# Superplasticizers: How They Work and Why They Occasionally Don't

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For a long time, concrete was (and still is in some places) simply a mixture of cement, water, and aggregates, whose workability was essentially controlled by the amount of water added during mixing. The setting characteristics were sometimes adjusted with an accelerator (mainly calcium chloride), or a retarder (mainly sugar derivatives). The importance of the water-cement ratio was rapidly recognized as the most important factor governing strength properties, but it was necessary to use excess water in order to obtain a workable mix.

Since the specified strengths were quite low, mixing water was used in abundance to obtain the desired workability. If needed, the concrete strength could be enhanced by increasing its cementitious content. It was eventually recognized, however, that concrete consisting of a simple mixture of cement, water, and aggregates could not last very long when submitted to severe environmental conditions (e.g., freeze-thaw cycles, sea water). Fortunately, chemical admixtures such as air-entraining agents can dramatically improve concrete durability.

To improve the workability of concrete at a given water-cementitious materials ratio, several organic admixtures were introduced to the concrete industry. Such admixtures, designated as water reducers, could achieve remarkable effects on concrete. They could either increase the strength by allowing less water to be used, while maintaining workability; or, they reduced quantities of both water and cement used to obtain a given strength and workability.

One particular type of water reducer was shown to be extremely effective in controlling the workability of concrete. These were water-soluble organic polymers designated as high-range water reducers, or superplasticizers. An important class of these polymers is the polynaphthalene sulfonates which, since 1938, have been known as cement-dispersing agents.[1] There was, however, little interest in these compounds, since concrete design strengths were low, and water contents could readily be adjusted to achieve the desired workability. Also, because of the relatively low cost of cement, there was no economic incentive for reducing the cement contents.

The first polymeric water reducers adopted by the concrete industry were the polymeric dispersants derived from lignin, the lignosulfonates. The latter, being a by-product of the pulp and paper industry, were relatively inexpensive, and their water reducing properties could be exploited at minimal cost. However, it later became apparent that the variance in composition of these by-products, especially their sugar content, could induce significant problems in set retardation and air entrainment.

The benefits of synthetic polymers such as polynaphthalene sulfonates (PNS) were then re-examined and developed further, particularly in Japan in the early 1960s. Polymelamine sulfonates (PMS), another family of synthetic polymers, were also developed as concrete superplasticizers and patented in Germany.[2]

When superplasticizers made their entry in the concrete industry, they were used at moderate dosage, generally 1 to 3 L/m$^3$ (0.2 to 0.6 gal./yd$^3$) — for admixtures at approximately 40 percent by weight of active material — to fluidify concrete just before placing. At these moderate dosages, very few problems were observed, except perhaps when used with some air-entraining admixtures.

Today, superplasticizers are often used as high-range water reducers, to make concrete stronger by lowering the water-cement ratio. To achieve water reduction levels as high as 30 percent, superplasticizers have to be used at high dosages ranging between 5 and 20 L/m$^3$ (1 and 4 gal./yd$^3$). As the water-cementitious materials ratio was decreased, unexpected behavior was sometimes experienced with particular cement-superplasticizer combinations, despite the fact that both components satisfied their respective acceptance requirements. With time, these types of phenomena became more frequent, especially in the case of very low water-cementitious materials ratio concrete. Such phenomena are usually referred to as cement-superplasticizer incompatibility.

This paper, prepared jointly by a physical chemist, a materials engineer, and a structural engineer, is intended for practitioners. Readers interested in detailed information on specific aspects of superplasticizers may consult various treatises,[3-7] proceedings of dedicated conferences,[8-11] or research papers cited in the references.

## The nature of superplasticizers

### Chemical composition

Modified lignosulfonates, polymelamine sulfonates (PMS), and polynaphthalene sulfonates (PNS) are the most commonly used superplasticizers, alone, or in mixtures. Other compounds — polyacrylates and polystyrene sulfonates, for example — also exhibit water-reducing and concrete fluidifying properties and can be used as superplasticizers. As noted earlier, lignosulfonates are obtained as a by-product of the pulp-and-paper industry. The modified lignosulfonates are lig-

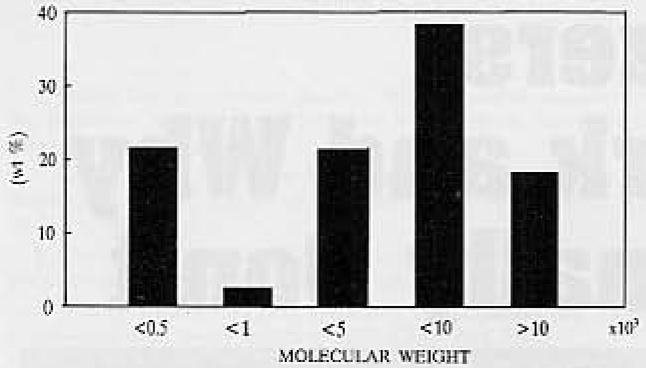


Fig. 1 — Molecular weight characterization of a PNS superplasticizer.

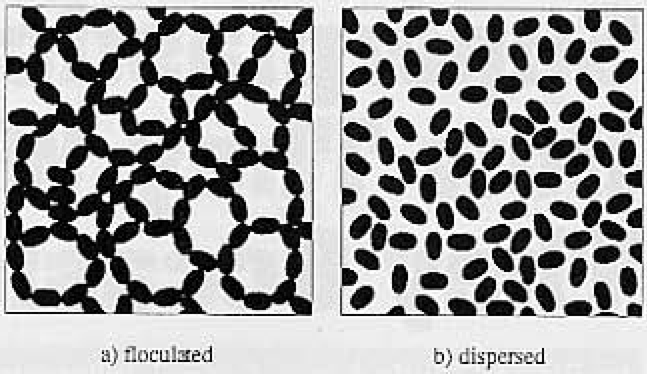


Fig. 2 — Schematic representation of flocs of cement particles.

nosulfonates from which sugars, which cause excessive retardation, have been removed. Other superplasticizers are synthetic products, produced directly from pure components. The general schemes for the synthesis of PNS and PMS superplasticizers are presented by Rixom and Mailvaganam.[7]

### Characterization and specification

Commercially available superplasticizers are usually supplied with the chemical analysis data required to calculate dosages (e.g., percent by weight of active material for a liquid or percent by weight of moisture for a solid), or to ensure compliance with specific application requirements (e.g., type of salt; pH value; sulfate, chloride, and formaldehyde contents). While these data are essential to allow proper utilization of the superplasticizers, they do not provide any clue to the performance of the product. The viscosity of the concentrated superplasticizer solution is also usually specified. To some extent, the viscosity reflects the average molecular weight of the polymers, a property that greatly influences product performance.

To assess the performance of superplasticizers, extensive product characterization must be pursued, both in the intrinsic properties of the polymers and in their functional properties. While the detailed description of such characterization is beyond the scope of this paper, it may be noted that the relevant intrinsic properties of the polymers include: percentage of sulfonation, average molecular weight, distribution of molecular weights, and polymer configuration (linear, branched, cross-linked). The average molecular weight and the distribution of molecular weights are particularly important with respect to the fluidification of cementitious systems. Molecular weight data obtained by ultrafiltration for a typical, efficient polynaphthalene sulfonate are shown in Fig. 1. The relevant functional properties to be characterized include dispersion and fluidification indices. Some of these properties and examples are discussed below.

### Standards

Superplasticizers are known in the industry under many different names (high-range water reducers, plasticizers, fluidifiers, polynaphthalene sulfonates, polymelamine sulfonates, etc.). This, together with the added complexity of many proprietary-mixed formulations, has tended to create a level of confusion that may be a deterrent for practitioners. To help minimize such complications, recall that superplasticizers are chemical admixtures that can be used either as high-range water reducers in the production of concrete with normal consistency or as plasticizers in the production of flowing concrete. The characteristics of these two applications are defined, respectively, in ASTM C 494 and C 1017 standard specifications. Updated guidelines for their use are presented in the *ACI Manual of Concrete Practice*.[12]

The fact that all superplasticizers meet standard specifications for application in concrete does not mean that they are all equivalent. The various superplasticizers available on the market are clearly not equivalent, neither in their chemical parameters, nor in their functional properties. Standard specifications define minimum or maximum values for some parameters so that a specific superplasticizer may meet the minimum of the standard, while another may exceed this minimum specification by a large margin.

## How superplasticizers work in concrete

### Deflocculation

Portland cement particles have a strong tendency to flocculate when mixed with water.[7] This tendency is the result of several types of interactions: van der Waals interactions between particles; electrostatic interactions between sites bearing opposite charges; and strong interactions (or bridging) involving water molecules or hydrates.[13]

The flocculation process leads to the formation of an open network of particles depicted schematically in Fig. 2a. The network voids can trap part of the water, which is then unavailable for surface hydration of the cement particles and for fluidification of the mix. These effects result in a stiffening, or increase in apparent viscosity, of the cementitious system. To achieve a homogeneous distribution of the water and the optimal water-cement contact, the cement particles must 1) be properly deflocculated and 2) be kept in a state of high dispersion (Fig. 2b).

The flocculation of cement particles in water and the dispersing influence of superplasticizers can easily be demonstrated through a simple sedimentation experiment. A fixed quantity of cement is vigorously mixed with water and the suspension transferred in a 1-L graduated cylinder. Upon standing, within less than twenty minutes, all the cement particles will have flocculated and settled to the bottom of the cylinder. Their apparent volume is larger than that occupied by the same amount

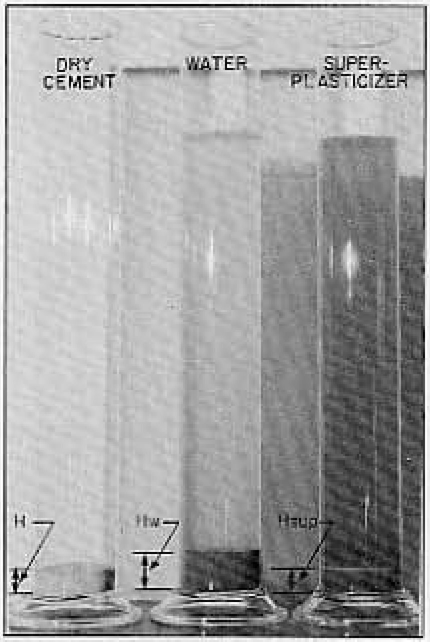


Fig. 3 — Sedimentation of cement particles in water and in the presence of a superplasticizer.

of dry cement (Fig. 3). However, when the same quantity of cement is mixed in the presence of a small amount of dispersing admixture, it is observed that, after twenty minutes, very few cement particles have settled (only the coarse ones), as shown in Fig. 3. It may take 24 to 48 hours for the cement particles to settle, in which case they form a dense layer occupying almost the same volume as the dry cement. This experiment clearly shows that the superplasticizer is highly effective in deflocculating and dispersing cement particles. This approach has been proposed to evaluate the required superplasticizer dosage.[14]

### Other aspects

In high solids-content slurries, such as low water-cement ratio concretes, the deflocculating and dispersing action of superplasticizers described above in dilute suspensions must still play an important role in the fluidification effect. However, other phenomena are also likely to be present and different authors have proposed a variety of effects, or mechanisms, to explain the combined dispersion-fluidification properties of superplasticizers in concrete. These explanations invoke one or more of the following:[15]

- reduction of the surface tension of water;
- induced electrostatic repulsion between particles;
- lubricating film between cement particles;
- dispersion of cement grains, releasing water trapped within cement flocs;
- inhibition of the surface hydration reaction of the cement particles, leaving more water to fluidify the mix;
- change in the morphology of the hydration products; and
- induced steric hinderance preventing particle-to-particle contact.

It is likely that many of these phenomena contribute to the fluidifying effect of superplasticizers in fresh concrete, but some effects are currently better documented than others. For example, superplasticizers do not generally reduce the macroscopic surface tension of water. On the other hand, air-entraining agents, which efficiently reduce the surface tension of water, are not considered superplasticizers, at least at the concentration normally used (their ability to increase the fluidity of concrete is generally attributed to the entrapped air bubbles which act as fine aggregates). Hence, the lowering of the surface tension of water is probably of little or no importance in the fluidifying mechanism of superplasticizers.

There is, on the other hand, broad agreement that the superplasticizer molecules adsorb strongly onto the surface of the cement grains.[16-20] The adsorption of charged polymers conveys a high surface charge (zeta potential) to all cement particles. These charges contribute important repulsive forces between the particles and most certainly play a role in deflocculating and dispersing cement particles in water. This effect can be observed in slurries of many different types of particulate materials for which important changes in zeta potential can be measured and correlated with rheological properties.[20-21]

With regard to the influence of superplasticizers on the morphology of the hydration products, several authors[22-24] have shown that the morphology of ettringite produced during the hydration of cement is altered in the presence of superplasticizers. Instead of being needle-shaped, the crystals formed are very small, nearly cubic. The latter are expected to be much less detrimental to the fluidity of the hydrating paste. This morphology change can certainly contribute to the fluidification mechanism, but it is yet unclear to what extent, since superplasticizers are also efficient in fluidifying fresh concrete prepared and partially hydrated in the absence of a superplasticizer.

Given the current knowledge of the mode of action of superplasticizers and the level of detail relevant here, the concrete fluidifying effects can be summarized as follows.

The flocculation of cement particles is mainly provoked by two kinds of attractive forces: van der Waals forces and electrostatic forces. The adsorption of a charged polymer on the particle creates particle-to-particle repulsive forces which overcome the attractive forces. This will disperse the particles and prevent their re-agglomeration. This action will last as long as sufficient superplasticizer molecules are available at the particle/solution interface; that is, the quantity of available superplasticizer will progressively decrease as the polymers become entrapped in hydration products.

In addition to the electrostatic effect, specific effects, such as the adsorption of PNS on the surface of the $C_3A$ phase, lead to additional benefits. The sulfonate $-SO_3-$ group can substitute for the sulfate group ($SO_4^{=}$) in the $C_3A$ adsorption process, but the PNS then alters the course of the hydration reactions and modifies the hydration products as noted above. The latter effects retard the surface hydration reactions and should be especially important in preventing slump loss.

## Superplasticizer efficiency

The workability (slump and slump loss) of a fresh concrete mix depends, to some extent, on the characteristics of the superplasticizer used. However, the mix composition, the variability in cement composition or properties, and other factors, such as the mixing procedure and equipment, often play an important role.

### Superplasticizer parameters

It is now well established that the average molecular mass of the superplasticizer is of prime importance for its efficiency in reducing water in portland cement mixes. The higher the molecular mass, the higher the efficiency. This relationship has been established for naphthalene-based superplasticizers[25] as well as for melamine-based superplasticizers.[26] The increase in molecular mass influences both the dispersion properties[25] and the morphology of the $C_3A$ hydration product.[23] It should be noted, however, that there is a maximum value of molecular mass beyond which the dispersion effect is expected to decrease, and this has indeed been observed.[25]

The chemical nature of the superplasticizer, whether naphthalene-based or melamine-based, can also have an effect on the rheological behavior of a concrete mix. However, no definite trend could be identified from a literature survey for properties like slump and slump loss, retardation, air entrainment, etc. This clearly indicates that several intrinsic properties of the superplasticizer may influence its performance. The chemical features of the other components of the mix can also play an important role. Hence, to enable valid comparative studies, an adequate characterization of both the superplasticizer and the other mix constituents is essential.

### The cement

Portland cement is a complex mixture of inorganic compounds — mainly calcium silicates, calcium aluminate, calcium ferroaluminate, and calcium sulfate — ground together at varying degrees of fineness (many of these compounds can exist in different crystalline forms). Some cements also contain filler (limestone) or pozzolanic material (slag, fly ash). Chemical admixtures used as grinding aids can also remain present in the cement.

The influence of cement fineness on the amount of superplasticizer needed to reach a certain level of workability in the case of concretes (or of fluidity in the case of grouts) has been clearly established.[27] The finer the cement, the higher the superplasticizer dosage required to achieve a given workability.

Due to the wide variability in the chemical and physical properties of cements, it may be expected that different cements will behave in different ways in the presence of the same superplasticizer. To rationalize this behavior, many studies have been made with cements of controlled composition. Among the cement chemical parameters which have been found to exert a major influence on the properties of superplasticized cement mixes are the $C_3A$ content,[6,27] the morphology of the $C_3A$, the alkali content,[6] and the form of calcium sulfate added to the clinker.[28] The critical role of sulfates on the rheology of portland cement slurries has been shown: it is not the total amount of $SO_3$ in cement that is important, but rather the availability, or the rate of dissolution of $SO_4 2-$ ions, that must be balanced with the chemical reactivity of the $C_3A$.[29]

### External factors

The action of a superplasticizer on a particular cement depends also on factors that are not related to the physicochemical properties of the cement and the superplasticizer, but in the way these are blended or mixed. For example, the type of mixing equipment affects the concrete workability. It is very frequently observed that the same workability of concrete prepared in a large industrial mixer can be obtained with 1 to 3 L/m$^3$ (0.2 to 0.6 gal./yd$^3$) less superplasticizer than in a small laboratory mixer.

It has been advocated that multiple additions of the superplasticizer, when possible, result in a reduction of the total amount of superplasticizer needed to achieve a given workability. This technique consists of introducing from one-half to two-thirds of the total amount of the superplasticizer at the beginning of the mixing, and delaying the introduction of the remaining quantity of the superplasticizer until the end of the mixing sequence or in the field. This technique has been shown to work well in the laboratory, but is not easily implemented in practice. The typical mixing period in industrial preparations is from one to two minutes. Thus it is difficult to fractionate the introduction of the superplaticizer in so short a period of time. On the other hand, the delayed addition of part of the superplasticizer at the delivery site can offer significant advantages. Instead of transporting a very high slump concrete that can spill from the truck (upon emergency braking), or that can destabilize the truck, drivers prefer to transport a 100 mm (4 in.) slump concrete and to fluidify it just before placement in the forms.

## Superplasticizer dosage

Ultimately, the performance of a superplasticized concrete mix is established in field trials. However, many small-scale tests have been developed on cement pastes or on mortars to rapidly get information on the performance of various cement-superplasticizer combinations and to determine the optimal superplasticizer concentration.

On mortar, the percentage of water reduction can be determined rapidly for various experimental conditions by the flow table method described in the ASTM C 109 standard specification. In this method, the quantity of water of the superplasticized mortar is reduced to obtain the same consistency as that of a control mortar.

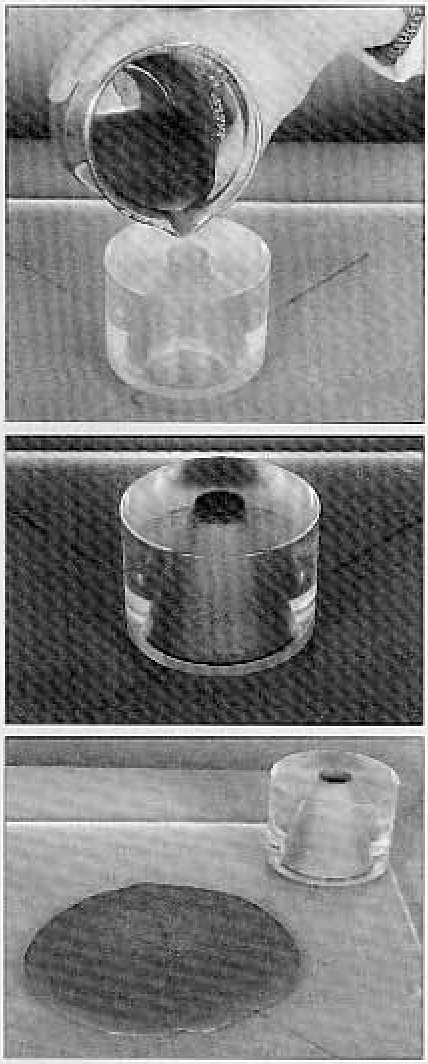

Fig. 4 — The mini-slump test.

For cement pastes, the mini-slump test described by Kantro[30] allows a rapid comparison of the fluidity of various cement-superplasticizer mixtures. As shown in Fig. 4, this test is very similar to the familiar concrete slump test; the dimensions of the cone are changed, but the proportions remain the same. After removing the mini-cone, the spread of the paste is measured and the results given as the average of the spread area measured on two perpendicular diameters. One advantage of this test is that it requires a minimal amount of cement.

Another way to compare the behavior of various cement-superplasticizer mixtures is by using a Marsh cone

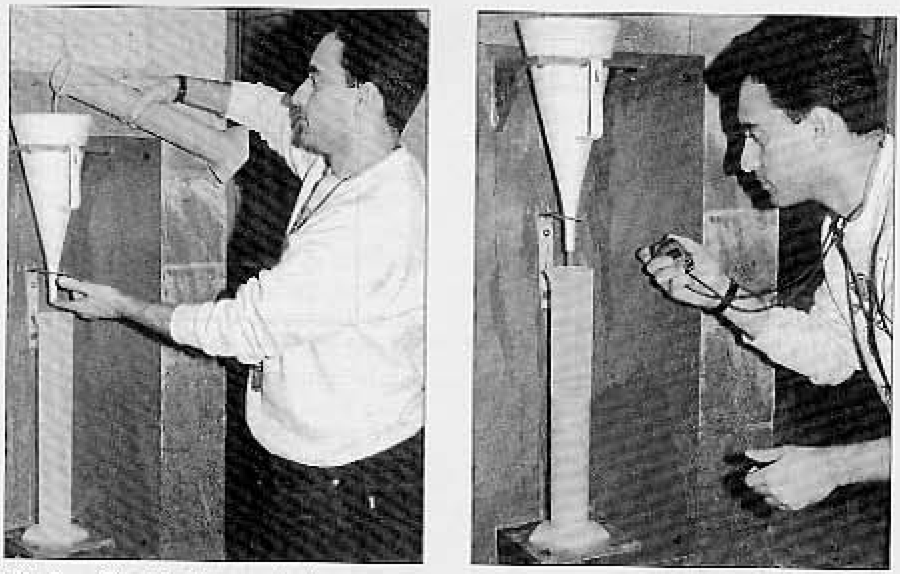

Fig. 5 — The Marsh cone test.

(Fig. 5). Marsh cones of different sizes and openings are already used in the cement and petroleum industry to measure or compare the fluidity of grouts not necessarily made of portland cement. After thoroughly blending the cement, water, and superplasticizer mixture, the time it takes for a given volume of grout to pass through the opening is measured. This time is called the Marsh flow time, and it is directly related to the viscosity of the grout.

If the apparent viscosity of a slurry of a given water-cement ratio is measured with a Marsh cone[27-31] and plotted as a function of the superplasticizer dosage as shown in Fig. 6, it is observed that the viscosity decreases as the superplasticizer dosage increases until a certain superplasticizer dosage is reached, after which any addition of superplasticizer does not significantly reduce the viscosity of the slurry. This point has been called the saturation point (Fig. 6).

There is no benefit to using more superplasticizer than the dosage corresponding to the saturation point. In fact, it could be detrimental to use a higher dosage: with excessive amounts of superplasticizer, the aggregates and cement particles start to segregate.

The saturation point varies from one cement to another, when using the same superplasticizer, and from one superplasticizer to another, when using the same cement. The viscosity and superplasticizer dosage at the saturation point depends on the water-cement ratio of the grout, the fineness of the cement, the total amount of $C_3A$, the reactivity of the $C_3A$, the sulfate content, and the rate of dissolution of the sulfates. The efficiency of the mixing system used to prepare the grout also influences the value of the saturation point and mix rheology, but these effects are readily minimized by following rigorous testing procedures.

With so many factors influencing the behavior of superplasticizers in the presence of a given cement, it is readily understood that a single "recommended" superplasticizer dosage for a given brand of superplasticizer makes little sense. For each cement-superplasticizer combination and mix design, there will be one optimal superplasticizer dosage.

## Potential problems

The introduction of an additive to fresh concrete sometimes leads to problems during utilization. For example, with lignosulfonates, a strong retardation and the entrainment of an excessive amount of large air bubbles have been observed at high dosages. These adverse effects are mainly due to the sugars and other contaminants present in commercial lignosulfonates, since these compounds are difficult to remove completely. Some incompatibility problems between cement and lignosulfonates have also been reported.[32-34] Such problems were mostly related to an unusually rapid stiffening of the concrete. The cements used complied with the required $SO_3$ content and the particular water-reducing admixtures met their acceptance standards. To explain this incompatibility, Ranc suggested that the admixture can exert an influence on the availability of sulfate and calcium ions, and suggested various possible situations leading to loss of concrete fluidity.[28]

With some superplasticizer-cement combinations, various problems have been reported, such as low fluidification effect, rapid slump loss, severe segregation, overretardation, loss of entrained air, and a particular phenomenon known as "bubbling concrete," or the "champagne effect". Again, these problems may originate in variations in cement composition and properties, together with changes in the characteristics of superplasticizers.

### Rheological problems

As long as polynaphthalene and polymelamine sulfonates were used at moderate dosages to fluidify normal-strength concrete, very few cement-superplasticizer compatibility problems were reported in the literature. But, as the use of superplasticizers at higher dosages developed in concretes with lower and lower water-cement ratios, it became evident that some cement-superplasticizer combinations were incompatible. In some instances, it was not possible to control the slump of concrete long enough to place it correctly.[35,36] It has also been observed in a few cases that further increasing the superplasticizer dosage could worsen the situation. This cement-superplasticizer compatibility is so critical when making high-performance concrete that some cements have to be rejected, not because it is impossible to achieve the desired strength, but because it is impossible to maintain the workability long enough to place the concrete correctly.[37]

The degree of cement-superplasticizer compatibility must thus be determined by measuring the concrete

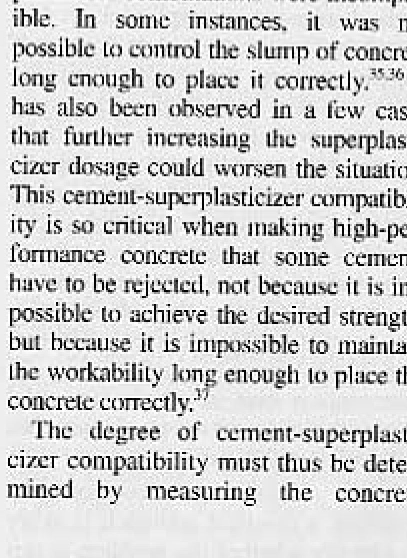


Fig. 6 — Saturation point.

slump and the loss of slump as a function of time. Reliable indications of the degree of compatibility between a cement and a superplasticizer can also be obtained from cement grouts using the Marsh cone test or the mini-slump test.

When measuring the flow time of a superplasticized grout with a Marsh cone, it is interesting to follow the change in flow time during the first hour that follows the mixing of the slurry. These results provide an indication of the behavior of the cement-superplasticizer combination during the critical period when concrete is transported and placed. The mini-slump method can also be used for the same purpose.

During this one-hour observation period, four types of behavior can be observed. Fig. 7a illustrates the case of a highly compatible cement-superplasticizer combination for which it is easy to have full control of the viscosity and slump during one hour. Fig. 7b depicts a case of poor compatibility between a cement and a superplasticizer. The saturation point corresponds to a very high dosage of superplasticizer (1.5 percent). Despite this high dosage of superplasticizer, the viscosity of the grout remains quite high and rapidly increases with time. Figs. 7c and 7d represent intermediate cases. Fig. 7c represents a case in which the initial viscosity and saturation point correspond to that of a compatible combination, but in which the viscosity increases with time so that, at one hour, the cement-superplasticizer combination is no longer compatible. Fig. 7d represents a case in which the initial compatibility is not so good, but does not evolve with time.

When facing an incompatibility problem, a practical approach is to try to identify whether the problem is primarily due to the high reactivity of the cement or to the poor performance of the admixture, by cross-testing with other superplasticizers and other cement samples. If no alternative cements or superplasticizers are available to alleviate the incompatibility, low levels of retarding admixtures may be tentatively incorporated. If retarding agents do not help, supplementary cementitious materials (slag, fly ash) may be blended in.[38] If none of these approaches can be successfully implemented, the water-cement ratio may then be increased progressively, while varying the dosage of superplasticizer to achieve the desired workability,[39] while ensuring that the concrete still meets the strength specifications.

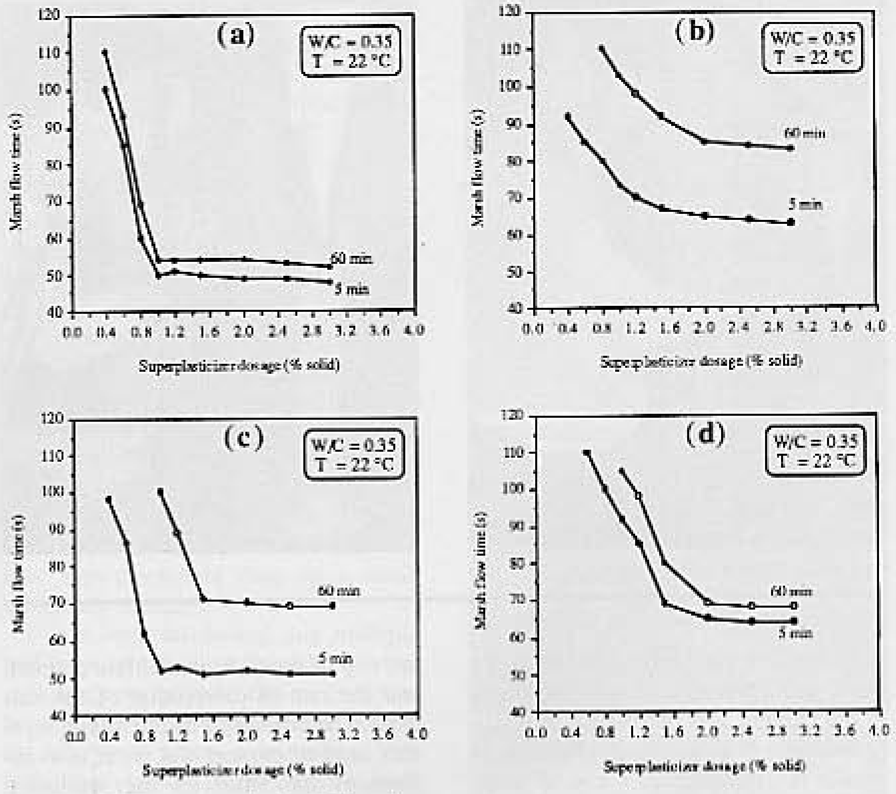

Fig. 7 — Different rheological behaviors.

## Segregation

After the introduction of an excessive dosage of superplasticizer, the cement paste may become too fluid and no longer maintain the coarse or even the fine aggregate in suspension, causing severe segregation (some researchers, however, contend that such a concrete could have been underdosed in aggregate and are proposing a new way of mixing concrete called the slurry method). This segregation phenomenon is always related to a superplasticizer overdosage beyond the saturation point.

In some cases, the hardened samples are covered with a white layer composed mainly of lime, calcium sulfate, and some calcium carbonate. In such cases, there is more than simple physical segregation, there is also some chemical-phase segregation. To correct this problem, additional quantities of cement may be added to the mix, if possible. This will decrease the water-cement ratio and consume the excess superplasticizer, both effects tending to restore adequate consistency.

## Overretardation

The retardation period of a superplasticized concrete is closely related to the Blaine surface area and to the chemical composition of the cement used to produce it (mainly the $C_3A$ content). It is also dependent upon the superplasticizer dosage[40] and temperature.

Excessive retardation problems may arise if the superplasticizer is accidentally overdosed or if the cement composition has changed significantly after the mix proportions have been established through trial mixtures.[41] The retardation effect due to the superplasticizer may last from minutes to many hours. However, when setting starts, it occurs rapidly, as evidenced by the time dependence of the heat of reaction.[40] A possible solution to an overretardation problem in concrete that has already been placed is to increase the temperature of the concrete.

## Air-entraining admixture compatibility

In order to improve the freezing and thawing resistance of concrete, air voids of proper dimension and spacing have to be present in the grout, whether or not it contains a superplasticizer. When superplasticizers are used without an air-entraining agent, very few air voids are created in concrete.[42] However, a proper quantity of air is easily entrained in superplasticized concrete when using a high-quality air-entraining admixture. This has been verified with naphthalene- and melamine-based superplasticizers.[42]

When superplasticizers are used with air-entraining agents in concrete, an increase of the spacing factor is sometimes observed, compared to the same mix without superplasticizer.[43-47] This is due to the coalescence of part of the small air voids. In such cases, the dosage of the air-entraining agent should be adjusted to compensate for this effect. For superplasticized concretes with low water-cementitious materials ratios, the air-void spacing factor has, in some cases, been reported to be less critical for the freeze-thaw resistance of concrete.[42] However, it remains good practice to conform to code specifications for air content and spacing factor.

In some instances, a loss of entrained air has been reported when using superplasticizers.[48] These problems further emphasize the need to check the superplasticizer/air-entraining agent compatibility during mix design.

### Bubbling concrete

In some cases, non-air-entrained concretes with low water-cementitious materials ratios exhibit an unusual behavior that has been referred to as "bubbling," or the "champagne effect," when some polynaphthalene superplasticizers have been overdosed (the authors have no experience with polymelamine sulfonates in this regard). During mixing, many large air bubbles are formed and momentarily entrapped in the fresh concrete. They rapidly sparkle out like champagne bubbles, but seem to be regenerated just as rapidly by the mixer paddles.

At such low water-cementitious materials ratios, the concrete mixtures are rather sticky, so that some large air bubbles can remain trapped in the hardening concrete, even after extensive vibration, resulting in a Swiss-cheese-type concrete.

## Blended superplasticizers

Polynaphthalene and polymelamine sulfonates can be used alone or blended with lignosulfonates. Very few attempts of mixing polynaphthalene and polymelamine sulfonates have been published.[49]

Blending polynaphthalene or polymelamine sulfonates with lignosulfonates presents two advantages when superplasticizers are used at low dosages (1 to 5 $L/m^3$ [0.2 to 1 $gal./yd^3$] of concrete). The first advantage for the admixture manufacturer is economical: lignosulfonates are less costly than polynaphthalene or polymelamine sulfonates. The second advantage is chemical: the sugars present in lignosulfonate in most cases slightly retard setting, so that concrete keeps its workability longer. However, as discussed earlier, with some cements, the effect of the lignosulfonate can be the opposite.

Despite the fact that the simultaneous use of polynaphthalene and polymelamine sulfonates has not been widely studied, the authors are convinced that both polynaphthalene and polymelamine sulfonates can be used in the same concrete. For example, when making high-performance concretes at very low water-cementitious materials ratios, polynaphthalene sulfonates could be used at the mixing plant, while polymelamine would be used at the job site to produce the desired level of workability. Such a combination would seem adequate for concretes in which polynaphthalene sulfonates induce a greater retardation than polymelamine sulfonates.

## Conclusion

Superplasticizers are highly efficient dispersing admixtures when they are properly used. For the first time in concrete history, it is possible to 1) increase concrete workability at will without any addition of water; 2) disperse efficiently cement particles so that concretes can be made using less water than needed for full hydration of cement particles; 3) produce hydrated cement paste stable and dense enough to bond very strongly to aggregates and reinforcing steel in order to produce a very strong composite material; and 4) make concrete so dense that it can be stronger and more durable than many natural rocks.

However, it must be realized that the introduction of superplasticizers in concrete involves a new chemical component in a complex hydraulic binder system that already contains several added chemicals: a grinding aid that may have been used during cement grinding, a water reducer, an air-entraining agent, and sometimes, a retarder or accelerator. It should not be surprising that, in such complex systems, in which each component has been individually optimized, incompatibility problems may develop.

Due to the variety of proprietary admixture formulations, it is difficult to provide the concrete industry with simple rules specifying the proper use of superplasticizers in the presence of other types of admixtures. It is likewise unrealistic to ban the use of superplasticizers because some other admixture entering into the composition of concrete is not compatible with a particular cement-superplasticizer combination. A better approach would be to investigate the origin of the incompatibility problems and eventually determine how to control or avoid them, while still taking full advantage of the benefits of superplasticizers in developing concretes.


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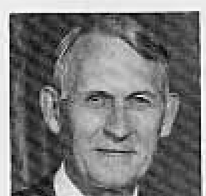

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