Effects of Superplasticizers on Properties of Fresh and Hardened Concrete

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The purpose of this study was to determine the effects of four commercially available superplasticizers on concrete. In each case three basic mixes were compared: one control proportioned for 100-mm (4-in) slump and 0.50 water-to-cement (w/c) ratio, a second control proportioned for zero slump and 0.50 w/c ratio, and a mix compositionally identical to the second but with sufficient admixture to produce a slump of 100 mm (4 in). The design air content for all mixes was 7 ± 1 percent, and the aggregate maximum size was 13 mm (0.5 in). Slump, air content, and unit weight were measured, as were initial and final setting times, compressive strength, flexural strength, freeze-thaw resistance, shrinkage, and creep. The four admixtures had quite distinct and different effects, but all induced varying degrees of slump loss and caused a marked increase or decrease in air content immediately after addition that was followed by a gradual decrease with time. Some increased setting times by about 20 percent. Compressive strengths increased at all ages up to 28 days and in some cases at ages of six months and a year. Flexural strengths were essentially unaffected. All mixes achieved durability factors greater than 96 percent at 300 cycles, but distinct differences in linear expansion, weight loss, and degree of scaling were noted. Some of the admixtures increased shrinkage while others had little effect. Their influence on total creep was similar, although basic creep and drying creep were affected in opposite ways.

In the last few years, a new group of admixtures has been introduced to the concrete industry. They are termed "superplasticizers," which was coined mainly by the manufacturer but is somewhat at odds with standard admixture nomenclature. The prefix "super" perhaps tends to create an aura of mystery about the products.

In reality, these admixtures function similarly to those categorized in current standards, but their water-reducing effect is of a greater order of magnitude than that of conventional admixtures. Therefore, additional requirement categories are being considered in a recent revision of ASTM C494 (1). However, this revision implies recognition of only one of the ways of using these admixtures, namely to produce water-reduced high-strength concrete (2). Another is to reduce cement content while maintaining water-to-cement (w/c) ratio and workability constant, as in this study. Yet another is to maintain water and cement content constant and greatly increase workability, thus introducing the concept of flowing concrete (2-4).

EXPERIMENTAL PROGRAM

The investigation reported here examined the effects of four commercially available superplasticizers on the properties of fresh and hardened concrete. The manufacturers' descriptions are given below, but the actual products represent a broad range of compounds rather than a single chemical entity. These admixtures are apparently being changed and refined continuously as research suggests improvements.

Admixture No.	Manufacturer's Description
I	Melamine formaldehyde condensate
II	High-molecular-weight sulfoaryl alkylene
III	Sulfonated polymer
IV	Polymerized naphthalene condensate

Materials

Concretes were made by using 13-mm (0.5-in) gravel, natural sand of fineness modulus 2.73, and local type 1 cement. The cement was within the following compositional range: C_3S = 58-62 percent, C_2S = 13-17 percent, C_3A = 8.2-8.5 percent, C_4AF = 5.5-6.1 percent, and SO_3 = 2.1-2.2 percent (based on manufacturer's data).

Concrete Mixes

The three types of mix identified all have a w/c ratio of 0.50. Mix A is a control proportioned to 100 ± 25 mm (4 ± 1 in) slump and 7 ± 1 percent total air content. Mix B is a second control proportioned to zero slump and 7 ± 1 percent air. Mixes subsequently identified by the letter C are compositionally identical to mix B but contain enough of one of the admixtures to change the slump from zero to the 100-mm (4-in) value characteristic of mix A while the 7 percent air content is maintained. Mix proportions are given below (1 kg/m^3 = 1.69 lb/yd^3).

Ingredient	Content (kg/m^3)	
	Mix A	Mix B
Gravel	882	872
Sand	813	982
Cement	393	290
Water	196	145
Total	2284	2289

In all, there are six mixes, control mixes 50/A and 50/B and plasticized mixes 50/C/I-IV. The latter contain 26 percent less cement than mix A, which is their job-site equivalent from the point of view of workability and w/c ratio.

Testing Schedule

The following program of tests was used:

1. Measurement of slump and air content at intervals up to 4 h after addition of each admixture to a single batch of type B mix plasticized initially to a collapse slump;

2. Measurement of slump, air content, and unit weight before and immediately after admixture addition, and at intervals during casting, for all three batches of concrete used to prepare specimens for steps 3-8 below;

3. Determination of initial and final setting times (three determinations for each mix) in accordance with ASTM C403;

Figure 1. Changes in slump after addition of admixtures.
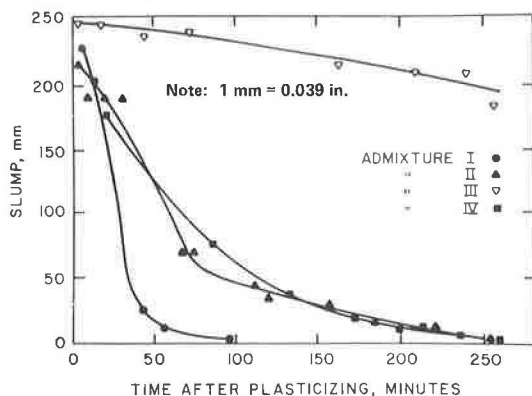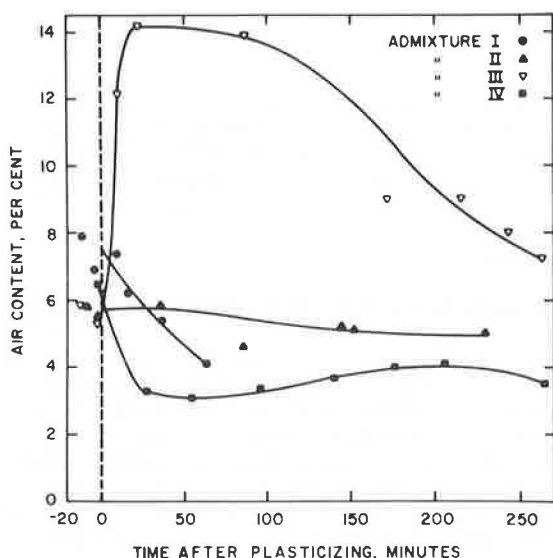

Figure 2. Changes in air content after addition of admixtures.

4. Determination of compressive strengths of 100x 200-mm (4x8-in) cylinders (sets of three specimens) at ages of 3, 7, and 28 days, six months, and one year for normal moist curing at 20°C (68°F) and after accelerated curing in general accordance with method B of ASTM C684;

5. Determination of flexural strengths of 350x100x 100-mm (14x4x4-in) beams (sets of three specimens) at ages of 3, 7, and 28 days;

6. Evaluation of the freeze-thaw performance of 380x 75x75-mm (15x3x3-in) prisms (sets of five specimens) in accordance with procedure A of ASTM C666;

7. Air-void analysis in accordance with ASTM C457; and

8. Measurement of shrinkage and creep at 50 percent relative humidity and a stress-to-strength ratio of 35 percent on 100x300-mm (4x12-in) cylinders.

BEHAVIOR OF FRESH CONCRETE

Some problems unique to mixes containing the new admixtures were experienced. First, their effect is such that a normal "static" slump is often difficult to record at the 100-mm (4-in) level selected as the reference in this study. Instead, the concrete flows continuously on removal of the cone and often topples or shears off before the measurement can be made. Second, the air con-

tent can change considerably during the hour or so needed to cast test specimens, which raises the question of which air content corresponds to the specified air content, the one measured immediately after mixing is completed or the one measured after the last test specimen is cast. Third, it was impossible in this case to adjust air content after plasticizing because further additions of air-entraining agent had no effect.

Slump and Air Content

Changes in slump and air content of an initially zero-slump type B mix plasticized to collapse slump were monitored for as long as 4 h on single batches of about 0.08 m^3 (3 ft^3) (not used subsequently to cast test specimens). Marked differences in the effects of the four admixtures were observed (Figures 1 and 2). Admixture I is associated with the fastest slump loss and admixture III with the least slump loss (Figure 1). Admixtures I and IV cause some loss of air, while II has little effect on air content (Figure 2). Admixture III, on the other hand, causes a marked though temporary increase in air content (Figure 2). Bleeding and considerable escape of air bubbles at the surface of concrete samples in the pressure air-meter test were observed for all four admixtures.

The problem of slump loss can be remedied, at least temporarily, by redosage (5), so perhaps the most serious problem with the new admixtures is the change in air content that can take place between addition of the admixture and the conclusion of casting an hour or so later. This is of particular concern for freeze-thaw testing. Therefore, for all three batches of each mix, air content was closely monitored during preparation of specimens for tests on hardened concrete.

The fluctuations in air content (mean value from three batches in each case) observed are illustrated below.

| Mix | Air Content (%) | | |
	Before Plasticizing	Just After Plasticizing	50-70 Min After Plasticizing
50/A	8.2	NA	7.7
50/B	6.9	NA	6.8
50/C/I	7.2	9.2	5.5
50/C/II	5.9	6.4	5.4
50/C/III	5.4	8.1	5.7
50/C/IV	7.7	7.3	5.7

Admixtures I and III cause a significant though temporary increase in air content in the 10- to 15-min period after plasticizing. However, the overall change in air content from before plasticizing to the conclusion of casting is a significant decrease for admixtures I and IV and little change for admixtures II and III. The patterns of increase and decrease closely resemble those observed in the fresh concrete tests (Figure 2), notably the temporary increase for admixture III (and, to a lesser extent, for admixture I if individual data points are examined) and the overall decrease for admixtures I and IV.

Setting Times

The effects of each of the admixtures on initial and final setting times (mean of three values) determined by penetration resistance (ASTM C403) are illustrated in Table 1. The method is not applicable to zero-slump concretes such as mix 50/B. In essence, it appears that, for the particular cement employed, admixtures II, III, and IV significantly increase both initial and final setting times, while admixture I has little effect.

Table 1. Setting times and increases.

	Initial Setting		Final Setting	
Mix	Time (min)	Increase (%)	Time (min)	Increase (%)
50/A	266	0	341	0
50/C/I	273	2.6	356	4.4
50/C/II	322	21.1	398	16.7
50/C/III	325	22.2	419	22.9
50/C/IV	327	22.9	412	20.8

Figure 3. Comparative compressive strengths with and without admixtures.
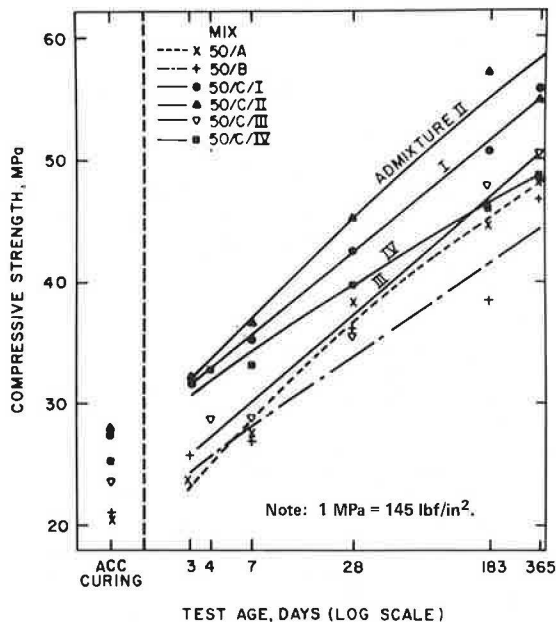
Table 2. Increases in compressive strength compared to mix 50/A.

	Increase in Strength with Curing (%)						
	Acceler-ated	Normal Moist (no. of days)					
Mix		3	7	28	183	365	Average
50/C/I	34.9	34.9	28.6	10.9	13.7	15.8	20.8
50/C/II	33.9	35.2	33.8	18.1	28.0	13.7	25.8
50/C/III	14.3	15.8	5.4	-6.5	7.6	5.4	5.5
50/C/IV	22.1	33.5	20.8	3.3	3.3	1.6	12.5

BEHAVIOR OF HARDENED CONCRETE

In identifying the true effect of each of the admixtures in the following sections, it should be noted that control mix 50/A is the job-site equivalent of the plasticized mixes from the point of view of both workability and w/c ratio. Mix 50/B, although compositionally identical to the plasticized mixes, has much lower workability and therefore is not equivalent from a practical viewpoint.

Compressive Strength

The average coefficient of variation (sets of from three to four specimens) achieved in compressive strength tests was 6.8 percent, indicating good quality control; the pattern of strength development with age is illustrated in Figure 3.

Table 3. Increases in compressive strength compared to mix 50/B.

	Increase in Strength with Curing (%)						
	Acceler-ated	Normal Moist (no. of days)					
Mix		3	7	28	183	365	Average
50/C/I	34.2	24.0	29.2	18.0	32.0	19.1	24.5
50/C/II	33.1	24.3	34.3	25.7	48.6	17.0	30.0
50/C/III	13.7	6.5[a]	5.8	-0.4	24.9	8.4	9.0
50/C/IV	21.4	22.8[a]	21.4	10.0	19.9	4.5	15.7

*Estimated from four-day data by using Figure 3.

In general, admixtures I and II produce significant strength gains at all ages, while admixtures III and IV produce smaller gains that tend to disappear later. The comparative performance of the admixtures becomes clearer when the percentage increases in strength for control mixes 50/A or 50/B are tabulated (Tables 2 and 3). Under accelerated curing conditions [the water temperature was 83°C (183°F) because of the equipment's inability to sustain the boiling temperature required by ASTM C684], admixtures I and II produce strength gains in excess of 30 percent, while the gains for admixtures III and IV are less though significant. Somewhat similar effects have been reported by others (6).

Under normal moist curing, all admixtures produce gains at early ages, but only admixtures I and II produce significant gains later. Considering that the gains relative to mix 50/A, the job-site equivalent in terms of workability, are accompanied by a 26 percent reduction in cement and water contents, the performance of admixtures I and II, in particular, is notable. An index of the overall performance of each admixture is given by the average percentage increase for all periods of normal curing (Table 2). Relative to mix 50/B, the compositional equivalent of the plasticized mixes, admixtures I and II are again superior overall (Table 3).

Since all mixes in this study have the same strength potential from the point of view of w/c ratio and mix 50/B has the same volumetric proportions of aggregate and paste as the plasticized mixes, it is clear that the observed strength differences are not associated with variations in w/c ratio. This is in marked contrast to the conclusions reached by others (2) that the effects of the admixtures on strength are related solely to change in w/c ratio. Instead, the results given here (Tables 2 and 3) show that the admixtures do indeed affect the hydration process in a positive way. The strength increases at early ages suggest that they may increase both the rate and the degree of hydration, while the results at later ages, at least for admixtures I and II, suggest that the final degree of hydration achievable may be greater than that for either of the equivalent control mixes without admixture. These effects are probably associated with the finer dispersion of the hydration products, observed microscopically (2), that results (a) in freer contact between water and unhydrated cement and (b) possibly in change in the gel-to-space ratio that favorably affects strength. Further fundamental studies of the effects of such admixtures on the structure of hydrated cement pastes at various ages could undoubtedly clarify these points.

Flexural Strength

The average coefficient of variation (sets of three specimens) achieved in flexural strength tests was 6.1 percent, which again indicates good quality control; the pattern of strength development with age is illustrated in Figure 3. In essence, the admixtures apparently have

little effect on flexural strength, although admixture II, which gave the best overall performance in compression (Figure 4), may impart some slight benefit. However, none of the admixtures has an adverse effect. The marked difference between the effectiveness of the admixtures in compression and in flexure may be due to the fact that failure in compression is governed primarily by the strength of the cement paste, while in flexure it is governed mainly by the paste-aggregate bond strength. The implication is that the admixtures have little effect on the latter, although they appear to significantly influence the former.

Shrinkage and Creep

Shrinkage and creep measurements were made on 100x 300-mm (4x12-in) cylinders taken from two batches of each mix type. Within the initial 28-day moist-curing period, specimens were each fitted with gauge points on three 200-mm (8-in) lengths spaced at 120° around the specimen. A demountable mechanical extensometer (DEMEC) was used to make strain measurements.

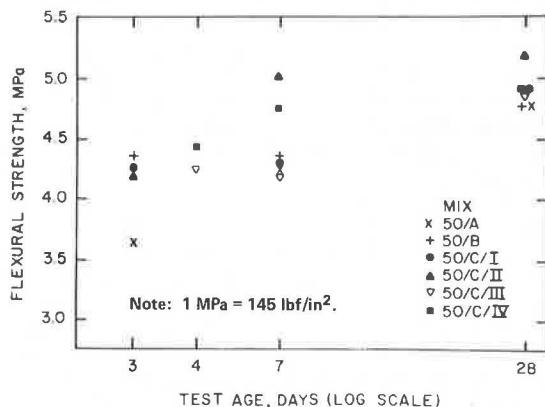Figure 4. Comparative flexural strengths with and without admixtures.

Table 4. Saturated creep for specimens loaded at age 28 days.

Mix	Initial Strain (10^{-6}/MPa)	Specific Creep (10^{-6}/MPa)			
		Duration of Loading (no. of days)			
		7	28	91	365
50/A	36.5	19.5	26.6	32.3	37.3
50/B	33.4	17.5	23.8	28.6	32.8
50/C/I	31.0	15.4	20.8	25.2	29.3
50/C/II	32.3	14.6	19.9	23.6	27.7
50/C/III	35.4	14.8	20.2	24.6	29.3
50/C/IV	32.1	12.7	17.3	20.8	24.0

Note: 1 MPa = 145 lbf/in².

Table 5. Shrinkage of specimens drying from age 56 days.

Mix	Shrinkage (10^{-6})			
	Duration of Drying (no. of days)			
	7	28	91	365
50/A	225	450	640	795
50/B	215	430	570	700
50/C/I	230	420	560	695
50/C/II	200	395	545	690
50/C/III	260	470	620	760
50/C/IV	275	500	635	775

Two pairs of specimens from each batch were arranged in series and loaded at age 28 days to a stress level not exceeding 35 percent of the 28-day strength by using constant-pressure hydraulic rams (7). These specimens were kept in a saturated condition in an absorbent wrapping and plastic jacket until an age of 56 days. Then one of the two loaded specimens from each pair was exposed by removing the wrapping. At the same time a companion shrinkage specimen was placed in the same environment. Thus, for each mix, information was obtained for three conditions:

1. Two specimens loaded at 28 days and saturated at all times,
2. Two specimens loaded at 28 days and kept saturated until 56 days and dried in 50 percent relative humidity thereafter, and
3. Two unloaded specimens kept saturated until 56 days and dried in 50 percent relative humidity thereafter.

During the first 28 days of loading it was possible to compare the performance of the four loaded specimens under identical conditions. This gave greater confidence in the subsequent results than if the two pairs had proceeded under different conditions from the start. Table 4 shows the initial strains per unit stress immediately after loading (mean of four specimens) and the mean values of specific creep (creep per unit stress) for the two continuously saturated specimens. The average range of specific creep values given in Table 4 for sets of four specimens is 15 and 13 percent after 7 and 28 days, respectively.

The values of specific creep are not substantially different for any of the plasticized mixes (mix 50/C/IV was loaded at a lower stress level, and a nonlinear creep-stress relationship accounts in part for the lower creep values in this case). However, all plasticized mixes show lower creep when saturated than either of the two control mixes: 11-17 percent lower for the compositionally equivalent mix, 50/B, and 21-27 percent lower for the job-site equivalent mix, 50/A.

Table 5 shows the average shrinkage of the two specimens from different batches. The maximum between-specimen range within seven days of the start of drying is 30×10^{-6} and only 20×10^{-6} after this time. Generally, admixtures I and II are associated with shrinkage, which is similar to 50/B, while admixtures III and IV cause increases in shrinkage of 10-14 percent, although the values do not substantially exceed those for 50/A.

Drying creep (ϵ_{dc}) is defined by the relationship

$$\epsilon_{tot} = \epsilon_s + \epsilon_{bc} + \epsilon_{dc} \qquad (1)$$

The total time-dependent strain (ϵ_{tot}) was observed under condition 2 above, while shrinkage (ϵ_s) was evaluated from condition 3. Although basic creep (ϵ_{bc}) is defined as creep occurring under conditions of no moisture exchange, it is for practical purposes the creep obtained under condition 1.

Figure 5 shows the drying creep calculated on this basis after various durations of drying. While admixtures I and II induce little change, admixtures III and IV cause drying creep to almost double in relation to control mix 50/B. Indeed, drying creep in each of these cases even exceeds that of mix 50/A.

It is known that shrinkage is not a particularly sensitive function of the age at which drying commences and also that there is a close relation between shrinkage and drying creep that is independent of many factors, including loading age and subsequent delays in drying (8). This means that the data in Table 4 and Figure 5 can be

used to estimate the total creep responses of specimens loaded at 28 days and also dried from that time. This is a more usual regime followed in creep and shrinkage work and approximates the standard curing condition of ASTM C512.

Accordingly, total creep can be estimated by adding the data for basic and drying creep at corresponding times after loading and/or drying commences, and total creep coefficients (ratio of total creep at any time to the initial strain at 28 days) computed as shown in Table 6. Again, as in the case of shrinkage and drying creep, admixtures I and II cause little change in properties, while

admixtures III and IV cause increases in total creep of up to 25 percent after one year under load compared to 50/B, although the values are not substantially different from those for 50/A.

From a practical viewpoint, when severe drying is possible, problems associated with creep and shrinkage could be accentuated by the use of some of the admixtures, because the higher strengths achievable permit higher design stresses and therefore greater creep and shrinkage.

Resistance to Freeze-Thaw Cycles

Freeze-thaw performance was evaluated by using sets of six specimens tested according to procedure A of ASTM C666 (rapid freezing and thawing in water). In addition to monitoring changes in fundamental transverse frequency to establish durability factors, changes in length and weight were also recorded, and the degree of scaling was estimated visually by using a 10-point scale similar to the 5-point scale given in ASTM C672. The resulting data from 35 specimens are too extensive to be presented in detail here, where only a summary can be given.

In the case of durability factor, guidelines for meaningful interpretation of the data were developed from the average of the standard deviations computed for each set of six specimens at the cycle intervals at which measurements were recorded. For durability factors of 95 or more, this value (the 1 S limit, as defined in ASTM C670) is 1.9 and for durability factors of 90 to 95 the value is 3.4, both considerably more than the corresponding 1.1 and 2.1 given in ASTM C666. Thus, damage cannot be regarded as significant (with a $p = 0.05$ level of being correct) when the durability factor falls within 100 ± 3.8. Hence, the symbol >96 is used in Table 7 for all such cases. By the same criterion, durability factors less than 96.2 are indicative of significant damage, although the actual values can only be stated with 95 percent confidence to be in the range encompassed by plus or minus twice the applicable standard deviation.

From a practical viewpoint, the relative durability factors in Table 7 fall into the following three categories: >96 or no significant damage, 80 to 96 = damage significant but not enough to contravene the requirements for admixture evaluation of ASTM C494, and <80 = failure to meet the requirements of ASTM C494.

As stated earlier, damage was also assessed in terms of changes in length and weight. Changes in length were monitored with a 200-mm (8-in) Demec gauge. The only

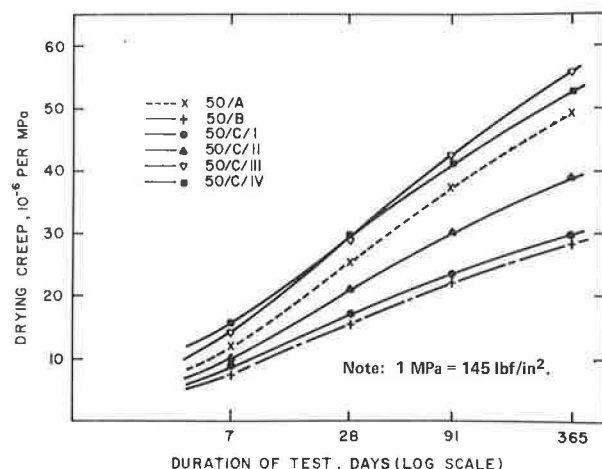Figure 5. Comparative drying creep with and without admixtures.

Table 6. Estimated total creep coefficients for specimens loaded and dried from age 28 days at 58 percent relative humidity.

| Mix | Creep Coefficients | | | |
| | Duration of Loading and/or Drying (days) | | | |
	7	28	91	365
50/A	0.86	1.42	1.91	2.38
50/B	0.76	1.18	1.51	1.92
50/C/I	0.79	1.22	1.60	1.90
50/C/II	0.75	1.26	1.66	2.07
50/C/III	0.81	1.39	1.89	2.43
50/C/IV	0.88	1.45	1.93	2.40

Table 7. Freeze-thaw test results.

Mix	Air Content[a] (%)	No. of Cycles	Durability Factor	Expansion (μ strain)	Weight Loss (%)	Degree of Scaling
50/A	7.7	300	>96	64[b]	0.03[c]	2.4
		600	91	56[b]	0.29	3.5
		1000			1.01	4.4
50/B	6.8	300	>96	43	0.69	5.9
		600	93		1.39	6.5
50/C/I	5.5	300	>96	92[b]	0.16[c]	2.8
		600	>96	47[b]	0.24	4.2
		900	>96[d]		0.54	5.3
50/C/II	5.4	300	>96	80[b]	0.21[c]	2.3
		600	>96	43[b]	0.13[c]	3.8
		1000	>96[d]		0.30	4.3
50/C/III	5.7	300	94	74	0.93	5.5
		650	86	108	2.19	7.5
50/C/IV	5.7	300	>96	73	0.39	3.8
		435	96	95	0.85	4.9

[a] Mean air-meter value for three batches at conclusion of casting.
[b] Contraction.
[c] Gain.
[d] Uncertain due to effect of temporary air drying during photography.

problem was that scaling in the vicinity of the gauge points progressively reduced the number of gauge lengths that could be monitored. The most important feature is whether the change represents an expansion or a contraction (Table 7). Obviously, significant expansion is indicative of internal structural damage caused by the freezing process and might be expected to be associated with a drop in fundamental transverse frequency, which is essentially a measure of internal structural integrity. In the case of weight change, a loss is primarily indicative of surficial damage and might be expected to be associated with an increase in the visual rating of scaling (Table 7).

Considering all the criteria of assessment summarized in Table 7, the following appear to be the salient points.

1. All mixes except mix 50/C/III suffer no detectable drop in durability factor to 300 cycles, the normal limit for the test procedure.

2. At 600 cycles and beyond, both control mixes suffer a significant drop in durability factor; the drop already observed for mix 50/C/III becomes more pronounced; and mix 50/C/IV begins to exhibit signs of impending deterioration.

3. Up to at least 600 cycles, mixes 50/C/I and 50/C/II suffer no detectable drop in durability factor, despite slightly lower air contents than the control mixes and apparently inferior air-void systems (discussed in the next section).

4. In general, weight loss and degree of scaling increase as the durability factor drops. Also, in most cases where the durability factor is 96 or less, linear expansions in excess of the 70 microstrain, often quoted as the approximate cracking strain for cement paste, are evident.

Air-Void Analysis

Since it has already been shown that major changes in the air content of the fresh concrete can take place between initial addition of admixture and the conclusion of casting of specimens, the most relevant air-meter (ASTM C231) value from the point of view of durability is that measured at or near the conclusion of casting. Equally relevant is the air content of the hardened concrete, which was computed for two samples of each mix by using the modified point-count procedure of ASTM C457. Unfortunately, while agreement between air-meter readings and the modified point-count values is within ±1.0 percent for all four samples of the control mixes, the point-count value is consistently higher by 2-5 percent for all samples of the plasticized mixes.

The reason for the discrepancy has not yet been ascertained, so it is not possible to state spacing factors or specific surfaces with certainty. What is obvious from visual examination is that the air contents of the plasticized mixes are not as high as the point-count method suggests and that the void-size distribution is quite different. Generally, the smaller air voids occur much less frequently in these mixes, and there is evidence of joined voids caused by bubble coagulation. Clearly, the trend to larger, more widely spaced bubbles caused by the apparent coagulating effect of the admixture is undesirable according to the established concept of spacing factor. Yet, as noted in the previous section, most of the plasticized concretes perform at least as well in freeze-thaw tests as the control mixes, and, in the case of admixtures I and II, noticeably better.

This anomaly of good freeze-thaw performance with apparently inadequate spacing factors has also been observed by others (4, 9, 10), and, in the absence of a satisfactory explanation, the question of whether some of the admixtures alter the structure of the hydrated cement paste in a beneficial way again arises, just as it arose in the context of compressive strength when admixtures I and II also gave the best performance.

CONCLUSIONS

The conclusions in this section, and indeed all the results on which they are based, describe the effects of four specific admixtures on a particular cement-aggregate combination. They are not necessarily valid either qualitatively or quantitatively for other nominally similar admixtures with different cement-aggregate combinations.

Effects on Fresh Concrete

1. Rates of slump loss vary widely. Admixture III is most effective at minimizing rate of slump loss, while admixture I causes the most severe slump loss. Likewise, the degree of fluctuation in air content between initial addition of admixture and the conclusion of casting varies considerably; the problem is most severe with admixtures I and III.

2. At the 100-mm (4-in) slump used in this study, all four admixtures increase bleeding, cause progressive loss of entrained air during the period normally needed for placement, and promote air-bubble coagulation that adversely affects the spacing factor.

3. The effect on setting times is also variable. Admixtures II, III, and IV have a significant delaying action, and admixture I has little effect.

4. Overall, admixture II seems to perform best because it induces only a moderate rate of slump loss and minimal changes in air content.

Effects on Hardened Concrete

1. Changes in properties of the hardened concretes vary widely with the admixture, and, in some cases, depend on whether the effect is rated in relation to the job-site equivalent control mix (w/c ratio and workability constant, but cement and water contents differ by 26 percent) or the compositionally equivalent control mix (mix proportions constant, but workabilities different). However, the effectiveness of each admixture relative to the others is quite consistent for the range of properties evaluated.

2. Overall, admixtures I and II are most effective because (a) they cause the largest increases in compressive strength, which, unlike those for admixtures III and IV, are sustained at later ages up to one year; (b) they induce little change in shrinkage and total creep while admixtures III and IV significantly increase shrinkage and total creep; and (c) they are associated with the best freeze-thaw performance, the level of which is not matched by either the control mixes or mixes with admixtures III and IV after 600 cycles (although all pass the ASTM C494 criterion of 80 percent for relative durability factor at 300 cycles) (Table 7).

Some of the admixtures significantly improve strength, while the w/c ratio remains constant, and improve durability even though they apparently increase the air-void spacing factor. Others increase shrinkage, drying creep, and total creep, while the water content and w/c ratio remain unchanged. These observations suggest that the admixtures induce major fundamental changes in the hydration process and in the structure of the hydration products that must be established to understand how to use them most effectively.

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Low-Slump-Loss Superplasticized Concrete

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The influence of a naphthalene-sulfonated polymer-based super-
plasticizer 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 com-
pressive 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 m³ of
concrete containing superplasticizers has been pro-
duced 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, be-
cause 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). How-
ever, flowing does not necessarily imply low segregation
as well. For this reason we suggest (4-7) that "rheo-
plastic" be used ("rheo" from the Greek "to flow") to
mean a cohesive, plastic, and nonsegregating concrete.