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Low-Slump-Loss Superplasticized Concrete

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The influence of a naphthalene-sulfonated polymer-based superplasticizer with a low slump loss on portland cement hydration and properties of concrete is examined. Differential thermogravimetric analysis shows that, in the presence of the superplasticizer, calcium-silicate hydration is retarded during early curing and increases at greater ages. Scanning electron microscopy indicates that addition of superplasticizer causes no substantial change in the microstructure. A rheoplastic concrete with a low slump loss can be obtained if it is a flowing and nonsegregating superplasticized mix. Tests of compressive strength, static and dynamic moduli of elasticity, shrinkage, creep, and frost and sulfate resistance were carried out on hardened concretes. Superplasticized rheoplastic concrete performs as well as the corresponding no-slump control mix at the same water-to-concrete ratio but much better than the following control concrete at the same workability.

The use of superplasticizers has grown a good deal in recent years, particularly in Europe and Japan. In Italy, for example, approximately 2.5 million m^3 of concrete containing superplasticizers has been produced in the last three years.

Normally these admixtures are used to produce concretes of a low water-to-cement (w/c) ratio and therefore high mechanical strength. The result is a considerable savings in cement and a flowing concrete that does not lose strength.

Extensive use of such applications depends on the cost of cement. Again, in Italy, where the cost of cement is relatively low ($25-35 U.S./t), the use of superplasticizers to make flowing concretes is very common. However, in countries where the cost of cement is noticeably higher, using superplasticizers to make flowing concretes is even more promising, because of potentially lower-cost technology, in terms of ease of placement in particular.

Addition of a superplasticizer will produce flowing concretes of a low w/c ratio approximately equal to that of a no-slump concrete (1). Low or no segregation at all is generally assumed for flowing concrete (2, 3). However, flowing does not necessarily imply low segregation as well. For this reason we suggest (4-7) that "rheoplastic" be used ("rheo" from the Greek "to flow") to mean a cohesive, plastic, and nonsegregating concrete.

A rheoplastic concrete may be obtained by adding a specific amount of superplasticizer to a no-slump concrete to produce a nonsegregating, flowing concrete that has a slump of at least 20 cm and the same w/c ratio as the plain no-slump concrete. Rheoplastic, then, will indicate a very flowable and nonsegregating concrete, and flowing will indicate a concrete displaying good flow properties only.

PURPOSE

The purpose of this paper is to examine the properties of a rheoplastic concrete in terms of loss of workability. It is generally well known that superplasticized concrete shows a relatively high workability.

Loss of workability may in fact to a large degree obviate whatever advantages the use of superplasticizers may have. As numerous authors (8-15) have pointed out, because most superplasticizers have revealed a rapid workability loss, discontinuous or delayed addition during transportation or just before placing has been adopted. This procedure, however, considerably limits the use of superplasticized flowing concretes in several ways.

First, a flowing concrete with a very low w/c ratio cannot be produced on a large scale because transportation of the stiff concrete before the addition of a superplasticizer could cause serious wear on the drum and blades of the mixer and great stress on the engines. Therefore such a procedure would at best be limited to producing flowing concretes of w/c ratio equal to that of a concrete at plastic consistency (slump of 60-100 mm) before addition of the admixture.

Second, discontinuous or delayed addition of the admixture could cause variations in workability (13, Figure 1) that could cause difficulties in the control of consistency of the fresh concrete at the time of placement. Moreover, because addition of the admixture would not be under the control of the concrete producer, the quality of the final concrete might not be watched or corrected. This problem should be carefully examined; the responsibility for the concrete quality should be divided between the producer and the contractor.

Finally, there are technical problems regarding operations after mixing, when delayed addition of superplasticizers is no longer possible. Pumping, for example, or transportation with buckets, particularly in hot weather, or vibration of the in-place concrete to eliminate cold joints is either not possible or extremely difficult for concretes with rapid workability loss.

MATERIALS

A superplasticizer particularly suitable for concrete to be transported long distances was used in our work. Other superplasticizers with higher workability losses have been examined.

All superplasticizers are based on a naphthalenesulfonated formaldehyde-condensed polymer, but they are differently formulated. The behavior of three different superplasticizers is reported in Figure 1, where the workability of the concrete is shown over time.

Superplasticizer C is particularly well suited for precasting concrete, because the length of time between mixing and placing is relatively short and a stiff concrete is desirable before the injection of steam. Superplasticizer B shows a lower workability loss, while superplasticizer A is recommended for concrete needing long-distance transport and thus a very low workability loss. It is possible in this case to transport rheoplastic concrete for about 2 h at room temperature with no substantial workability loss.

The influence of superplasticizer A on the properties of cement paste and concrete will now be examined.

EXPERIMENTS

Cement Pastes

ASTM types 1 and 5 portland cement were used to control the influence of cement composition, in particular the C_3A content, on the performance of superplasticizers as shown below.

Compound	Percentage of Composition Type 1	 Type 5
CaO	62.92	63.08
SiO_2	21.43	22.25
Al_2O_3	5.31	3.71
Fe_2O_3	2.68	4.58
MgO	1.63	2.46
K_2O	0.14	0.14
Na_2O	0.12	0.08
SO_3	3.37	2.10
C_3S	44.20	50.20
C_2S	28.10	25.90
C_3A	9.50	2.10
C_4AF	8.10	13.90
Blaine cm^2/g	3240	3763

Cement pastes with and without superplasticizer A were prepared. The following measurements were carried out: mini-slump test, isothermal calorimetry, differential thermal gravimetry (DTG), X-ray diffraction analysis, scanning electron microscopy, compressive strength, setting times, and polymer adsorption. However, as far as the pastes are concerned, only DTG and scanning electron microscopy results will be shown here.

DTG curves for pastes of type 1 portland cement with superplasticizers are shown in Figure 2.

Surprisingly, type A superplasticizer accelerates ettringite production during the first hours of hydration. Moreover, type A retards the calcium-silicate hydration rate early on and accelerates the same process later in curing. The influence of the superplasticizer is reversed at about seven days. The re-

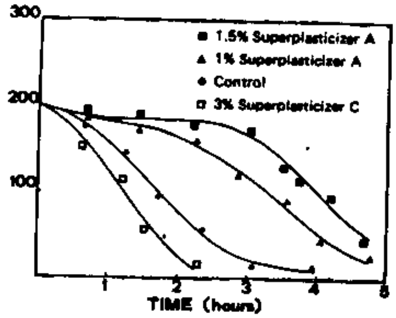


Figure 1. Slump loss for concretes with type 5 cement.

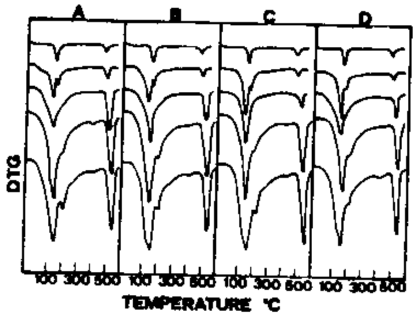


Figure 2. DTG curves for type 1 cement.

sults obtained on type 5 cement pastes show the same trend observed for type 1 cement pastes.

Cement pastes were observed by scanning electron microscopy in order to assess possible changes in the microstructure caused by superplasticizer. Figures 3 and 4 show the microstructures of type 5 cement paste with and without type A superplasticizer after seven days of hydration. No substantial change in the microstructure was observed. Similar results were obtained for type 1 cement.

Preliminary Tests on Concrete

The differences in workability between stiff and flowing concretes require different compaction efforts for the best consolidation. For this reason, some preliminary tests were carried out.

Two control mixes without admixture that had slumps of 20 and 200 mm, respectively, at stiff and flowing consistency were prepared. The flowing concrete showed remarkable segregation and bleeding. A superplasticized rheoplastic concrete with a slump of 215 mm and without segregation was also prepared. In Table 1 the concrete composition and the properties in the fresh state are shown.

Several specimens from the same batch of the three different concretes were vibrated from 0 to 40 s on a vibrating table. They were then cured at 20°C and the compressive strength at 28 days was measured (Figure 5). For both the flowing control mix and the rheoplastic superplasticized concrete, only 5 s are necessary for full compaction and highest strength, while the no-slump concrete needs 40 s for complete compaction. This result applies to all preliminary tests on all the other specimens of the no-slump and rheoplastic concretes. All these specimens were cured at the same temperature and humidity for 28 days. The properties that were determined and will be discussed here are compressive strength, modulus of elasticity, shrinkage, creep, and frost and sulfate resistance.

Final Tests

Compressive Strength

In Figure 6 compressive strengths of concretes with and without superplasticizer are shown.

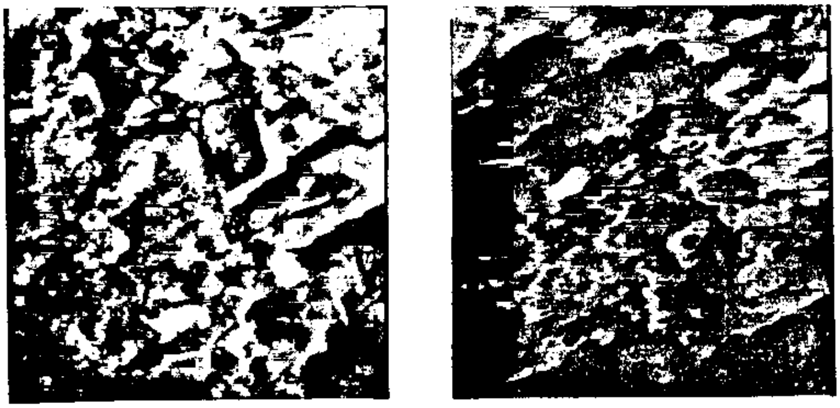


Figure 3. SEM micrographs of type 5 cement paste with superplasticizer at seven days (left = X 1000, right = X 10 000).

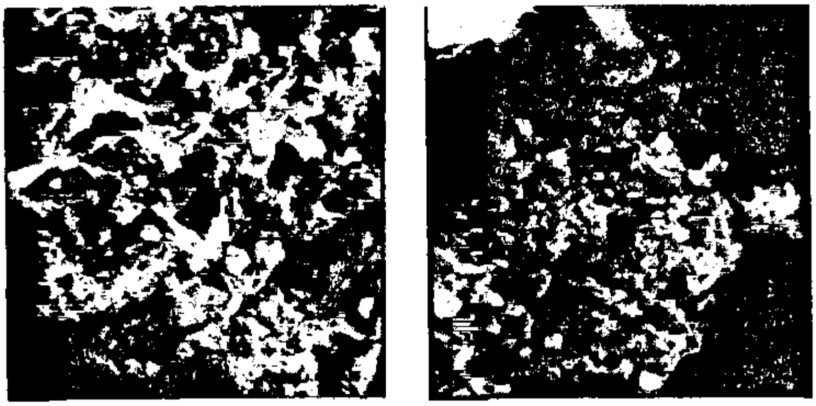


Figure 4. SEM micrographs of type 5 cement paste without superplasticizer at seven days (left = X 1000, right = X 10 000).

Table 1. Composition, workability, and bleeding capacity of fresh concretes.

Cement Type	Cement Content (kg/m^3)	Water Content (kg/m^3)	Aggregate Content (kg/m^3)	Air Content (% volume)	w/c Ratio	Bleeding Capacity (10^{-3})	Slump (mm)	Superplasticizer Content (L/100 kg cement)
1	347	149	1969	1.6	0.43	1.6	20	0
	352	218	1952	1.4	0.62	6.6	200	0
	340	150	1989	2.3	0.44	2.0	215	1.5
5	350	140	2005	0.8	0.40	3.8	20	0
	360	194	1950	1.1	0.54	8.8	200	0
	353	138	2015	2.2	0.39	2.0	220	1.5

When type A superplasticizer with no change in w/c ratio is used, a no-slump concrete is transformed into a rheoplastic one. Only negligible changes in the strength are then observed. In the presence of the superplasticizer there are slightly lower and higher strengths, earlier and later in the curing process, respectively, while the same strength is obtained at about three days. The effect, which is slightly more evident for type 5 cement, can be ascribed to the influence of the superplasticizer on the cement hydration, in particular on calcium-silicate hydration.

When the superplasticizer that has no change in consistency but a w/c ratio reduced to the flowing control mix of a rheoplastic superplasticized concrete is used, a remarkable increase in the strength occurs later in curing. In this case the effect of the water reduction on the strength is partially counterbalanced at early curing (one day) by the retarding effect on the cement hydration: the effect is emphasized at longer curing (after three days) due to the higher degree of hydration.

Figure 5. Influence of vibration time on compressive strength of concretes.

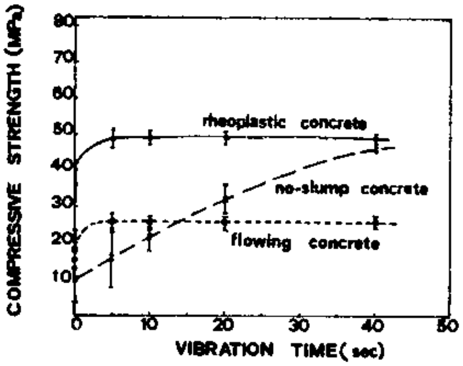


Figure 6. Compressive strength of rheoplastic concrete with 1.5 percent superplasticizer.

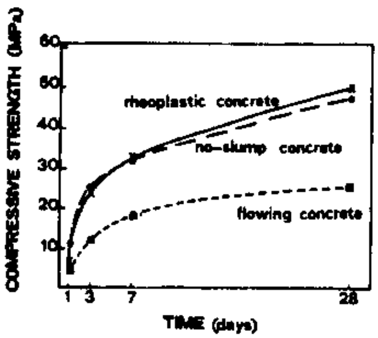
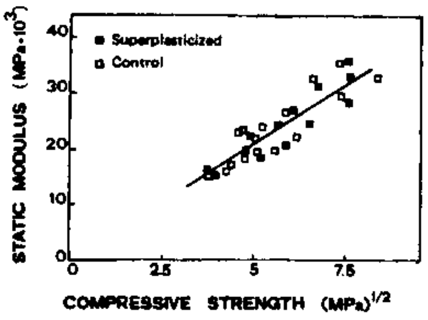


Figure 7. Static modulus of elasticity and compressive strength of concretes.



Modulus of Elasticity

The static modulus of elasticity at a stress of 30 percent of the ultimate strength and the dynamic modulus from pulse velocity measurements on prismatic specimens were determined at 7 and 28 days for concretes with cement contents of from 250 to 400 kg/m^3.

In Figure 7 the static modulus of elasticity is shown as a function of the square root of the compressive strength for superplasticized (solid symbols) and plain concretes (open symbols). In Figure 8 the dynamic modulus of elasticity versus the square root of the compressive strength is shown. The data demonstrate that the same curve represents the correlation between the static or dynamic modulus of elasticity and the square root of the compressive strength for both the control and the superplasticized concrete. This means that, while the addition of superplasticizer to the concrete has no substantial effect on the modulus of elasticity at the same compressive strength, it does have a substantial effect at the same w/c ratio. On the other hand, modulus of elasticity and compressive strength increase in the presence of the superplasticizer when the addition is made at the same flowability.

Shrinkage

Shrinkage was determined on prismatic specimens (160x160x640 mm) previously cured at 20°C for 28 days at a relative humidity of 95 percent and then stored at a relative humidity of 65 ± 5 percent (Figure 9). The

Figure 8. Dynamic modulus of elasticity and compressive strength of concretes.

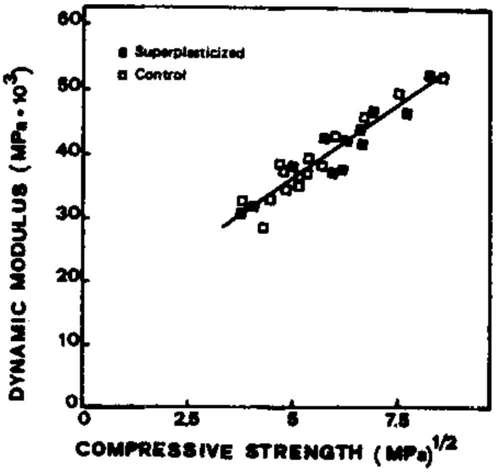


Figure 9. Shrinkage and creep for superplasticized concretes.

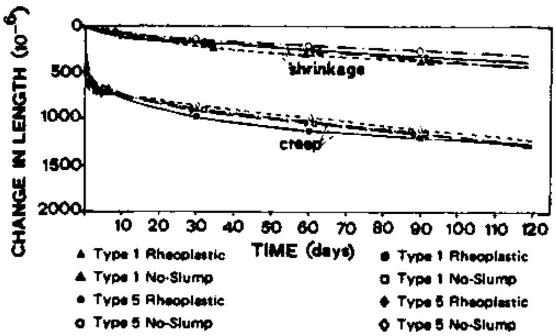


Table 2. Effect of superplasticizer A on freeze-thaw resistance of air-entrained concretes.

Cement Type	Cement Content (kg/m^3)	w/c Ratio	Superplasticizer Content (%)	AEA[a] (%)	Slump (mm)	Air Content (%) Entrapped	Air Content (%) Entrained	Air Content (%) Total	Durability Factor[b]	Relative Durability Factor
1	349	0.42	-	0.20	20	1.3	4.9	6.2	90	100
	351	0.42	1.5	0.25	225	2.3	5.0	7.3	85	94
5	353	0.40	-	0.20	25	0.8	5.4	6.2	92	100
	355	0.39	1.5	0.25	230	2.2	6.0	8.2	88	96

[a] Air-entraining agent by weight of cement. [b] Procedure A, ASTM C666.

Figure 10. Changes in length caused by sulfate attack over time (type 1).

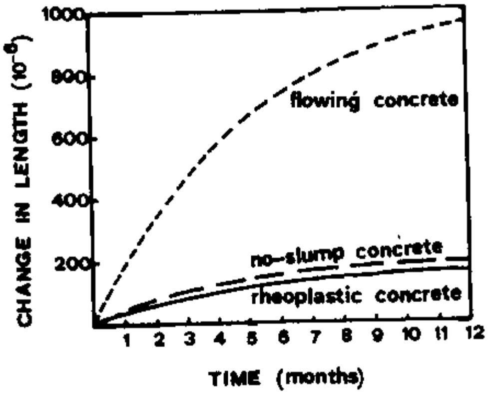
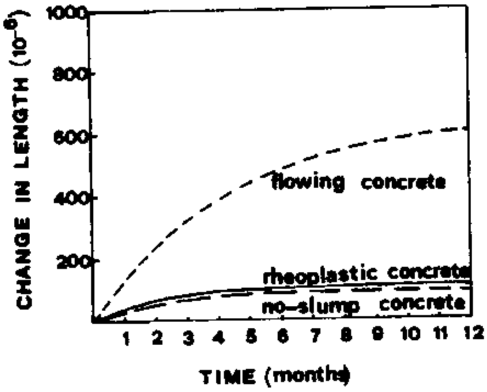


Figure 11. Changes in length caused by sulfate attack over time (type 5).



shrinkage of the control no-slump concretes (open symbols) and rheoplastic superplasticized mixes (solid symbols) made with types 1 and 5 cement shows no significant difference among the four concretes.

Creep

Creep was determined on the prismatic specimens stored under the same experimental conditions as those of the shrinkage tests. At the age of 28 days, a stress corresponding to a stress-to-strength ratio of 0.3 was applied and length-change measurements were carried out. For both type 1 and type 5 cements the effect of the superplasticizer on the creep was insignificant when the concretes of the same w/c ratio were compared (Figure 9).

Frost Resistance

Stiff control mixes and rheoplastic superplasticized concretes, both containing an air-entraining agent, were prepared. Slightly higher dosages of air-entraining agent were needed for superplasticized concretes in order to have the same air-entrained volume (5-6 percent) as the control mixes (Table 2).

Frost resistance was determined on specimens subjected to a freeze-thaw test (procedure A, ASTM C666). The results obtained indicate that superplasticized concretes show substantially the same durability factor as the control mixes without the addition of superplasticizer.

These data agree with those of Hattori (10), Ramakrishnan (14), and Perenchio, Whiting, and Kantro (15), who found similar results for the effect of polymer-based superplasticizers on frost resistance. Mather (16) and Mielenz and Sprouse (17) found that, in general, superplasticized concrete has a lower performance than control mixes. The disagreements among the results obtained by different researchers might be ascribed to differences in the type or brand of superplasticizer and in the air-entrained content as distinct from total air content. However, it seems to have been confirmed that, when superplasticized concretes give lower performances, an inadequate void system is also found (16,17).

Sulfate Resistance

After 28 days, prismatic specimens were stored in a sodium-sulfate solution. Strain on opposite sides of the specimens were measured, and the change in length of concretes made with type 1 cement is shown in Figure 10. Figure 11 presents concretes made with type 5 cement. The results indicate no substantial difference in the length change between control no-slump mixes and rheoplastic superplasticized concretes prepared with the same w/c ratio.

When the comparison is made between the flowing control mix and the rheoplastic superplasticized concrete, the latter shows a much higher sulfate resistance. Moreover, only when a higher w/c ratio is used, as in flowing mixes, do concretes containing type 5 portland cement resist sulfate attack better than those containing type 1 cement.

When rheoplastic concretes are compared there is no substantial difference in sulfate resistance of concretes containing different types of cement, which confirms the conclusion that sulfate attack depends much more heavily on w/c ratio than on the type of cement.

CONCLUSIONS

Tests on slump loss demonstrated that the superplasticizer used in this work allows rheoplastic concrete to be transported for long distances without requiring delayed or intermittent addition of the admixture.

The high workability makes the properties of the rheoplastic superplasticized concrete much less dependent on vibration time than the stiff control mixes when the same w/c ratio is used (Figure 5). This means that rheoplastic superplasticized concretes are much more reliable and cost less to place.

After about three days of hydration, compressive strength, modulus of elasticity, shrinkage, creep, frost resistance, and sulfate resistance of rheoplastic superplasticized concretes all have substantially the same values as the corresponding no-slump concretes with the same w/c ratio but without addition of superplasticizer. Early in curing (one day) a slightly lower compressive strength is recorded in superplasticized concrete, while later in curing (after three days) superplasticized concrete is slightly stronger than the no-slump concrete of the same w/c ratio.

These differences can be attributed to the influence of the particular admixture we used on the hydration rate of calcium silicate. However, when the comparison is made at the same workability, rheoplastic superplasticized concretes perform much better than the corresponding flowing mixes without admixture, both early and late in the curing process.

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