Self-Compacting Concrete: what is new?

By M. Collepardi

Synopsis*:* The paper summarizes the results on flowing and cohesive 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 concrete 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 in determining the main properties of these concretes, such as fluidity, on the one hand, and resistance to segregation, on the other. Some interesting new materials, such as ground fly ash or powder from recycled aggregates, appear to be very promising for manufacturing *SCC* in agreement with the requirements needed for sustainable progress.

Keywords: Bleeding, Ground Fly Ash, Fly Ash, Recycled Aggregate, Self-Compacting Concrete, Silica Fume, Superplasticizer.

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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 in many countries.

Data available in the international literature indicate that self-levelling and cohesive concretes were firstly studied in 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 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.

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/m^3 in the absence of superplasticizer [2]. The slump was increased by increased the amount of mixing water. 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*” as 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 cohesive 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 the heat of hydration of the cement [6-7].

Table 1 shows the composition of two typical concrete mixtures which were used to place self-compacting and cohesive 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 40,000 m^3 of concrete placed under water (Fig. 3 and 4) 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 concrete foundations for skyscrapers [6,7] or very high chimneys at the end of 1970 (Fig. 5 and 6).

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 pratical 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 40,000 m^3 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 m^3/hr with maximum of 350 m^3/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 conrete' 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 Hong 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 laboratory 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 laboratory specimens.

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. Due to this special behavior, 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/m^3).

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 [10]. These admixtures (0.1-0.2% by mass of cementitious materials) allow the manufacture of 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.

- Poliethielen-glycol and biopolymers [11] which appear to be the most effective *VMAs* for self-compacting concretes.

Figure 7 shows the molecular structure of the biopolymer *welan gum*. Due to its molecular composition (Fig. 7), 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 to 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 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 much higher than the yield stress is applied, the hydrogen bonds between the different polymer chains are broken and the biopolymers align in the direction of the mouvement of the cement mixture without any adverse effect on the fluidity of the concrete mixture.

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 are discussed below.

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, were proposed in the last decade [12] 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 [13].

Ultra Fine Amorphous Colloidal Silica (UFACS)

Ultra fine amorphous colloidal silica (*nanosilica*) is based on silica particles of 5-50 nm [14] and they are much smaller than those of silica fume (*microsilica*) which contains particles as “big” as 0.1-1 μm. Precipitated silica (another type of amorphous silica) also contains particles with the same size of colloidal silica, the main difference being that the former tends to aggregate (Fig. 8).

UFACS is available in the form of an opalescent liquid solution (10-50% of solid content). At a dosage of 3-5%, 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. 9), *UFACS* enhances the stability of *SCC*, particularly when the filler content is low [15]. Moreover *UFACS* increases the tolerance levels in *SCC* arising from errors in water additions made under mixing.

Ground Fly Ash

Ground fly ash (*GFA*) was studied [15] by Collepardi et al for manufacturing *SCC* with improved properties in terms of lower bleeding capacity and higher compressive strength with respect to corresponding concretes where fly ash (*FA*) or ground limestone (*GL*) was used as cementitious fillers.

Table 3 shows the composition of three mixtures with *GL*, *FA* or *GFA*, all with a reduced cement content (310 kg/m^3) of slag cement (*CEM III A* according to the European Norm EN 197/1) in order to produce special *SCC* mixtures for massive concrete structures without any risk of cracks induced by thermal stresses. Table 4 indicates that, at equal slump flow properties, in the presence of *GFA* the bleeding capacity is lower than that with *GL* or *FA*. On the other hand, due to its higher reactivity *GFA* increases the compressive strength of *SCC* with respect to that of the corresponding mixtures containing *FA* or *GL* (Fig. 11).

Fine powder from recycled aggregates

Corinaldesi et al. [16] have found that the use of fine powder from recycled aggregates produced by grinding demolished concrete performs very well as fine filler for the manufacture of *SCC*. The behavior of this powder in reducing segregation and increasing compressive strength is much better than fly ash and very close to that of silica fume. These results appear to be very encouraging and promising for the production of SCC in agreement with the requirements needed for a sustainable progress.

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 designers and civil engineers. However, the basic principles of this material are substantially based on those of flowing, cohesive, 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 even in the form of fine recycled aggregate) at an adequate content (> 400 kg/m^3 of cement and filler), with some limits in the maximum size of the coarse aggregate (< 25 mm).

Supplementary materials, particularly for lean *SCC* mixes (about 300 kg/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.

Modified mineral additions such as ground fly ash and/or crush recycled aggregate.

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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

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

****** Typical self-levelling concrete for mass concrete foundations [7].

Table 2 – Density and strength of laboratory 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 (150 mm) Strength (MPa)		Below the concrete surface (m)	Density (kg/m^3)	Equivalent* Cube Strength (Mpa) at 96 days
	7 days	28 days			
2320	24.5	43.0	0.5	2310	57.5
2320	25.0	43.5	1.0	2320	57.5
2310	24.0	40.0	3.0	2320	54.0
		Average = 42.2			Average = 56.3

*Equivalent cube strength = Cylinder strength/0.80

Table 3 –Composition of SCC at w/c of 0.58 [15].

Mix	Cement * (kg/m^3)	Mineral addition:		Sand (kg/m^2)	Gravel (kg/m^2)	Water (kg/m^3)	AP (%)***
		amount (kg/m^3)	s.s.a.** (m^2/kg)				
GL	306	157	310	964	824	178	0.70
FA	307	128	350	965	824	178	0.96
GFA	312	130	2100	981	838	181	1.12

* Slag cement CEM III A 32.5 R according to EN 197/1 with 60% of GGBS

** s.s.a.: specific surface area

*** By cement and mineral addition

Table 4 –Properties of SCC mixtures in the fresh state [15].

Mix	Specific gravity (kg/m^3)	SLUMP FOW				Bleeding capacity (% by vol. of concrete)	Aspect (Visual Rating)
		After mixing		After 30 min.			
		mm	sec*	mm	sec*		
GL	2429	790	20	720	25	0.12	Slight segregation
FA	2402	790	30	750	35	0.11	Slight segregation
GFA	2442	790	20	700	25	0.06	Cohesive

*time needed to reach the final slump flow

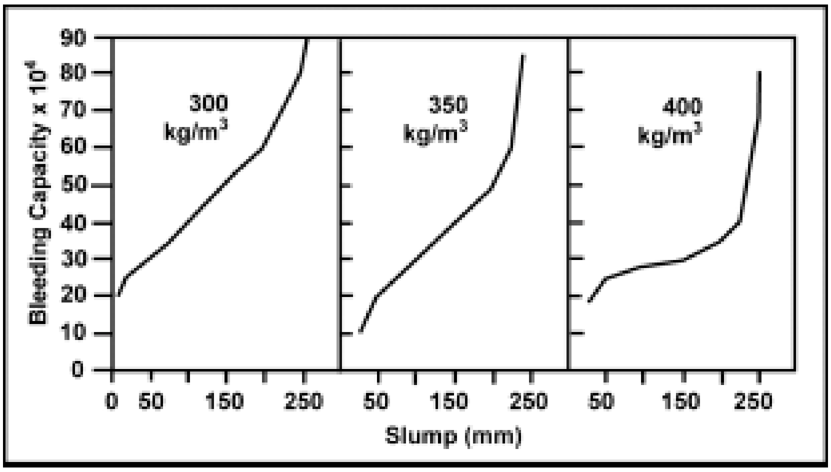

Fig. 1 – Bleeding capacity as a function of slump for concretes not containing additives [2].

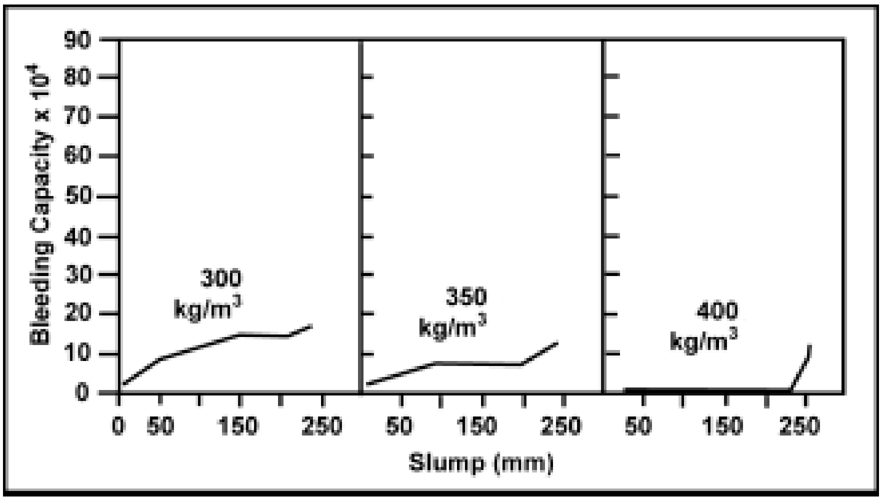

Fig. 2 – Bleeding capacity as a function of slump for concretes containing superplasticizer [2].

Fig. 3 – Aerial view of the dry dock after removing sea water [4].

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

Fig. 5 - Self-compacting concrete placed by chute [8].

Fig. 6 - Congestion of reinforcement of a slab foundation where concrete (in the background) is placed without vibration [8].

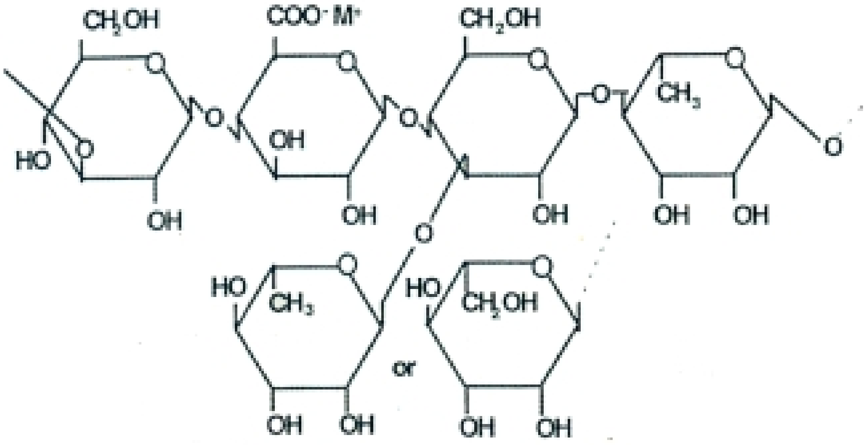

Fig. 7 - Molecular structure of the welan gum biopolymer

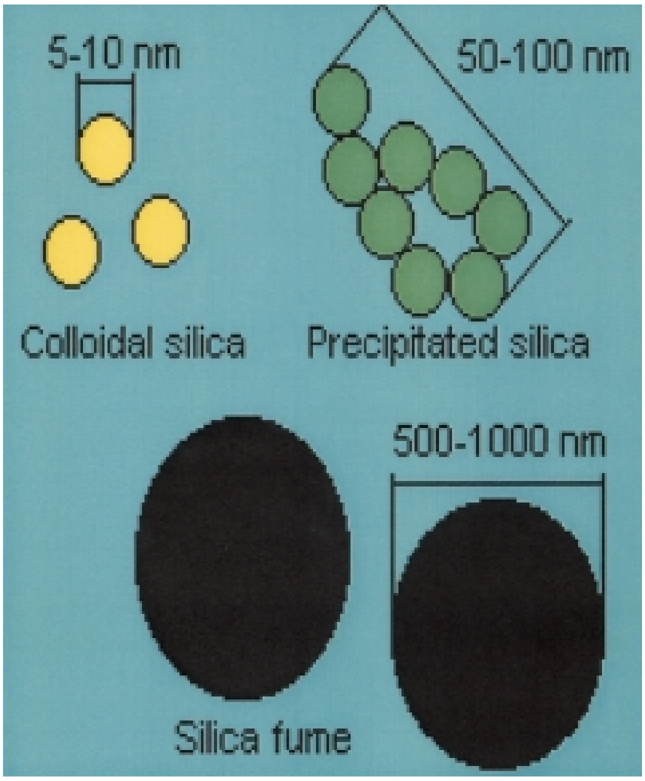

Fig. 8 – Colloidal silica vs. precipitated and silica fume [9].

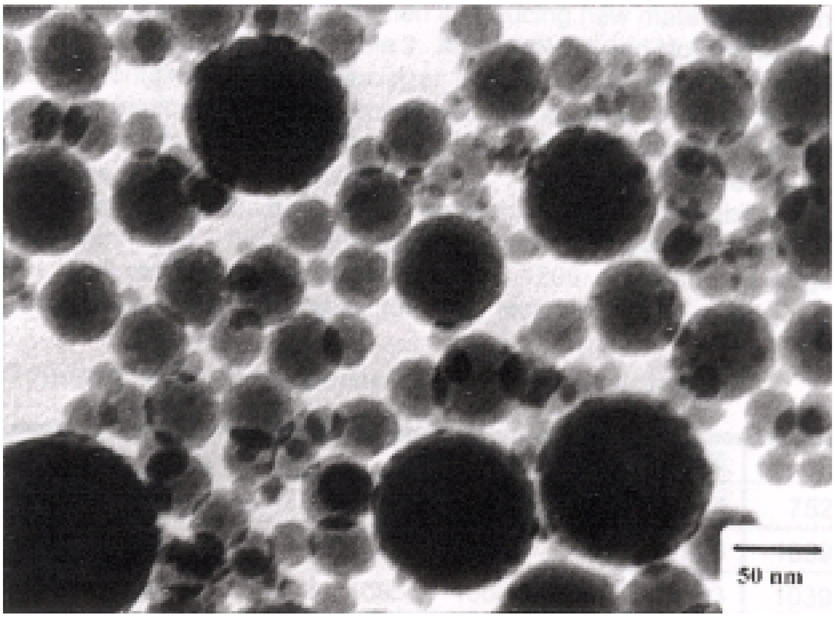

Fig. 9 - Ultra fine amorphous colloidal silica particles under transmission electron microscope [13].

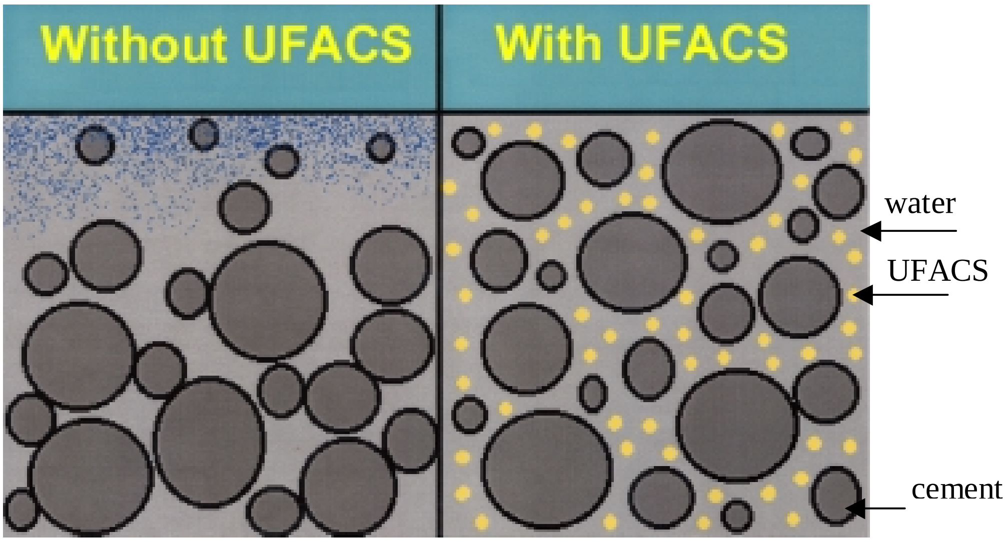

Fig. 10 – UFACS improves safety and tolerance towards errors in the addition of mixing water [15].

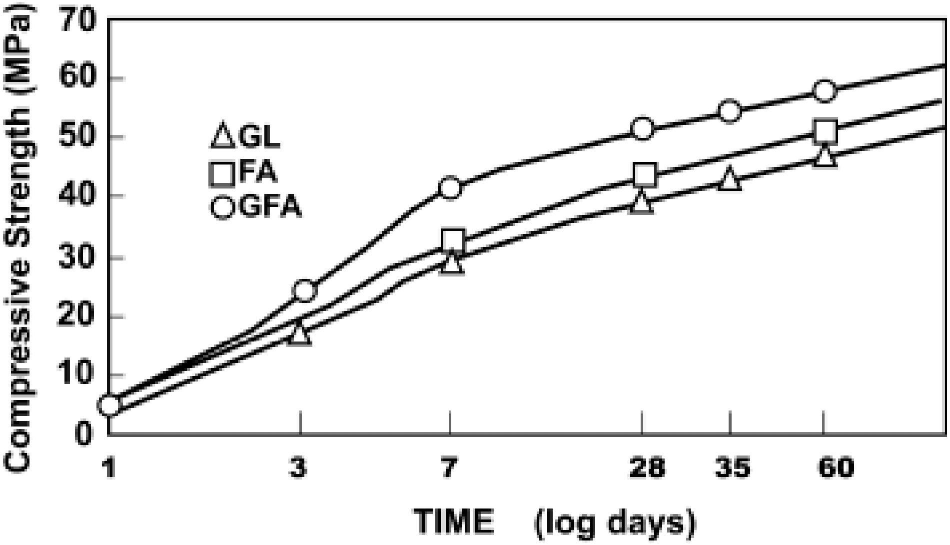

Fig. 11 – Cube-compressive strength as a function of time of SCC with ground fly ash (*GFA*), fly ash (*FA*) and ground limestone (*GL*).