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Mechanisms of Actions of Different Superplasticizers for High-Performance Concrete

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Synopsis: The invention of superplasticizers is one of the most important breakthrough that has led to the development of high performance concrete. Superplasticizers can be used for three different purpose, namely (a) to increase workability without changing the mixture composition, (b) to reduce the amount of mixing water in order to reduce the water-cement ratio and then to increase strength and/or improve durability, and (c) to reduce both water and cement in order to reduce cost in addition to reducing creep, shrinkage and thermal strains caused by heat of cement hydration.

Practical examples of these different ways of using superplasticizers are given by referring to the traditional superplasticizers (naphthalene- and melamine-based) and to the recent advances in this area (acrylic polymer-based admixtures).

In particular the following topics are examined: composition of superplasticizers, mechanism of action (electrostatic repulsion and steric hindrance), influence of the cement composition (C_3A, alkali, SO_3), mode of addition of superplasticizer, slump loss, blending of superplasticizers.

Keywords: acrylic polymer; compressive strength; slump loss; superplasticizer

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INTRODUCTION

Superplasticizers can be used in concrete mixtures for three different purposes or a combination of these:

- to increase workability, at a given mix composition, in order to enhance placing characteristics of concrete;
- to reduce the mixing water, at given cement content and workability, in order to reduce the water-cement ratio (*w/c*) and therefore to increase strength and improve durability;
- to reduce both water and cement, at given workability and strength, in order to save cement and reduce creep, shrinkage, and thermal strains caused by heat of cement hydration.

All the above three changes are essential to produce truly high-performance concrete structures characterized by low *w/c* and high workability level without attaining to high cement contents (1).

COMPOSITION OF SUPERPLASTICIZERS

During the last two 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 present decade (2-8) 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 in Europe and Japan, these new superplasticizers - all based on the family of acrylic polymers (AP) - have been investigated in depth, and numerous papers on these admixtures were presented at the Fifth CANMET-ACI International Conference on "Superplasticizers and Other Chemical Admixtures" (9-24).

Figures 1 and 2 show 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. However, the AP superplasticizers appear to be more expensive than the others. Table 1 shows the comparative cost of the main ingredients (SNF, SMF, MLS, AP) used as water-reducing component in the superplasticizing admixtures (15). Since commercial products of these polymers are available in different concentrations of aqueous solutions (40% for NSF; 30-40% for MSF; 30-50% for MLS; 30% for AP) the comparative costs of these four products are referred to 1 kg of dry polymer (Table 1). These data are based on the cost of the raw materials presently available in Italy, and may be different for other countries.

MECHANISM OF ACTION OF SUPERPLASTICIZERS

Superplasticizers cause dispersion into smaller agglomerates of cement particles which predominate in the cement paste of the concrete mixture. 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 (25). The 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 would be related with the electrical repulsion produced by the adsorption of negatively charged groups (Fig. 3) and determined through zeta potential measurements.

Additional available experimental results did not confirm this mechanism for the superplasticizing action of the acrylic polymers (4, 7, 8, 14, 17, 20). Table 2, for instance, indicates that AP-based superplasticizers produce negligible zeta potential change (0.3-5 mV), with respect to that caused by SNF-based admixtures (23-28 mV), in aqueous suspensions of cement particles (14).

Figures 4 and 5 show the adsorption on cement particles and zeta-potential measurements of CAE copolymer (a special product belonging to the AP family) in comparison with SNF polymer. In particular, Fig. 5 shows the percentage of polymer adsorbed on cement particles as a function of the admixture dosage expressed as percentage of dry polymer by mass of cement. The adsorption of CAE copolymer (about 85%) appears to be higher than that recorded for the SNF polymer (75%). Figure 6 indicates that the zeta potential of cement particles treated by CAE appeared to be much lower than those recorded in the presence of SNF. In particular, when 0.3% of CAE by mass of cement was used, the cement particles appeared to be almost electrically neutral.

All 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 AP-based admixtures, the polymer adsorption itself (Fig. 4) rather than the electrostatic repulsion (Fig. 5) is responsible for the dispersion of large agglomerates of cement particles into smaller ones resulting in a remarkable increase in the fluidity of cement mixtures.

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. 6). This mechanism would be in agreement with the relatively smaller number of negative anionic groups (COO^-) in the AP products in comparison with those present as SO_3^- in the SMF and SNF polymers (4).

INFLUENCE OF CEMENT COMPOSITION

The fluidizing effect of superplasticizer is influenced by the type of cement used. Hanna et al. (26) have examined the properties of cement grouts with SNF superplasticizer and have confirmed (27, 28) that the C_3A content and the fineness of cement are among the most important factors: the higher the C_3A content and the cement fineness, the lower the fluidizing effect.

Basile et al. (29) have found that cements manufactured with the same clinker, but with different forms of calcium sulfate as set regulators, perform much differently when treated with SNF polymer: in the presence of calcium sulfate dihydrate, the fluidizing effect is much more significant than with hemihydrate. Table 3 indicates that by using two different clinker sources (A and B) the fluidizing effect of a SNF based superplasticizer on the Portland cement paste is more effective when gypsum in the form of dihydrate is used instead of hemihydrate, even though the zeta potential and the polymer adsorption are almost equal for the cement (30). These results have been confirmed by Nawa et al. (31) who found that in the presence of SNF superplasticizer cement pastes are much more fluid when dihydrate is used instead of hemihydrate. However, for a cement with very low alkali content the difference in fluidity caused by the two calcium sulfate forms is negligible.

Nawa et al. (31) have found that with calcium sulfate in the form of anhydrite as a set regulator, the fluidity of superplasticized cement paste lies between the values obtained with dihydrate and hemihydrate, except that in a cement with very low alkali content the fluidity is much lower.

Nawa et al. (31) have examined the complex influence of the water soluble alkali sulfate of the cement on the fluidizing effect of the SNF-based superplasticizer. They have confirmed that SNF, as well as SMF as found by Ramachandran (32), adsorb on C_3A and C_4AF more quickly and selectively than on C_3S and C_2S. In the presence of alkali sulfate the adsorption of superplasticizer on C_3A and C_4AF is inhibited, leading to increased adsorption on C_3S and C_2S. Consequently since the silicate phase adsorbs a much lower amount of polymer than the aluminate phase does, an increase in the alkali content of the cement causes a reduction in the total amount of polymer adsorbed on cement and this results in a higher amount of polymer in the aqueous phase to promote dispersion and reduction of the viscosity of the cement paste (Fig. 5).

However, according to Nawa et al. (31), excessive amount of alkali sulfate compresses the electric double layer causing a small increase in viscosity of the cement paste. These results would indicate that there is an optimum alkali sulfate content with respect to the fluidity of superplasticized cement paste (31, 33).

Portland cement contains sulfur compounds from the clinker phase and from added calcium sulfate (e.g. gypsum) which acts as a set regulator: Coppola et al. (34) studied the influence of the sulfate content in the clinker phase on the performance of superplasticized concrete mixtures in terms of initial slump level at a given water-cement ratio, slump-loss rate, and compressive strength at early and later ages. Two batches of clinker from the same kiln source were studied, the main difference being the content of sulfur in the clinker (0.72% and 1.40% as SO_3 respectively). Different percentages of natural gypsum, as set regulator, were interground in a laboratory mill to manufacture portland cements. The levels of total sulfate content in terms of SO_3 were in the range of 3-4%. At a 3% sulfate content in portland cement, the lower the clinker sulfur content, the more effective is the slump increase of the concrete caused by the superplasticizer addition (Fig. 7). Moreover, the lower is the clinker sulfur content, the lower is the slump-loss rate of the superplasticized concrete mixture (Fig. 7). At a higher sulfate content in portland cement (4%), the differences in the slump and slump loss behaviors related to the clinker sulfur content were significantly reduced. These results indicate that the superplasticizing effect depends on the sulfur content of the clinker phase as well as the total sulfate content determined by gypsum addition as set regulator.

MODE OF ADDITION

The SMF- or SNF-based superplasticizers are able to transform a no-slump concrete into a self-levelling mix with a slump increase of about 200 mm. However, the method of addition of these superplasticizers affects the slump-increase effect. An immediate addition procedure (superplasticizer with gauging water) produces a less workable mix with respect to a delayed addition of the same superplasticizers (after an initial mixing period of 1 min).

The influence of the method of addition on the effect of superplasticizer has been ascribed to the different capability of SMF or SNF polymer molecules to be adsorbed on anhydrous or hydrated cement particles (35). For instance, a preliminary treatment of cement even with a small amount of water (1-2%) produces superplasticized concrete mixes which, independently of the method of addition of the superplasticizer, always perform as well as the best concrete produced by delayed addition (36). This effect seems to be related with the production of an ettringite coating on the surface of cement particles during the preliminary water treatment. It seems that addition of superplasticizers with mixing water causes a strong incorporation of the polymer molecules into the C_3A-gypsum system, leaving only small amounts of polymer for dispersion of C_3S and C_2S. Consequently, the adsorption of SMF or SNF polymer molecules on the pre-hydrated cement surface is reduced and the subsequent dispersing action appears to be much more effective than that recorded in the absence of the preliminary water treatment.

A superplasticizer which could perform independently of the method of addition would be much appreciated at the batching plant of ready-mixed or precast concrete in order to reduce the variability in the slump of fresh mix or in the strength of hardened concrete caused by change in the procedure of superplasticizer addition. The acrylic polymer based superplasticizers seem to be very interesting admixtures because they perform without depending on the addition procedure. Table 4 shows the slump of concrete mixes as a function of the superplasticizer procedure addition (delayed or immediate) when SMF and SNF or CAE based polymers are used (3).

Results by Uchikawa (7) confirm that NSF polymer is more adsorbed, particularly on the C_3A hydration products, when the immediate addition procedure is adopted. Moreover, according to Uchikawa (7), the superplasticizing effect is improved with a delayed NSF-polymer addition because of the lower adsorption of the polymer on the C_3A hydration products; on the other hand, the adsorption of the PC acrylic polymer (Fig. 2) does not depend on the mode of addition (immediate or delayed).

SLUMP LOSS

The slump loss problem appears to be even more serious than that related with different performances caused by the superplasticizer addition procedure. When a concrete mixture must be transported for a long time, particularly in hot weather, it should keep as far as possible at the initial slump level to avoid the practice of redosing the concrete with water above and beyond that required in the mixture design. Results of investigations of retempered concrete indicate that many of the properties of the hardened concrete (strength, durability, abrasion resistance, etc.) are significantly affected, since retempered concrete does not perform as well as concrete which has not been retempered (37). However, slump loss is un-avoidable because of the intrinsic requirement for cement mixes which should set and harden in a relatively short time. Therefore, a right and proper compromise would be a zero-slump-loss concrete mix for about 1 hour. By using traditional superplasticizers based on SNF or SMF polymers it is not easy to achieve this target, because in general slump loss is higher in superplasticized concrete with respect to the corresponding plain mix at given initial slump (Fig. 8). The lower the *w/c*, the higher is the slump loss for the same initial slump level. It seems that the lower *w/c* in superplasticized concrete and the consequent lower distance among cement particles cause a more significant slump loss when the same amount of water is lost through evaporation or by reaction with cement during the transportation time (Fig. 9).

Several methods have been adopted to control the rate of slump loss. One method is to add the superplasticizer at the point of discharge but there are some practical problems associated with this approach. For instance, the concrete into the truck-mixer before the superplasticizer addition would be too stiff at the placement when a high-quality concrete, (with low *w/c*), should be produced. Moreover, dosing the superplasticizer at the work site is too time consuming and does not allow an accurate control of the final slump and admixture dosage.

Other methods to control slump loss include adding a higher than normal dosage of superplasticizer or using some type of retarding admixture in the formulation. However, there are some limitations to this approach, because sometimes the final effect is to produce concrete with un-acceptable low early strength or to aggravate more seriously slump loss. For instance, slump loss accompanied by a surprisingly quick set may be recorded by using retarders such as sugar, sucrose, corn syrup or calcium lignosulfonate (38). The cement content, as well as the chemical and mineralogical composition of cement, play an important role in determining such a singular slump loss although the detailed mechanism is not clear: it seems that the content of C_3A, gypsum and alkali, as well as the form of calcium sulfate used as set regulator, can affect the rate of slump-loss.

Also redosing the superplasticizer at different intervals of time has been suggested (39) to reduce slump-loss, but this method appears to be not always easy to be adopted in practice. Moreover, the total dosage of superplasticizer, as well as the relative cost, cannot be kept under control according to a given plan.

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. Collepardi et al. (3) studied the effects of a water-soluble monocomponent copolymer (CAE) on the properties of ready-mixed concrete mixtures. This superplasticizer acts as both an immediate dispersant and a slump loss reducing agent. The concentration of the active CAE ingredient in the aqueous phase of this superplasticizer is lower than that of traditional SNF based superplasticizer (30% versus 40%). However, although both of these superplasticizers have been used at the same dosage (1% by mass of cement), and therefore with different contents of active polymer (0.30% s/s versus 0.40% s/s), the CAE based superplasticizer 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. 10). 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. 11).

Tanaka et al. (8) studied the effect of an AP-based superplasticizer on the slump -loss of concrete mixture. This superplasticizer is a partially cross-linked copolymer of acrylic acid and polyethylene glycol mono-alkyl ether (Fig. 2). According to Tanaka and coworkers (8) the cross-linked polymer is hydrolyzed by the alkaline water phase of the cement paste and than converted into an acrylic polymer. Both the steric hindrance effect and the electrical repulsive force due to the negative carboxylic groups would be responsible for the dispersion of cement particles and the fluidizing action of the admixture. The low slump-loss effect of this superplasticizer should be related with the protruding side chains of the acrylic polymer which would prolong the dispersion of hydrated cement particles through a steric hindrance effect.

BLENDING OF SUPERPLASTICIZERS

Combinations of different superplasticizers have been investigated (39). For instance, blending of MLS with SMF or SNF has economical advantages since MLS is cheaper than SMF and SNF. A blend of SNF and SMF may be used to increase early strength with respect to SNF alone (40).

More recently the performance of a combined chemical admixture based on AP and one of the other available superplasticizers (SNF, SMF and MLS) was studied (15).

In some cases concrete producers use a combination of acrylic polymer with the cheaper naphthalene-based superplasticizer (Table 1) in order to reduce the cost of the chemical admixture for a superplasticized concrete with a low rate of slump-loss. However, under some circumstances, the effect produced was worse than that expected for the individual superplasticizers (15). This effect is shown in Fig. 12 where slump as a function of time is reported for concrete mixtures with pure and blended superplasticizers (a 30% aqueous solution of AP was blended with a 40% aqueous solution of SNF). In general, when AP is replaced by SNF in the blended superplasticizers the initial slump level of the concrete mix is reduced and the slump-loss is increased, in comparison to the performance of the pure AP-based superplasticizer. However, a sort of antithetical effect (as the opposite of synergic) is sometimes and surprisingly recorded for the slump of the concrete mixture when the superplasticizer composition is 25% of AP and 75% of SNF. This specific blended superplasticizer performes significantly worse than any other blended superplasticizers or pure individual polymers. This effect, is more evident when the slump at different mixing times is plotted as a function of the superplasticizer composition (Fig. 13).

However, by changing the source of a given cement type, the antithetical composition effect occurs erratically and independently of the type or strength class of the cement. In some cases, even batches of the same cement type and coming from the same source, but stored for different periods of time, performed erratically with (Fig. 13) or without (Fig. 14) the antithetical composition effect of the AP-SNF blended superplasticizer.

Although the available data cannot explain the mechanism of the antithetical *A-N* composition effect and why it is so erratic, from a pratical point of view these data are able to explain why, under some circumstances, the combined use of AP and SNF on concrete batching plants performed worse than that of each individual superplasticizer.

The performance of blended AP-SMF superplasticizers always decreases when the content of SMF increases (Fig. 15). In other words, the antithetical composition effect, which sometimes was recorded for the AP-SNF blended superplasticizer (Fig. 13), does not occur for the AP-SMF blended polymers regardless of the cement used.

Figures 16 shows slump loss curves for pure and blended AP-MLS superplasticizers. Again, pure acrylic polymer performs better than pure lignosulfonate in terms of higher initial slump. However, the difference is smaller than that found in the AP-SNF or AP-SMF combination. The initial slump level of pure MLS treated concretes is relatively high due to the very high air content in form of large bubbles. The subsequent slump loss of this concrete is substantially due to the loss of part of this unstable air.

The blended superplasticizer with 25% of MLS performs quite well in terms of high initial slump level and negligible slump loss up to 60 min. Moreover, since the air content of the concretes with this AP-MLS blended superplasticizer is as low as that of the other acrylic superplasticized concrete mixtures (< 2%), even the strength development is as good as that of the pure acrylic concretes (Fig. 17). This result appears to be very interesting in view of the lower cost of lignosulfonate with respect to that of the acrylic polymer (Table 1).

With higher lignosulfonate contents (> 25%), the slump loss is more remarkable (Fig. 16) and the strength is reduced to a level lower than that of the reference mix (Fig. 17).

CONCLUDING REMARKS

Superplasticizers are able to enhance the placement characteristics of concrete mixtures by increasing the workability level at a given *w/c*. Therefore they permit easy placement of concrete mixtures even with very low *w/c* required by strength or durability considerations.

The superplasticizing effect depends on: *a*) the chemical composition of the cement and in particular the type of calcium sulfate present as a set regulator (dihydrate, hemihydrate, anhydrite); *b*) the sulfate, alkali and C_3A content of the clinker phase; and *c*) the total sulfate content in Portland cement.

With traditional sulfonated polymer-based admixtures two drawbacks are associated: *a*) the effectiveness of the fluidizing action depends on the addition procedure (immediate or delayed); *b*) the slump-loss can reduce or cancel the advantage of using these superplasticizers particularly in hot weather, with long transportation times and reactive cements.

Now, a new family of superplasticizers - all based on acrylic polymers - is available with improved placing characteristics: *a*) flowing concretes can be produced at lower *w/c* with respect to concrete mixtures containing sulfonated superplasticizers; *b*) the effectiveness does not depend on the addition procedure (immediate or delayed); *c*) the slump-loss is much more reduced with respect to concrete mixes with traditional sulfonated superplasticizers.

Since the acrylic polymer (AP) is more expensive than the sulfonated polymers, a combination of AP with the other ingredients would reduce the cost. However, there is no technical or economical advantage in blending AP with naphthalene- or melamine-based polymers. On the other hand, a combination of 75% of AP with 25% of modified sugar-free lignosulfonate would reduce the cost without any significant loss in the performance with respect to the pure acrylic polymer.

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TABLE 1—COMPARATIVE COSTS OF SUPERPLASTICIZERS IN PERCENTAGE WITH RESPECT TO THAT OF 1 kg OF DRY ACRYLIC POLYMER (15).

Type of Superplasticizer	**Cost of dry polymer**	**Concentration of the aqueous solution**	**Cost of aqueous solution**
AP-based	100	30%	30
MSF-based	80	40%	32
NSF-based	40	40%	16
MLS-based	20	40%	8

TABLE 2—ZETA POTENTIAL OF CEMENT PARTICLES IN SUSPENSION WITH SUPERPLASTICIZERS (14).

Superplasticizer	**Main component**	**Zeta-potential (-mV)**
A	AP*	5.0
B	AP	0.3
C	AP	1.0
D	AP	4.0
E	AP	4.0
F	AP	2.0
G	SNF	23.0
H	SNF	28.0

**AP=Polycarboxylate type*

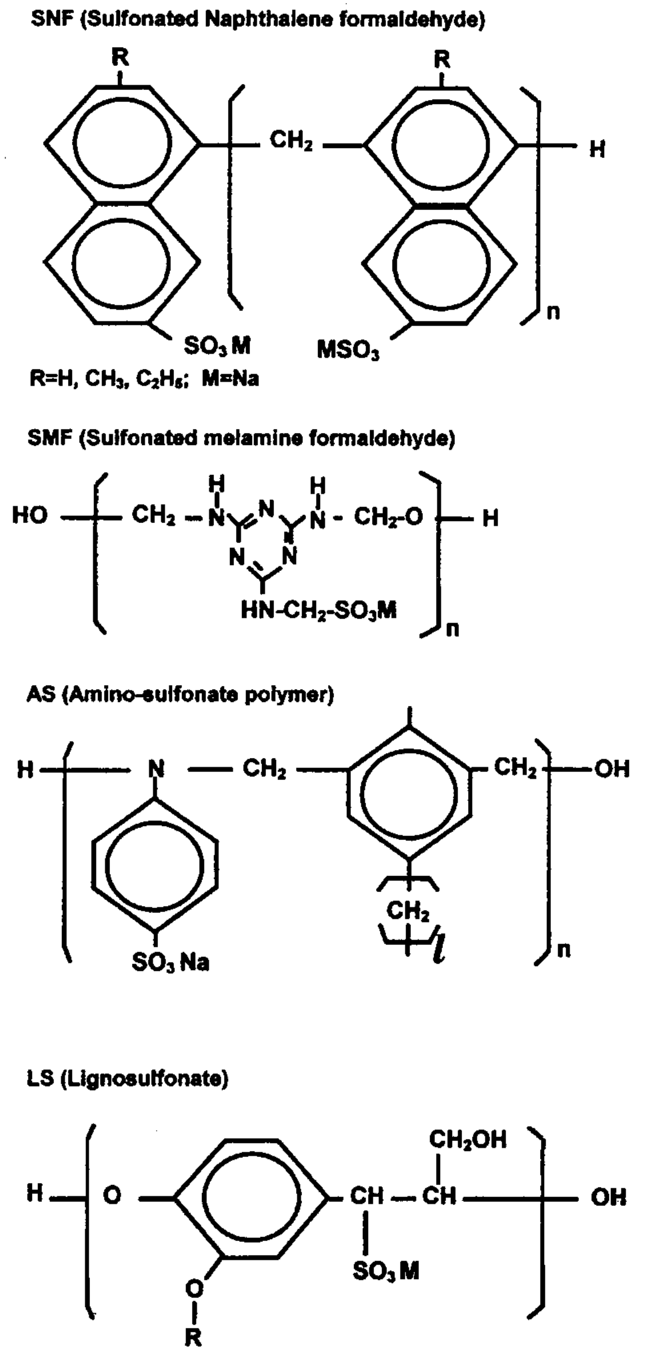
TABLE 3—INFLUENCE OF FORM OF GYPSUM AS SET REGULATOR ON CHARACTERISTICS OF SUPERPLASTICIZED CEMENT PASTES (30).

CLINKER SOURCE	GYPSUM FORM	EFFECT OF 0.4% SNF POLIMER ON:		
		Minislump (cm^2)	Zeta Potential (mV)	Adsorption (% of original polymer)
A	$CaSO_4 \cdot 2H_2O$	175	-24.1	82
A	$CaSO_4 \cdot 1/2H_2O$	79	-23.7	82
B	$CaSO_4 \cdot 2H_2O$	189	-23.2	82
B	$CaSO_4 \cdot 1/2H_2O$	83	-22.4	82

TABLE 4—EFFECT OF MODE OF ADDITION OF CAE, SMF, AND SNF SUPERPLASTICIZERS ON SLUMP OF PORTLAND CEMENT CONCRETE MIXES (4).

ADMIXTURE			CONCRETE MIXTURE	
TYPE	DOSAGE (% dry polymer by cement mass)	MODE OF ADDITION*	W/C RATIO	SLUMP (mm)
SMF	0.50	IMMEDIATE	0.41	100
SMF	0.50	DELAYED	0.41	215
SNF	0.48	IMMEDIATE	0.40	100
SNF	0.48	DELAYED	0.40	230
CAE	0.30	IMMEDIATE	0.39	230
CAE	0.30	DELAYED	0.39	235

** Immediate: admixture with mixing water. Delayed: admixture after 1 min of mixing.*



SNF (Sulfonated Naphthalene formaldehyde)

R=H, CH₃, C₂H₅; M=Na

SMF (Sulfonated melamine formaldehyde)

AS (Amino-sulfonate polymer)

LS (Lignosulfonate)

Fig. 1—Chemical structure of sulfonated superplasticizing polymers (3).

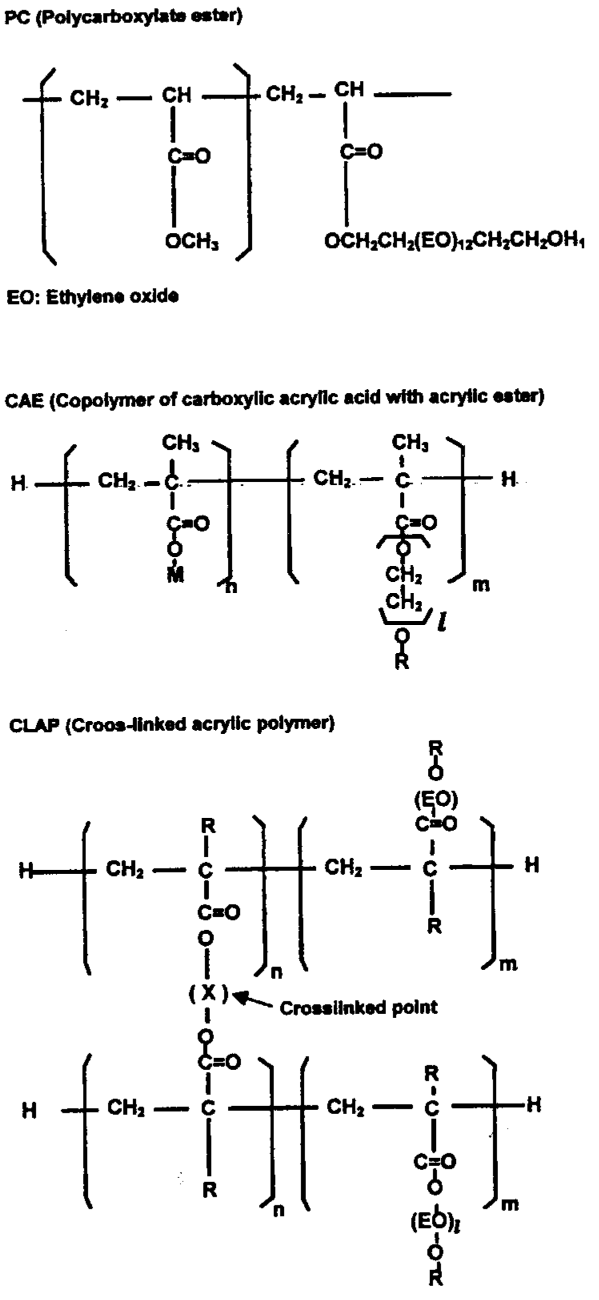


Fig. 2—Chemical structure of superplasticizing acrylic polymers (3, 7, 8).

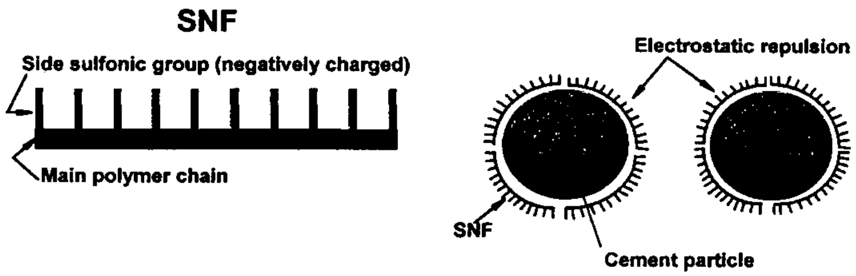


Fig. 3—Schematic picture of sulfonated polymer (SNF) and its electrostatic repulsion effect on dispersion of cement particles.

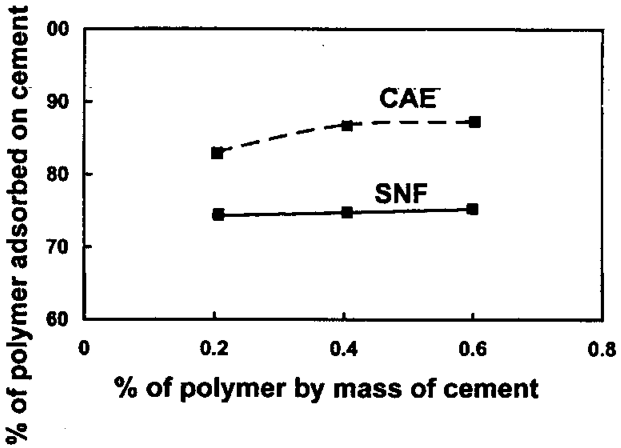


Fig. 4—Adsorption of CAE or SNF on cement as a function of polymer dosage (3).

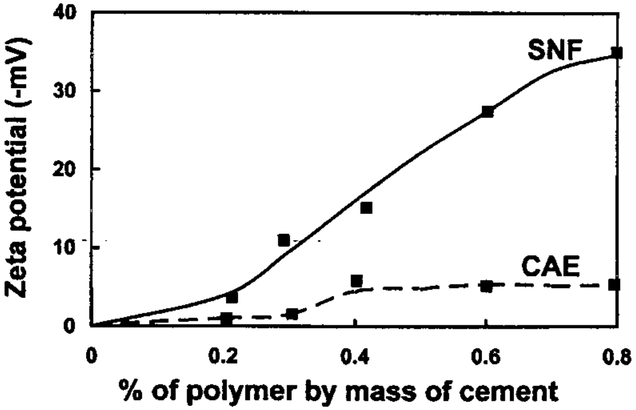


Fig. 5—Zeta potential of CAE or SNF cement pastes as a function of polymer dosage (3).

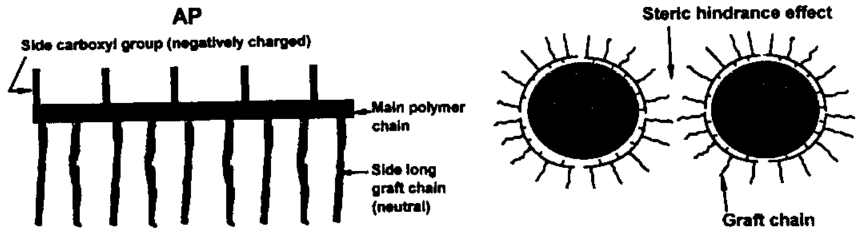


Fig. 6—Schematic picture of acrylic polymer (AP) and its steric hindrance effect on dispersion of cement particles.

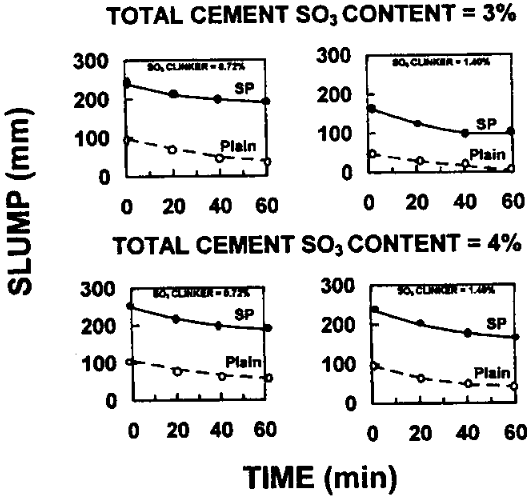


Fig. 7—Slump as function of time for plain and superplasticized (SP) concrete mixes (34).

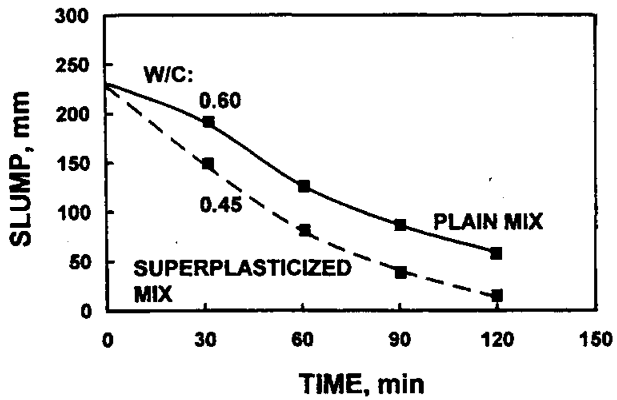


Fig. 8—Slump loss at 20 C for plain and superplasticized mix at same initial slump. Superplasticizer: 0.4 percent as dry SNF polymer by weight of cement.

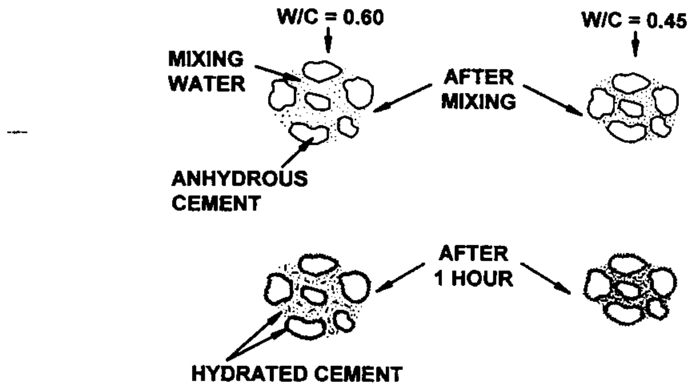


Fig. 9—Schematic picture of cement paste in a plain (*w/c* = 0.60) and superplasticized concrete (*w/c* = 0.45).

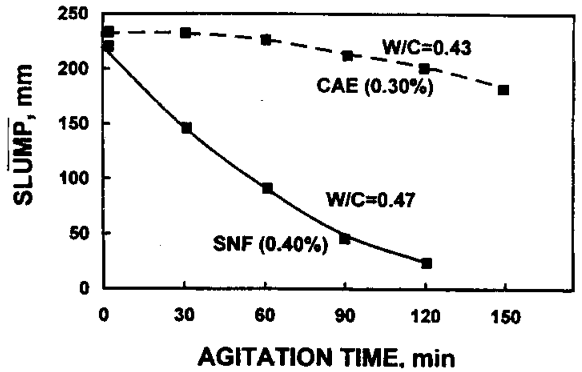


Fig. 10—Slump loss of superplasticized concretes with OPC and CAE or SNF polymer based admixtures (5). Percentages refer to dry polymer.

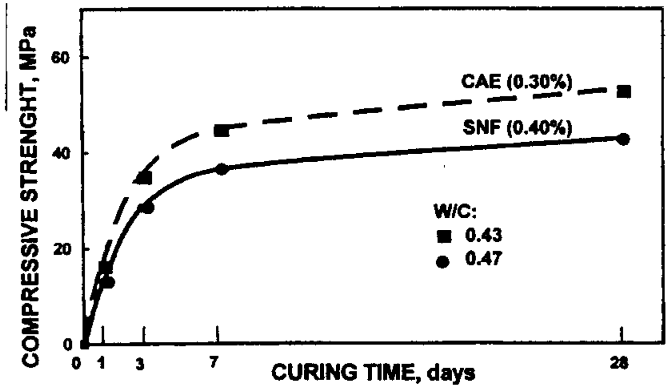


Fig. 11—Compressive strength of superplasticized concretes with CAE or SNF polymer based admixtures (5). Percentages refer to dry polymer.

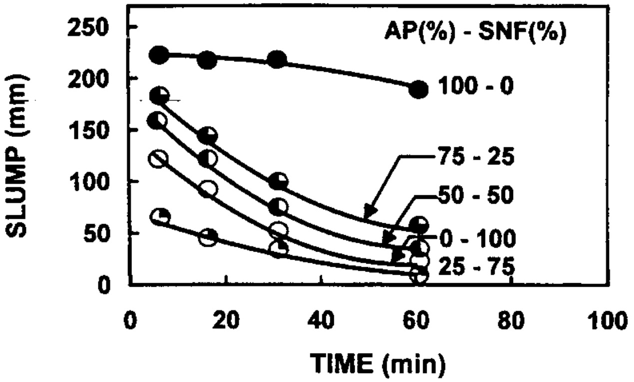


Fig. 12—Slump loss of superplasticized concretes in the presence of pure or blended AP-SNF admixtures (15).

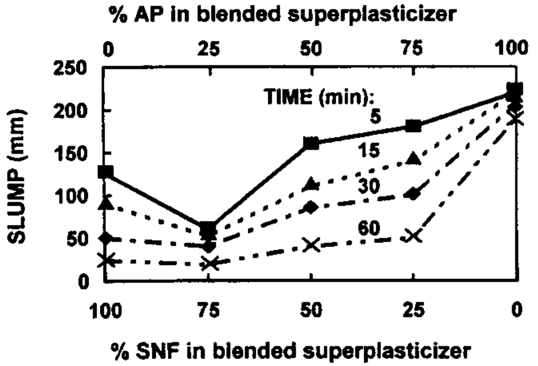


Fig. 13—Influence of the blended AP-SNF superplasticizer composition on the slump of concretes (15).

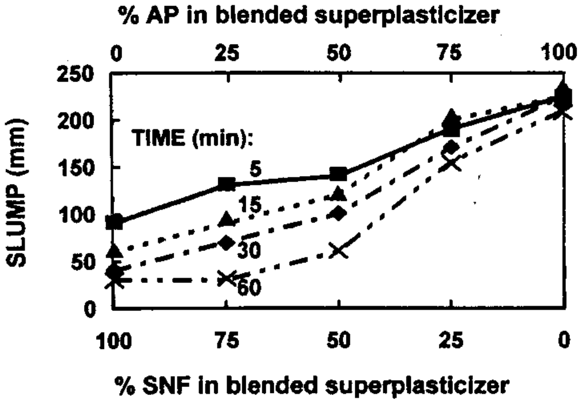


Fig. 14—Influence of the blended AP-SNF superplasticizer composition on the slump of concretes (15).

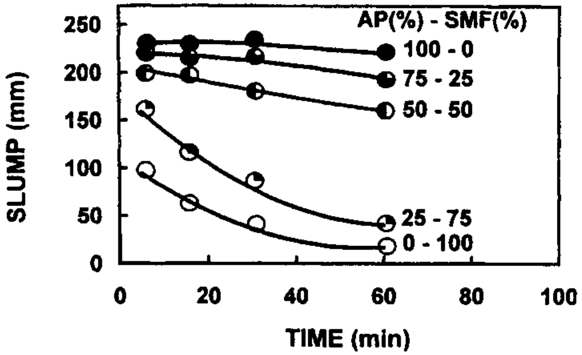


Fig. 15—Slump loss of superplasticized concretes in the presence of pure and blended AP-SMF admixtures (15).

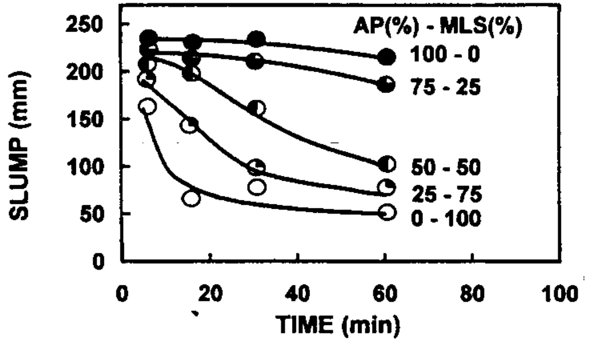


Fig. 16—Slump loss of superplasticized concretes in the presence of pure and blended AP-MLS admixtures (15).

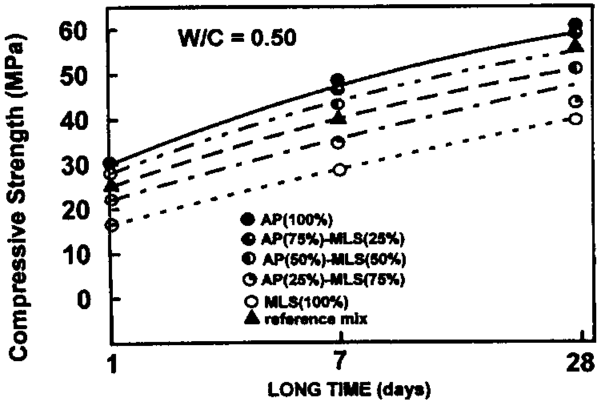


Fig. 17—Compressive strength versus time for concretes with pure polymers AP-MLS superplasticizers (15).