

A Very Close Precursor of Self-Compacting Concrete (SCC)

By Mario Collepardi

Abstract: The paper summarizes the results on flowing and unsegregable superplasticized mixtures studied and placed in the 1970's and 1980's with properties very close to those of Self-Compacting Concretes (*SCCs*) presently considered to be the most advanced cementitious material.

Case histories (from Hong Kong, New York, and Trieste, Italy) concerning placing of superplasticized self-levelling concretes without any vibration at all, published in the 1980's, are re-examined to compare them with the present *SCCs*

In particular, the paper deals with the ingredients of these mixtures (superplasticizer, cement, fly ash, ground limestone, silica fume, etc) by examining their specific role played in determining the main properties of these concretes such as fluidity, on one hand, and resistance to segregation, on the other.

Keywords: Bleeding, Fly Ash, Rheoplastic Concrete, Segregation, Self-Compacting Concrete, Self-Levelling Concrete, Superplasticizer.

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1. INTRODUCTION

The term *Self-Compacting Concrete (SCC)* refers to a “new” special type of concrete mixture, characterized by high resistance to segregation, that can be cast without compaction or vibration. According to the opinion of the author of the present paper such a concrete – or a sort of its very close precursor – was studied and used in practice 20-25 years ago.

Data available in the international literature indicate that self-levelling and unsegregable concretes were firstly studied on 1975-1976 [1, 2]. At that time the maximum slump level admitted by ACI was 175 mm [3]. Moreover, case histories concerning placing of self-levelling concretes **without any vibration at all** were published in the 1980's [4-8].

The present paper summarizes the main progressive advances in the concrete technology from the middle of 1970's, after the advent of superplasticizers, until the end of 1990's when the term *SCC* was coined. During this period of time, other concrete ingredients, beside superplasticizers, were found to play an important role in determining or improving the rheological properties needed for *SCCs*. In the following sections of the present paper these ingredients will be examined along with their effect on the properties of these concretes.

2. THE ROLE OF SUPERPLASTICIZERS AND POWDER MATERIALS

Figure 1 shows the bleeding capacity as a function of the slump level for three different concretes with a cement factor of 300-350-400 kg/m³ in the absence of superplasticizer [2]. When the slump is over 175 mm the bleeding increases too much and this was the reason why ACI in 1973 did not recommend slump higher than 175 mm [3].

With the advent of superplasticizers, flowing concretes with slump level up to 250 mm were manufactured with no or negligible bleeding (Fig. 2), provided that an adequate cement factor was used [2]. In the middle of 1970's, it was suggested [1, 2] to define *rheoplastic* a concrete which, besides being very flowable, is also very cohesive and therefore has a low tendency to segregation and bleeding.

The most important basic principle for flowing and unsegregable concretes including SCCs is the use of superplasticizer combined with a relatively high content of powder materials in terms of portland cement, mineral additions, ground filler and/or very fine sand. A partial replacement of portland cement by fly ash was soon realized to be the best compromise in terms of rheological properties, resistance to segregation, strength level, and crack-freedom, particularly in mass concrete structures exposed to restrained thermal stresses produced by cement heat hydration [6-7].

Table 1 shows the composition of two typical concrete mixtures which were used to place self-compacting and unsegregable concretes at the end of 1970's and at the beginning of 1980's. Special attention was used in selecting coarse aggregate with maximum size smaller than 20 mm (preferably smaller than 15 mm), in order to enhance the mobility of all the concrete ingredients without any significant segregation effect.

Mixture **A** in Table 1 corresponds to the composition adopted for 40000 m³ of concrete placed under water (Fig. 3-5) by using the Tremie method for the construction of a dry dock at the end of 1970 [4, 5]. Mixture **B** with fly ash (Table 1) corresponds to the composition typically adopted for massive structures such as reinforced foundations for skyscrapers [6,7] or very high chimney at the end of 1970 (Fig. 6-9).

The following two statements quoted from reference [8] indicate that the precursor of the SSC at the beginning of 1980 was already available not only for laboratory studies but even for practical and important applications. The first statement refers to a work described in references [4,5]: *“The placement of the foundation slab for the construction of the dry dock, where 40000 m³ of rheoplastic concrete were poured under water, exploited the **self-levelling** underwater placement **without vibration**, on one side, and the **great cohesion** of the mix to minimize the washing away by sea water, on the other”*.

The second statement refers to a mass concrete for foundation slabs: *“For the contractor the rapid placement of concrete allows **economies** to be realized during the execution of the work. Obviously the saving due to the employment of **less manpower and less time of execution**, must be higher than the cost of the addition of superplasticizer. This usually occurs in most reinforced concrete works and is more and more advantageous the more intricate the reinforcement and the more complicate the shape of the structure are “*.

There is an other interesting statement of the engineers involved in the placement of concrete (190 m³/hr with maximum of 350 m³/hr) for the Hong Kong slab foundation in 1983-84 [7]: *“It was decided to use poker vibrators initially, to ensure the concrete was adequately compacted under and round the bottom mat of reinforcement. At the end it was considered unnecessary to continue vibrating the concrete, as the superplasticizer produced a ‘flowing concrete’ which was **self-compacting**. The self-compacting property of the concrete was shown by the apparently large volume of water displaced during*

the pour which finally had to be pumped away to allow surface finishing-off to proceed”.

The above sentences seem to be quoted from a present paper on SCC rather than on its precursor of least 20 years before.

Table 2 shows some interesting results on the degree of compaction, in terms of density, and compressive strength of the concrete used for a 4.7 m thick slab in the Tin Hau Station of the Mass Transit Railway Island Line of Honk Kong [7]. There is no difference in the density of the specimens and that of the cores taken from 0.5 m, 1 m and 3 m below the surface of the **reinforced slab foundation placed without any vibration at all**. Moreover, the range as percentage of the average strength is a little higher for the specimens at 28 days (7.1%) than for cores taken at 96 days from the slab foundation (6.2%). This indicates that, even in the absence of vibration, the concrete of the structure was as reliable as that of the specimens.

3. THE ROLE OF SILICA FUME

Silica fume or *microsilica* (very fine amorphous silica particles < 1 μm) was studied as concrete mineral admixture in the early 1950's at the Norwegian Institute of Technology [9]. However, only in the mid 1970's, after the advent of superplasticizers, silica fume both in practice and in laboratory started in several Scandinavian countries: Norway, Sweden, Denmark and Iceland. After then, research work and practical use of silica fume in concrete started in many countries outside Europe.

Silica fume and superplasticizer are complementary materials to manufacture self-levelling concretes with great cohesion of the fresh mix. Their combined action can be illustrated through the rheological behaviour of cement mixes.

Cement mixes behave as plastic fluids according to the Bingham equation:

$$\tau = f + \eta D$$

where τ is the shear stress, D is the shear rate, f is the yield stress, i.e. the threshold value over which the material acts as a liquid, and η is the plastic viscosity which is lower the higher is the slopeness of the $D - \tau$ curve (Fig. 10).

Figure 11 shows some $D - \tau$ curves recorded in 1988 [10] through rheological measurements by using co-axial cylinders with cement paste between them. For each test two curves can be recorded: the up-going curve with growing shear rate from zero to the maximum value of 200 s^{-1} , and the down-going curve with shear rate decreasing from 200 s^{-1} to zero. For a cement paste with w/c of 0.38, the yield stress (f) is about 40 Pa without any significant difference between the up-going and down-going curves (Fig. 11.A). The addition of superplasticizer (Fig. 11.B) at the same w/c strongly reduces the f value, with a small decrease in the plastic viscosity (η) and a small increase in

the loop area between the two curves. The yield stress in the plain cement paste and its disappearance in the superplasticized mix are related to the agglomerated and dispersed cement grains, respectively (Fig. 12).

The addition of 10% silica fume (Fig. 11.C) strongly increases both the hysteresis loop and the f value up to about 300 Pa. This behaviour is related to weak chemical bonds among silica fume grains. These bonds can be broken only with a relatively high yield stress. Then, the cement paste moves and becomes much more fluid, and a lower shear stress (τ) is needed to increase the shear rate (D). In the down-going curve the plastic viscosity (η) is similar to that of the plain cement paste (Fig. 11.A).

With a combined addition of superplasticizer and silica fume (Fig. 11.D), the f decreases to about 60 Pa for the dispersion of cement and silica fume particles. The plastic viscosity (η) in the up-going curve strongly decreases by increasing the shear stress. This seems to be the best cement paste for a concrete which must be very cohesive and unsegregable when it is stationary, and very fluid when it moves. The down-going curve in Fig. 11.D is very close to a Newtonian fluid (Fig. 10) without yield stress:

$$\tau = \eta D$$

Due to this special behaviour, silica fume in the presence of superplasticizer can compensate the absence of fine materials such as fly ash or ground limestone in relatively lean cement mixtures (about 300 kg/m³).

4. THE ROLE OF VISCOSITY MODIFYING ADMIXTURES

The use of *Viscosity Modifying Admixtures (VMA)* is definitely the most innovative material for the present self-compacting concretes with respect to those manufactured in the 1970's and 1980's [11]. These admixtures (0.1-0.2% by weight of powder) allow to manufacture self-compacting concrete with a reduced volume of fine materials.

There are two basic types of *VMA*:

- Traditional pumping aids, admixtures used to improve the cohesiveness of lean concrete mixtures to be pumped, and chemically based on modified cellulose or hydrolized starches.
- Poliethilen-glycol and biopolymers [12] which appear to be the most effective *VMAs* for self-compacting concretes.

Figure 13 shows the molecular structure of the biopolymer *welan gum*.

Due to its molecular composition (Fig. 13) hydrogen-bonds are present between two glucosidic rings belonging to polymer chains. This produces a significant different increase in the viscosity of the aqueous phase. Moreover, since these polymers can be adsorbed on the surface of cement particles, they

produce a long-range bridging effect throughout the cement paste involving the aqueous phase and many cement grains. This can explain the strong increase in the yield stress (f) of the cement paste and the subsequent cohesiveness of the concrete mixture at rest or under a moderate shear stress. However, when a shear stress (τ) much higher than f is applied, the hydrogen bonds between the different polymer chains are broken and the biopolymers align in the direction of the movement without any adverse effect on the fluidity of the concrete mixture.

5. OTHER RECENT ADVANCES FOR SCC

Due to the progress in the last 30 years, concrete can be considered to be one of the most innovative building materials. Even for the SCC technology there are promising advances related to new available ingredients.

Two of these will be shortly discussed in this section of the present paper.

5.1 Acrylic polymers

During the last three decades the main ingredients in the superplasticizers were synthetic water-soluble polymers such as sulfonated melamine formaldehyde (SMF) condensate, sulfonated naphthalene formaldehyde (SNF) condensate, and modified sugar-free lignosulfonate (MLS). Advances in superplasticizers, containing alternative water soluble synthetic products, have been proposed in the last decade [13] to reduce the slump-loss drawback which can partly or completely cancel the initial technical advantage associated with the use of superplasticizers (low w/c ratio or high slump level). More recently, these new superplasticizers - all based on the family of acrylic polymers (AP) - have been deeply investigated, and numerous papers on these admixtures were presented at the Fifth CANMET-ACI International Conference on "Superplasticizers and Other Chemical Admixtures", in Rome (Italy), 1997.

Figure 14 shows the chemical structure of the most important sulfonated (SNF, SMF, AS, LS) and acrylic polymers (CAE, PC, CLAP) used as active ingredients of superplasticizing admixtures.

Besides a lower slump loss, AP-based superplasticizers perform better than the traditional sulfonated polymers even in terms of either higher reduction in the w/c at a given workability or higher slump level at a given mixture composition.

Superplasticizers cause dispersion into smaller cement particles of coarse agglomerates which predominate in the cement paste of the concrete mix (Fig. 12). Due to the dispersion effect, there is a fluidity increase in the cement mixture. In the past time the dispersion effect was ascribed only to the development of the same electrostatic (negative) charge on the cement particles [14]. The electrostatic attractive forces, existing among cement particles and causing agglomeration, would be neutralized by the adsorption of anionic

polymers negatively charged, such as SNF or SMF, for the presence of SO_3^- groups on the surface of cement particles. The dispersion of cement particles (Fig. 12) would be related with the electrical repulsion (Fig. 15) produced by the adsorption of negatively charged groups (SO_3^-) and determined through zeta potential measurements.

Additional available experimental results did not confirm this mechanism for the superplasticizing action of the acrylic polymers [15-17]. These results would indicate that the dispersion of cement particles, responsible for the fluidity increase caused by superplasticizer, is not necessarily related to the electrostatic repulsion associated with zeta potential measurements. It would seem that, at least for the acrylic polymer-based admixtures, the polymer adsorption itself rather than the electrostatic repulsion is responsible for the dispersion of large agglomerates of cement particles into smaller ones resulting in a remarkable increase in the fluidity of cement mixes.

The dispersion mechanism performed by the AP-based superplasticizers could be related more to a steric hindrance effect (produced by the presence of side long graft chains) rather than to the presence of negatively charged anionic groups (COO^-). In other words, the graft chains of the polymer molecules on the surface of cement would hinder by themselves from flocculating into large and irregular agglomerates of cement particles (Fig. 16). This mechanism would be in agreement with the relatively smaller number of negative anionic groups (COO^-) in the acrylic polymers in comparison with those present as SO_3^- in the SMF and SNF polymers [15]. When a concrete mixture must be transported for a long time, particularly in hot weather, it should keep as far as possible the initial slump level to avoid the practice of redosing the concrete with water above and beyond that required in the mixture design.

Therefore a superplasticizer is required which by itself is capable to maintain the slump for a long period of time independently of the temperature or the type and content of cement.

Collepari et al. [15] studied the effects of a water soluble copolymer (CAE) on the properties of ready-mixed concrete mixtures. The CAE based superplasticizer, shown in Fig. 14, was more effective than that based on SNF for the water reducing capability ($w/c = 0.43$ versus 0.47) as well as for the maintainance of the initial slump level (Fig. 17). The compressive strength of the CAE superplasticized concrete was higher than that of the corresponding concrete with the SNF based superplasticizer at early and especially at longer ages because of the lower w/c : the retarding effect of the CAE superplasticizer, which was beneficial to the reduction in slump loss, did not reduce the 1-day compressive strength with respect to the concrete containing the less retarding SNF superplasticizer (Fig. 18).

5.2 Ultra Fine Amorphous Colloidal Silica (UFACS)

Ultra fine amorphous colloidal silica (*nanosilica*) is based on silica particles of 5-50 nm [18] and then much smaller than those of silica fume (*microsilica*) which contains particles as “big” as 0.1-1 μm (Fig. 19). Precipitated silica too (an other type of amorphous silica) contains particles with the same size of colloidal silica, the main difference being that the former tends to aggregate.

UFACS is available in form of an opalescent liquid solution (10-50% of solid content). At a dosage of about 5%, it is able to reduce bleeding and increase the resistance to segregation. Due to the very high specific surface area (80-1000 m^2/g) and the spherical shape of the colloidal silica particles (Fig. 20), *UFACS* enhances the stability of *SCC*, particularly when the filler content is low [19].

Moreover *UFACS* increases the tolerance levels in *SCC* towards to errors in water additions made under mixing (Fig. 21).

6. CONCLUSIONS

Self-Compacting Concrete is considered to be the most promising building material for the expected revolutionary changes on the job site as well as on the desk of designer civil engineers. However, the basic principles of this material are substantially based on those of flowing, unsegregable, and superplasticized concretes developed in the mid of 1970's.

The necessary ingredients for manufacturing *SCC* are superplasticizers and powder materials (including cement, fly ash, ground fillers or other mineral additions) at an adequate content ($> 400 \text{ kg}/\text{m}^3$), with some limits in the maximum size of the coarse aggregate ($< 25 \text{ mm}$).

Supplementary materials, particularly for lean *SCC* mixes (about $300 \text{ kg}/\text{m}^3$), are silica fume and/or viscosity modifying admixtures.

The most important progress achievable in the future for this technology depends on the availability and use of some new ingredients such as:

- More effective superplasticizers (those based on acrylic polymers) with respect to the traditional ones (naphthalene or melamine based) in terms of lower slump loss.
- Viscosity modifying admixtures (based on organic polymers) and ultra fine amorphous colloidal silica, both focused to reduce bleeding and to increase the resistance to segregation particularly in *SCC* with low content of fillers and/or cement.

7. REFERENCES

1. M. Collepardi, «“Rheoplastic” Concrete», *Il Cemento*, pp. 195-204, 1975.
2. M. Collepardi, «Assessment of the “Rheoplasticity” of Concretes», *Cement and Concrete Research*, pp. 401-408, 1976.
3. ACI Manual of Concrete Practice, «Recommended Practice for Selecting Proportions for Normal Weight Concrete», 1ACI 211.1-70, Part 1, pp. 211-214, ACI Publications, 1973.
4. M. Collepardi, S. Gennari, A. Triantafillis and S. Zorzi, «Execution of reinforced concrete foundation for the S. Marco Dry Dock at Trieste through Under-Water Placements of Rheoplastic Concrete» (in Italian), *Proceedings of the Giornate AICAP, Ravenna (Italy)*, 1981.
5. M. Collepardi, R. Khurana, and M. Valente, «Construction of a Dry Dock Using Tremie Superplasticized Concrete» *Proceedings of the ACI International Conference on “Superplasticizers and Other Chemical Admixtures in Concrete”*, Editor V.M. Malhotra, pp. 471-492, ACI SP-119, 1989.
6. J.P. Colaco, J.B. Ames, and E. Dubinsky, «Concrete Shear Walls and Soandrel Beam Moment Frame Brace New York Office Tower», *Concrete International*, pp. 23-28, 1981.
7. D.J. Sharpe, A.G. Ford, and M.G. Watson «Concrete for the Future?», *Hong Kong Engineer, The Journal of the Hong Kong Institution Engineers*, pp. 17-28, 1985.
8. M. Collepardi, «The Influence of Admixtures on Concrete Rheological Properties», *Il Cemento*, pp. 289-316, 1982.
9. E.J Sellevold, and T. Nilsen, «Condensed Silica Fume in Concrete: a World Review», *Supplementary Cementing Materials for Concrete*, Editor V.M. Malhotra, CANMET, 1987.
10. M. Collepardi, «Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Europe: Future Directions», *International Workshop on the Use of Fly Ash, Slag, Silica Fume, and other Siliceous Materials in Concrete*, Sydney, Australia, Concrete Institute of Australia & CANMET, 1988,
11. K.H. Khayat and Z. Guizani, «Use of viscosity-modifying admixtures to enhance stability of fluid concretes», *ACI Materials Journal*, 94, pp. 332-340, 1997.
12. G. Robinson, C.E. Manning, and E.R. Morris, «Conformation and physical properties of the bacterial polysaccharides gellan, wellan, and rhamsan», *Food Polymers, Gels, Colloids, Special Publication R.Soc. Vol. 82*, pp. 22-33, 1991.

13. M. Collepardi, «Advances in Chemical Admixtures for Concrete», “Advances in Cement and Concrete”, Editors: M.W. Grutzeck and S.L. Sarkar, Durham USA, pp. 257-291, 1994.
14. M. Collepardi, and V.S. Ramachandran, «Effect of Admixtures», Proceedings of the 9th International Congress on the Chemistry of Cement, New Dehly, India, Vol. 1, Theme III D, pp. 529-570, 1992.
15. M. Collepardi, L. Coppola, T. Cerulli, G. Ferrari, C. Pistolesi, P. Zaffaroni, and F. Quek, «Zero Slump Loss Superplasticized Concrete», Proceedings of the Congress “Our World in Concrete and Structures”, Singapore, pp 73-80, 1993.
16. H. Uchikawa, «Hydration of Cement and Structures Formation and Properties of Cement Paste in the Presence of Organic Admixtures», Proceedings of the “Concrete in the Service of Mankind”, Editors: R.K. Dhir and M.J. McCarthy, pp. 3-47, 1995.
17. M. Collepardi, «The World of Chemical Admixtures in Concrete», Proceedings of the Congress “Our World in Concrete and Structures”, Singapore, pp 63-72, 1993.
18. U. Skarp, and S.L. Sarkar, «Enhanced Properties of Concrete Containing Colloidal Silica», Concrete Producer, pp 1-4, December 2000.
19. U. Skarp, Eka Chemicals, private communication.

Table 1 – Typical Self-compacting concretes in 1970’s and 1980’s

Ingredient/Property	Mix A	Mix B
Ordinary Portland cement	400 kg/m ³	300 kg/m ³
Fly ash	-	90 kg/m ³
Very fine sand (0.075 – 0.60 mm)	180 kg/m ³	-
Sand (0-5 mm)	990 kg/m ³	670 kg/m ³
Gravel (5-15 mm)	630 kg/m ³	305 kg/m ³
Gravel (10-20 mm)	-	710 kg/m ³
Water	190 kg/m ³	187 kg/m ³
Superplasticizer	7 kg/m ³	4 kg/m ³
Water/cement	0.47	0.62
Water/binder (c+f.a.)	0.47	0.48
Slump	260 mm	220 mm

A = Typical self-levelling and very cohesive concrete placed under water [4,5].

B = Typical self-compacting concrete for mass concrete foundations [7].

Table 2 – Density and strength in specimens and cores taken 0.5-1-3 m below the surface of the 4.7 m thick slab foundation placed without any vibration at all [7]

SPECIMENS			CORES		
Density (kg/m ³)	Cube Strength (Mpa)		Below the concrete surface (m)	Density (kg/m ³)	Equivalent Cube Strength (Mpa) at 96 days
	7 days	28 days			
2310	24.5	42.5	0.5	2310	57.5
2320	25.0	43.5	1.0	2320	57.5
2320	24.0	40.5	3.0	2320	54.0
		Average = 42.2			Average = 56.3
28 days: Range = 3MPa; Range as % av. = 7.1%			96 days: Range= 3.5MPa; Range as % av. = 6.2%		

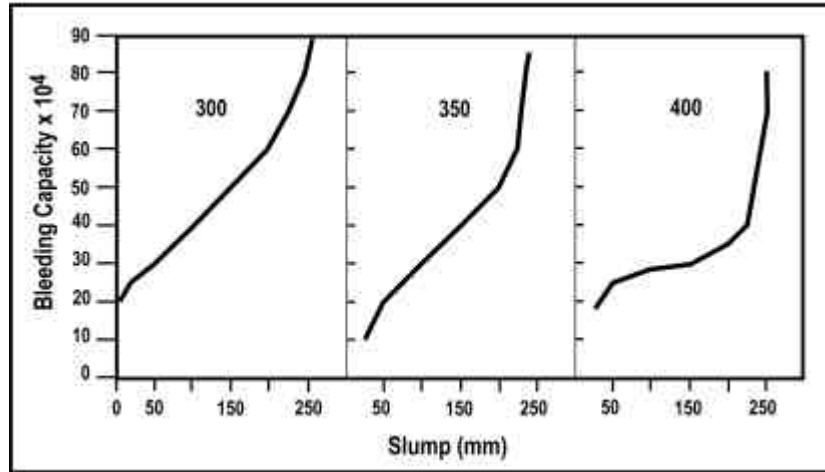


Fig. 1 – Bleeding capacity as a function of slump for concretes not containing additives. The figures into the diagrams show the cement content in kg/m^3 [2].

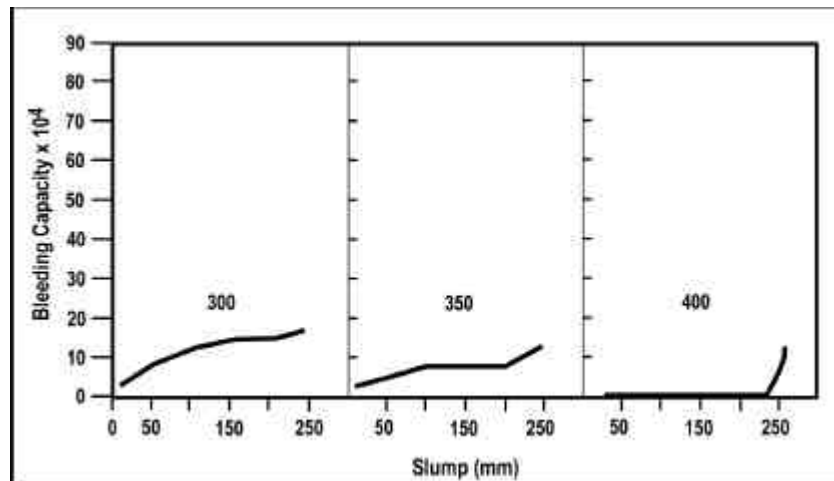


Fig. 2 – Bleeding capacity as a function of slump for concretes containing superplasticizer and with cement content of 300-350-400 kg/m^3 [2].



Fig. 3 – Tremie method to place self-compacting concrete under water [4].



Fig. 4 – Aerial view of the dry dock after removing sea water [4].



Fig. 5 - View of the reinforced slab foundation placed under water without vibration [4].



Fig. 6 - Self-compacting concrete placed by chute [8].



Fig. 7 - Congestion of reinforcements of a slab foundation where concrete (on the background) is placed without vibration [8].



Fig. 8 - Placement of self-compacting concrete in a reinforced slab foundation of a skyscraper (Commercial Center) in New York (1978).



Fig. 9 - Placement of self-compacting concrete only chutes for the slab through foundation of the Trump Tower – New York (1978).

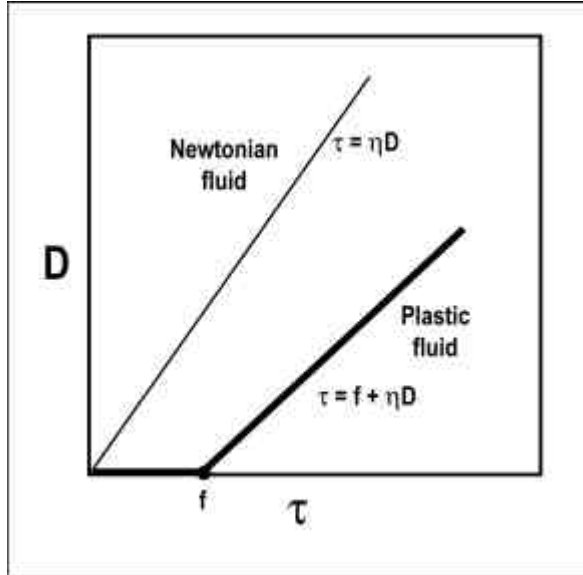


Fig. 10 – Shear rate (D) as a function of the shear stress (τ) for Newtonian and plastic fluids.

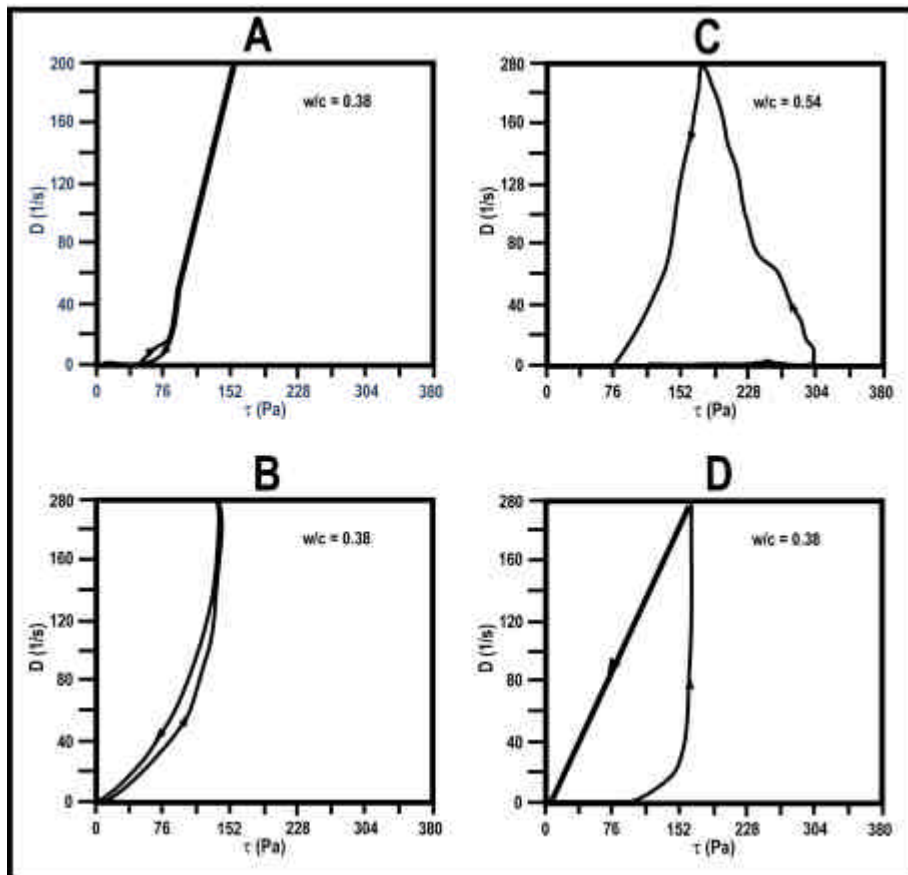


Fig. 11 – Shear stress (τ) versus shear rate (D) for plain cement paste (A); superplasticized cement paste (B); cement paste with silica fume (C); and superplasticized cement paste with silica fume [10].

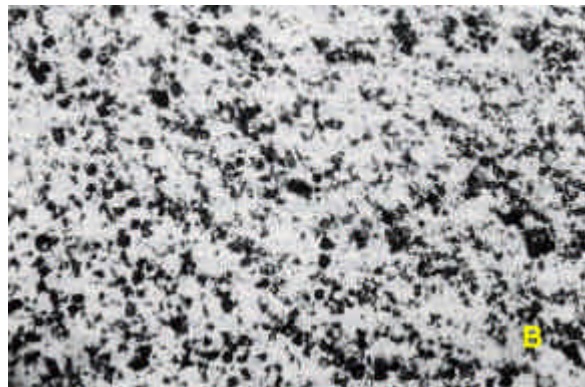
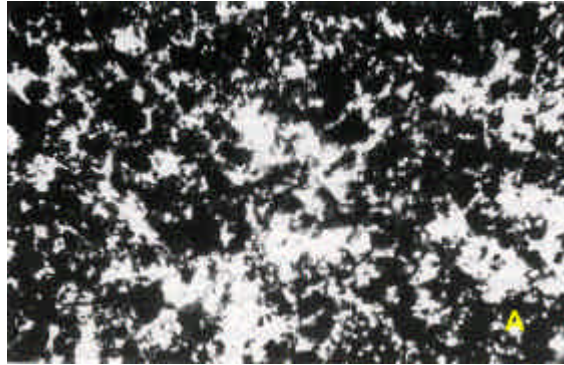


Fig. 12 - Agglomeration (A) of cement particles and their dispersion (B) produced by superplasticizers.

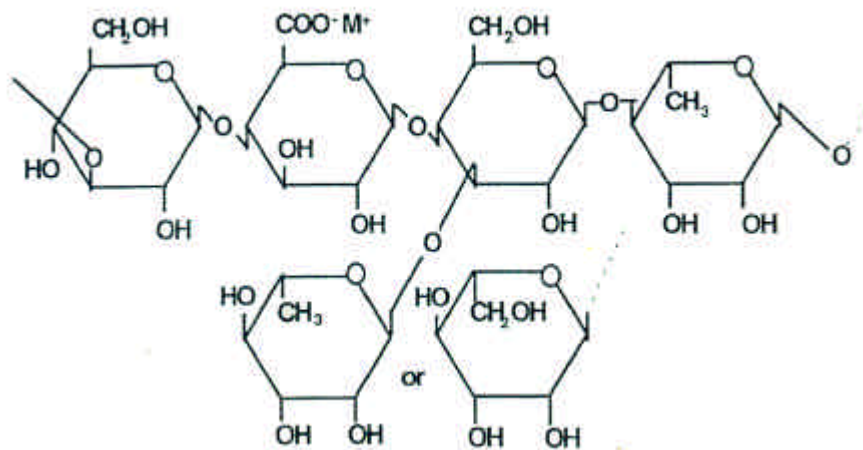


Fig. 13 - Molecular structure of the welan gum biopolymer

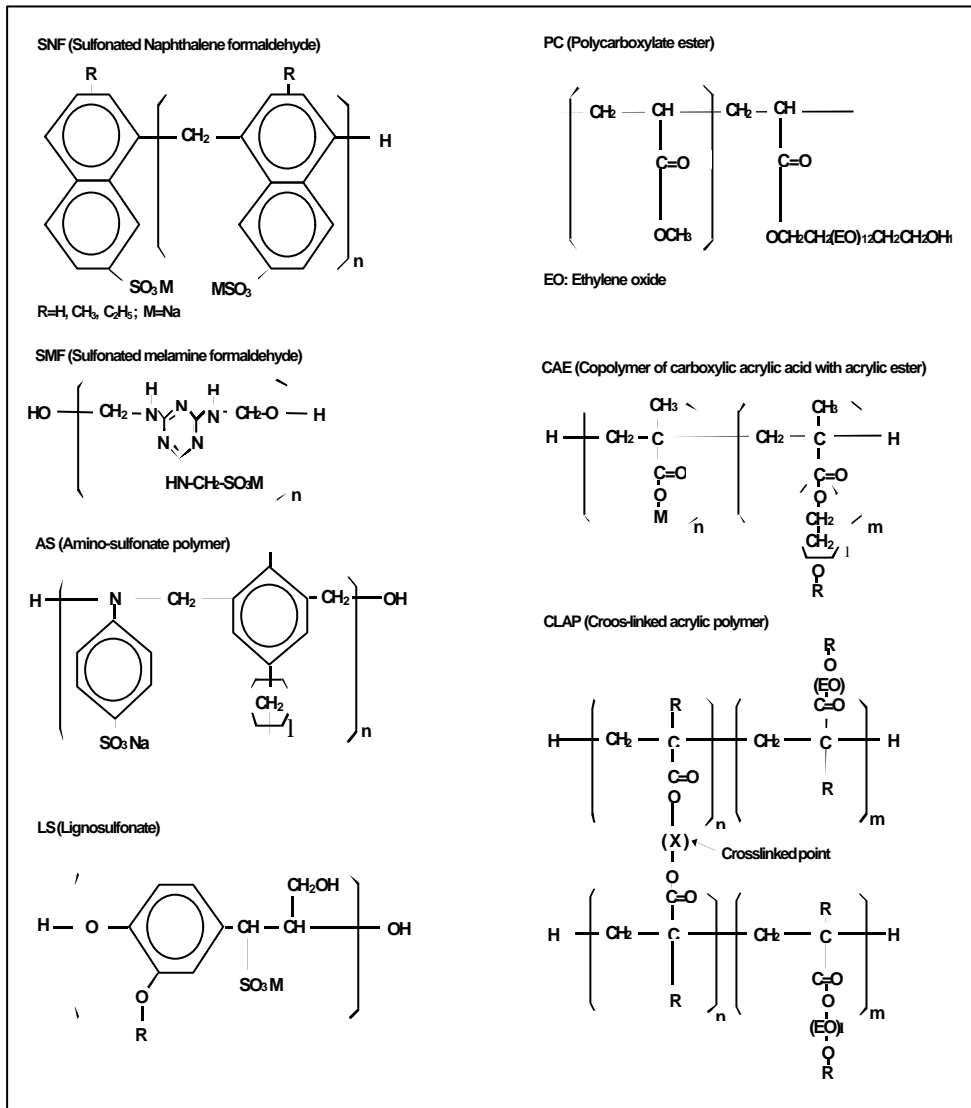


Fig. 14 - Chemical structure of sulfonated superplasticizing polymers and acrylic polymers

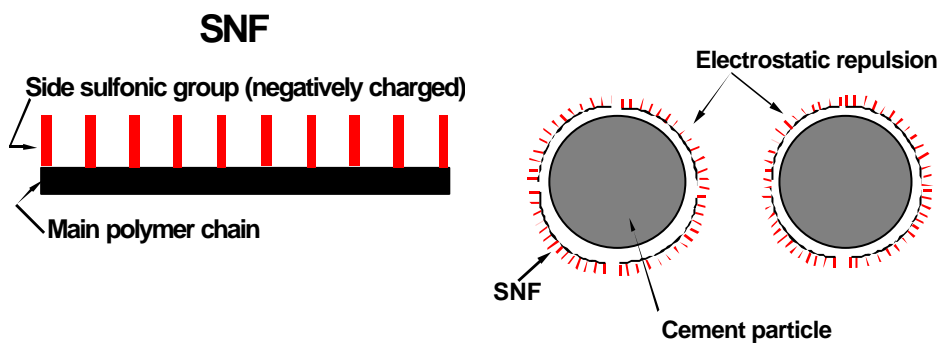


Fig. 15 - Schematic picture of sulfonated polymer (SNF) and the related electrostatic repulsion effect on the dispersion of cement particles.

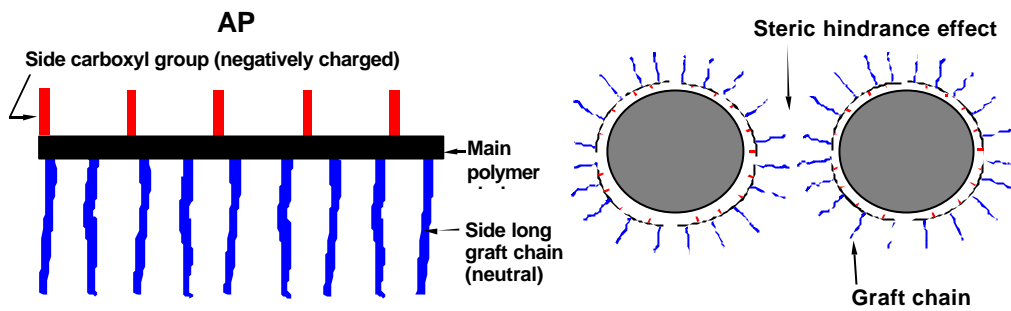


Fig. 16 - Schematic picture of acrylic polymer (AP) and the related steric hindrance effect on the dispersion of cement particles.

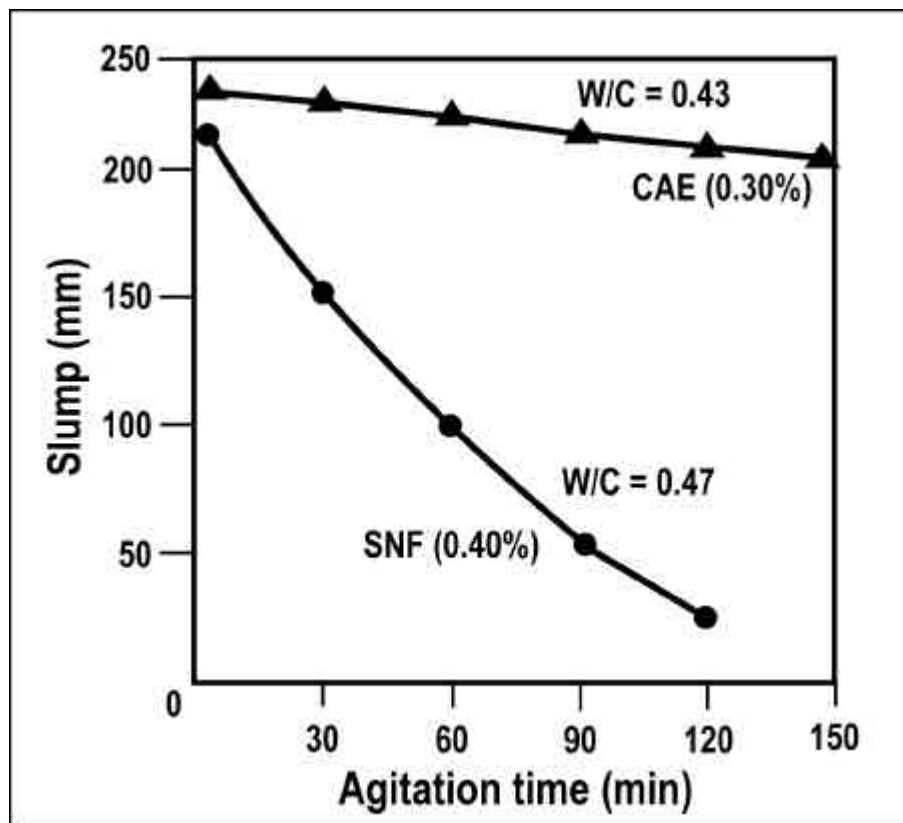


Fig. 17 – Slump-loss of superplasticized concretes with OPC and CAE or SNF polymer based admixtures. Percentages on the curves refer to dry polymer.

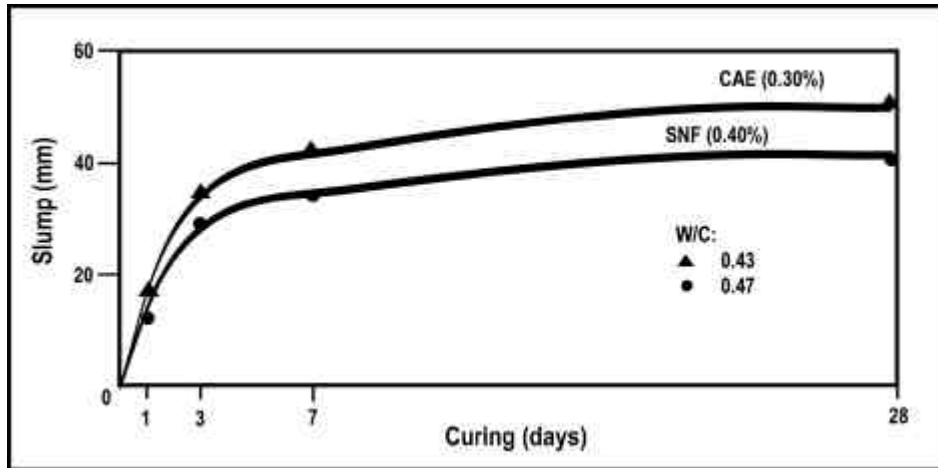


Fig. 18 – Compressive strength of superplasticized concretes with CAE or SNF polymer based admixtures. Percentages on the curves refer to dry polymer.

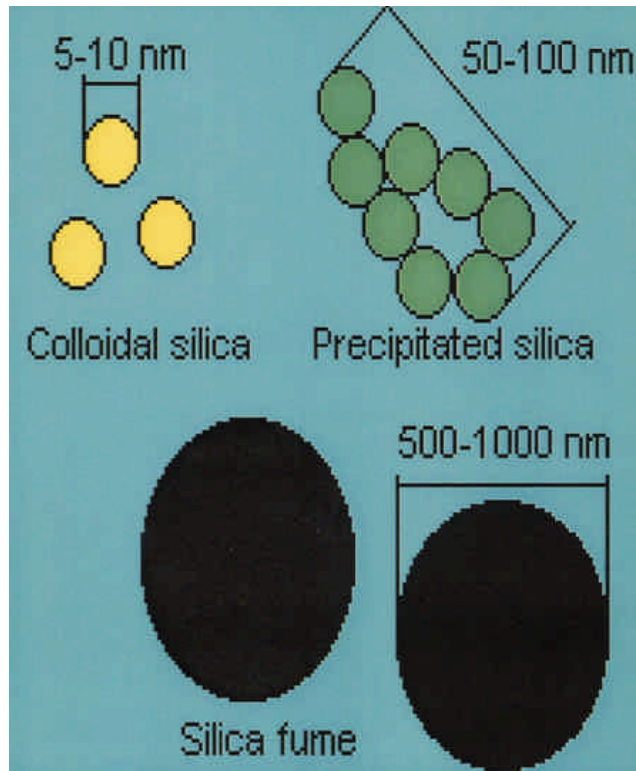


Fig. 19 – Colloidal silica vs. precipitated and silica fume [19].

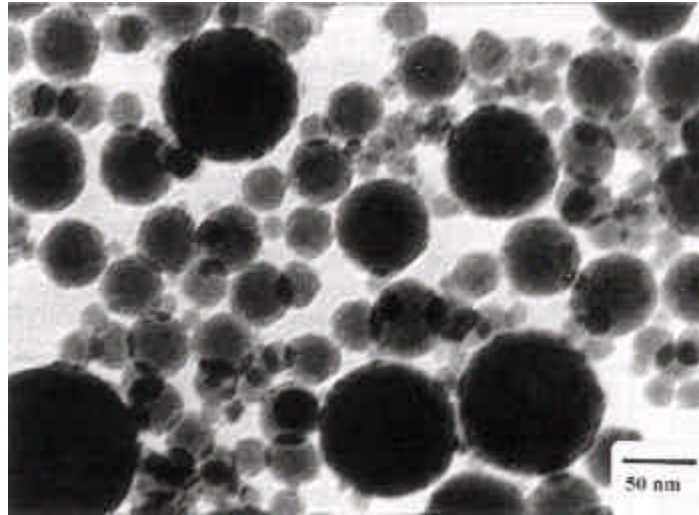


Fig. 20 - Ultra fine amorphous colloidal silica particles under the transmission electron microscope [18].

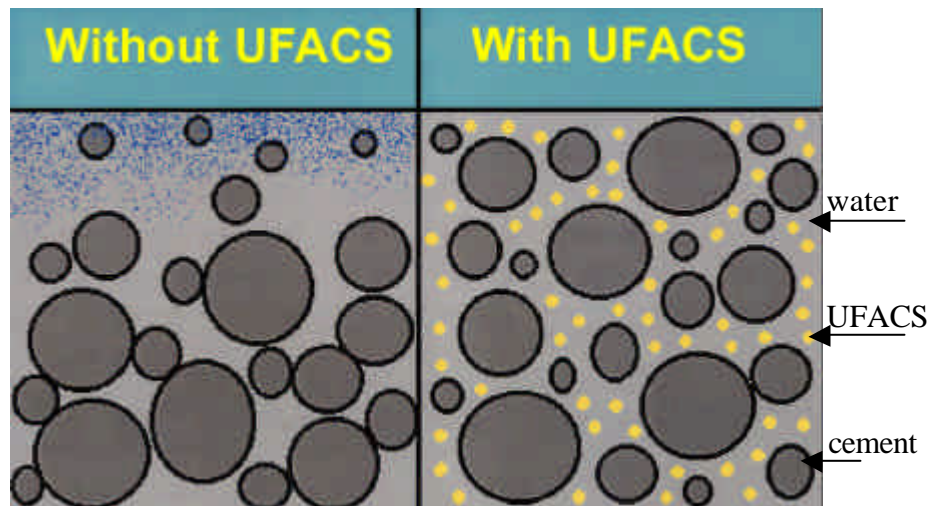


Fig. 21 - UFACS improves safety and tolerance towards errors in the addition of mixing water [19].