $\phi = 100$, $\Phi = 200$, h = 300 mm), on a polished support, and under 23°C temperature conditions. Flow slump at t_0 (time of departure from the concrete plant) was 615 mm (with standard slump $\delta > 250$ mm). The concrete mix had a nice greasy aspect and was fully homogeneous, without any bleeding or segregation. Flow slump after 1 h under a temperature of some 25°C and direct sun exposure was 670 mm (see Fig. 6), with a standard slump δ still above 250 mm (after a concrete mix transportation time of around 45 min).

The concrete mix placing was performed without any vibration, using a 120-m^3/h throughput pump and a hose, which had initially been descended at the bottom of the framework (see Fig. 7), then was lifted up progressively as concreting progressed. Fill-up time of the entire mould was less than 4 min. Perfect coating of the rebars could be observed.

Standardized ($\phi = 16$ cm and h = 32 cm [bounding $\lambda = 2$]) cylindrical probes were completed in order to measure concrete strength at age 18 and 24 h, then at age 2, 7, 28, and 90 days (mechanical tests being performed by C.E.B.T.P., Centre d'Études et d'Essais de Grenoble, France). Results up to the age of 28 days are plotted on Fig. 8.

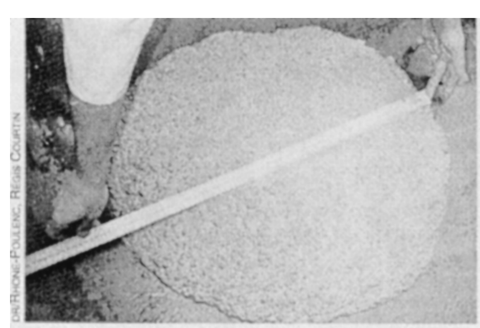

Fig. 6. Aspect of the flowable mix at time t_{60}.

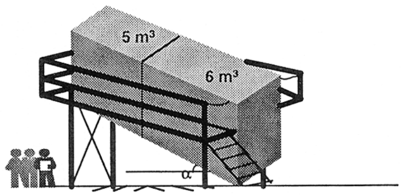

Fig. 7. Experimental thrust block.

Density values ($\rho_s = 2.43$) are in line with values one can expect from a high strength type concrete. We could furthermore observe during mechanical stress loading that cracking then rupture ran through the core of the aggregates as opposed to taking place at the interface between the cement paste and the aggregates; no baring of the grains occurred.

The measured mechanical performance thus effectively corresponds to that of a high strength type concrete. By plotting the compressive strength values on a logarithmic time scale (Fig. 8), one can then derive the following simple linear relationship (correlation coefficient equal to 0.993): $\sigma_{cs}{}^{d} = 17.5 + 33.2 \log_{10} d$, for $d \geqslant 0.3$ day, and for the time interval considered with $\sigma_{cs}{}^{d}$ = breaking constraint (MPa) at an age of d days and d = age (in days) at which measurement takes place.

Extrapolating those first measurements up to age 60 days, one could expect a compressive strength of some 75 MPa, which lab measurements actually confirmed (median value: 74.7 MPa; minimum value: 71.5 MPa; maximum value: 77.9 MPa).

2. Early demoulding ability

Demoulding was performed after 18 h, in line with the (short demoulding time) specification. At that age, compressive strength obtained was around 18 MPa. According to Venuat [8], a strength of some 5 MPa is required to demould, store, or transport relatively small parts. 15 MPa are supposed to be required for handling large concrete elements. According to the same author, a 3-MPa strength sometimes is enough.

If we consider that a minimal strength of 5 MPa is required to start demoulding then [using Eq. (1)] a lag time of some 10 h would be needed, or some 12 h if we use a calculation based on a higher safety coefficient. As an indication, the mix design used in the comparative test required a 48-h demoulding time.

As one can observe on Fig. 9, the hardened concrete obtained in this trial displays a smooth and homogeneous aspect. The whiteness of precipitated silica accounts for its lighter color, such color lightening being a function of the silica slurry addition rate.

3. Conclusion

This trial has confirmed the feasibility of high strength concrete mix designs combining a relatively high, compared to usually recommended values, water/cement ratio (0.43 to 0.45) with a material flowability that allows pumping into place (even in highly steel-reinforced parts), without any vibration (thus permitting better surface aspect), while ensuring perfect rebar coating. In spite of concrete's high initial flow, demoulding time shows no increase over conventional mix designs. And, upon demoulding, excellent surface aspect is obtained.

The use of admixtures such as precipitated nanometric silica, when combined with most current commercial superplasticizers, provide excellent rheology control (ability to adjust both flowability and workability life), while avoiding both the bleeding and the segregation that the use of superplasticizers alone would normally generate. Demoulding time, in the case of the mix design studied, can be made as short as some 10 h. It is worth noting that equivalent (and even superior) lab results were obtained with the silica slurry alone (dosed at 5% per cement weight $\rightarrow$ some 74 MPa at 28 days, 85 MPa at 60 days), as well as with a combination of 2% silica slurry plus 0.15% hydrocolloid (66 MPa at 28 days, 75 MPa at 60 days). This confirms that within the limits of final extra cost allowed, the above method definitely provides excellent control over final concrete performance.

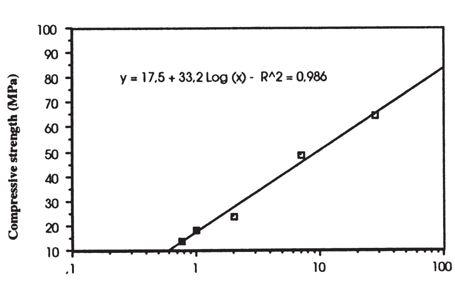

Fig. 8. Mechanical strength development over time of the self-compacting HSC designed.

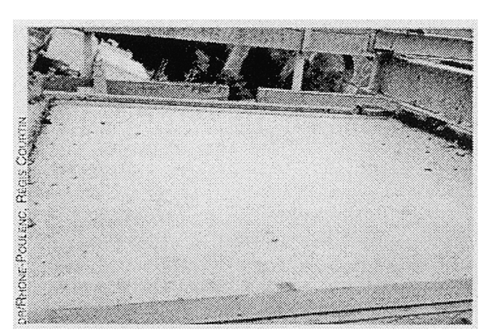

Fig. 9. Upper part surface aspect of the thrust block after 18 h demoulding time.

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