TRANSPORTATION RESEARCH RECORD 720

Superplasticizers in Concrete

TRANSPORTATION RESEARCH BOARD

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Contents

page 16, column 2, line 15 from bottom and lines 10-11 from bottom
    Change "19.93 kN" to "2032 kg"
page 16, column 2, lines 5-6 from bottom
    Change "19.88 kN" to "2028 kg"
page 18, column 1, lines 6 and 12
    Change "10.05-kN" to "1025-kg" and "1.913-kN" to "195-kg"
page 18, column 1, line 20, and column 2, lines 20 and 23
    Change "62.27-kN" to "6350-kg"
page 26, column 1, lines 13-15
    Change each "nt·s" to "N·s" and each "lb-s" to "lbf·s"
page 26, column 2, lines 4-6
    Change each "nt" to "N" and each "lb" to "lbf"
page 27, column 1, lines 1-2 and following table
    Change to "production lot (1 kN = 225 lbf):

Test Piece	Axial Load (kN)
CT 7-11-1	136.3
CT 7-11-2	115.6
CT 7-11-3	116.1
CT 7-12-3	119.7
CT 7-12-4	122.1
Average	121.9"

page 27, column 1, lines 9-11 from bottom and following table
    Change to "table (1 kN = 225 lbf):

Test Piece	Shear Load (kN/coupling)
CT 7-11-4	28.0
CT 7-11-5	17.3
CT 7-11-6	23.6
CT 7-12-1	17.3
CT 7-12-2	19.6
Average	21.2"

page 27, column 2, line 13
    Change "227 kg (500 lb) and 4536 kg (10 000 lb)" to "2.2 kN (500 lbf) and 44.5 kN (10 000 lbf)"
page 28, column 1, lines 3, 14-15, 18, and 22
    Change each "nt·s" to N·s" and each "lb·s" to "lbf·s"
page 29, Abstract, line 15
    Change "362 kg·s" to "3.6 kN·s"
page 30, column 2, line 21
    Change "1145, 1105, and 1060 kg·s" to "11.2, 10.8, and 10.4 kN·s"
page 30, column 2, line 17 from bottom
    Change "492, 487, 500, and 464 kg·s" to "4.93, 4.89, 5.02, and 4.65 kN·s"
page 31, column 1, line 11
    Change "350, 360, 350, and 357 kg·s" to "3.43, 3.53, 3.43, and 3.50 kN·s"
page 31, column 1, line 39
    Change "338, 349, and 388 kg·s" to "3.31, 3.43, and 3.80 kN·s"
page 31, column 2, line 35
    Change "91 kg·s" to "0.89 kN·s"
page 31, column 2, line 44
    Change "Tunnel momentum change, kg·s 504 351 338 452" to "Tunnel momentum change, kN·s 4.93 3.43 3.31 4.43"
page 31, Table 3
    Change the momentum change values from kg·s to kN·s for each category: "Speed Trap Measurement: NM, 4.75, 3.51,–,4.96"; "Integration of Tunnel Acceleration: 11.17, 4.93, 3.42, 3.31, 4.50"; "Integration of Rear-Deck Acceleration: 10.8, 4.89, 3.53, 3.43, 4.10"; "High-Speed Film Analysis: 10.4, 4.89, 3.43, 3.80, 4.48"
page 32, column 1, lines 7 and 10
    Change "91 kg·s" to "0.89 kN·s" and "457, 418, 457, and 506 kg·s" to "4.43, 4.11, 4.25, and 4.97 kN·s"
page 33, column 1, lines 7-8
    Change "500 kg·s" to "4.89 kN·s" and "350 kg·s" to "3.34 kN·s"
page 33, column 1, text table
    Change the momentum change values from kg·s to kN·s for each test: "Test 1:–, 11.22, 10.83, 10.39"; "Test 2: 4.75, 4.94, 4.89, 5.02"; "Test 3: 3.51, 3.44, 3.53, 3.43"; Test 4:–, 3.31, 3.42, 3.80"; "Test 5: 4.96, 4.48, 4.10, 4.48"
page 33, column 1, line 31
    Change "350 kg·s" to "3.34 kN·s"
page 33, column 2, lines 5 and 7
    Change "500 kg·s" to "4.89 kN·s" and "91 kg·s" to "0.89 kN·s"

Transportation Research Record 681
page 19, column 2, line 22
    Change "frequently" to "infrequently"

✓ **Transportation Research Record 720**
page ii, Library of Congress data
    Change "[666'.89]" to "[66';893]"

Transportation Research Record 721
page ii, Library of Congress data
    Add "National Research Council. Transportation Research Board.
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page ii, column 1
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Special Report 175

page 67, column 2, line 36

Change "because it has a larger size aggregate" to "if it had had a larger-size aggregate"

Special Report 176

page 3, caption for Figure 1.3

Change "Segeto" to "Shigeto"

page 13, column 2, line 4

Change "Figure 2.6" to "Figure 2.5"

page 15, Figure 2.10, Zone A

Change heading "E" to "C"

page 17, column 2, line 37

Change "fluids, as shown in Figure 2.1p5." to "fluids."

page 18, column 1, line 11 from bottom

Change "site" to "side"

page 18, caption for Figure 2.17

Change "(7 to 6 ft)" to "(7 to 16 ft)"

pages 92 and 93, Figures 4.8 and 4.9

Reverse captions for figures

page 231, column 3, line 18

Change "13, 17" to "17"

Transportation Research Record 667

page 41, column 1, line 9 from bottom

Change "versus" to "per unit of"

page 41, column 2, line 3 from bottom

Change "versus" to "and"

page 42, column 2, line 17 from bottom

After "All scenarios" insert "chosen"

page 43, column 1, lines 24-26

Change no. 4 to read: "4. A table of fuel consumption versus emission rates is accessed each second for each vehicle by using the vehicle's speed-acceleration couplet (8)."

page 43, column 1, line 31

Change "fuel consumption" to "fuel efficiency"

page 43, column 2, last line

Change Equation 6 to read: "FE = 0.695 + 0.182*(average speed) - 0.0023*(average speed)^2"

page 44, Figure 3, caption and vertical axis

Change "fuel consumption" to "fuel efficiency"

page 45, Figure 8, caption and vertical axis

Change "fuel consumption" to "fuel efficiency"

page 47, column 1, line 1

Change "fuel consumption" to "fuel efficiency"

page 47, column 1, line 3

Change Equation 7 to read: "HC = 8.342 - 0.240*(average speed) + 0.007 25*(average speed)^2"

page 47, column 1, line 6

Change Equation 8 to read: "HC = 1.36 + 34.522 ÷ (average speed)"

page 47, column 1, line 8

Change Equation 9 to read: "CO = 171.71 - 9.222*(average speed) + 0.164*(average speed)^2"

page 47, column 1, line 11

Change Equation 10 to read: "CO = 16.03 + 766.0 ÷ (average speed)"

page 47, column 1, lines 16-17

Change "the cycle length, which minimizes delay at an isolated intersection, also" to "a cycle length that minimizes delay at an isolated intersection also"

page 47, column 1, line 4 from bottom

After "is not considered" insert "in these other papers."

Transportation Research Record 673

page 52, column 2, line 12 from bottom

Change "90 and 100" to "90 and 10"

Transportation Research Record 675

page 19, column 1

Insert the following before the last paragraph:

Hydrated Portland Cement Pastes

Hydrated portland cement pastes were used to test the hypothesis discussed above. The second-intrusion method was applied to hydrated portland cement pastes, which were mixed in vacuum with a water-cement ratio of 0.4 and cured for 3 and 60 days in saturated calcium hydroxide solution at 20°C. The pastes were oven dried at the end of curing periods, and duplicate specimens (1-3 g each) were tested. The specimens were taken out of the sample cell at the end of the first pressurizing-depressurizing cycle and placed and tested in the porosimeter again as a new specimen. The surface tension of mercury was taken as 484 dyne/cm^2 and the contact angle as 117° for all cycles. Thus, the Washburn equation becomes

$$P = 127.500/D(\mu m) \qquad (3)$$

where P is in pounds force per square inch.

Winslow and Diamond (3) determined the contact angle of mercury on oven-dried hydrated portland cement pastes by observing the penetration pressure of mercury into small boreholes of known diameters. The assumption of equal contact angle in first and second intrusions is supported by Winslow and Diamond's procedure, since they intruded and extruded mercury into the small holes in cycles and observed no change in penetration pressure.

Conventional and uniform pore-size distributions of hydrated portland cement pastes are shown in Figures 6 and 7. The first-intrusion curves are similar to those reported in early investigations (3). There is practically no intrusion up to the threshold diameter D_t, and a major fraction of the total pore volume is within a small range of sizes smaller than D_t; finally, the slope tends to become smaller and smaller as smaller diameters are intruded. Thirty-six percent of the total mercury intruded is retained in the paste hydrated for 3 days and 40 percent in the paste hydrated for 60 days at end of depressurizing.

Transportation Research Record 679

page 1, column 2, line 13

Change "4895 N/s (1100 lb/s)" to "4895 N·s (1100 lbf·s)"

page 16, column 2, line 20 from bottom

Change "10.05 kN" to "1025 kg" and "62.27-kN" to "6350-kg"

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page ii, column 2

Change sponsorship data to

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Transportation Research Circular 180

page 14, column 2, line 3 from bottom

Change "must be applied" to "must not be applied"

page 15, column 1, line 3 from bottom

Change "and 2 percent lime gives" to "but at least two consecutive percentages of lime give"

page 15, column 2, line 1

Change "If the highest pH is 12.30 and only 1 percent lime gives" to "However, if only the highest percentage checked gives"

NCHRP Synthesis of Highway Practice 62

page 34, Table A-7

Add as footnote "Note: In Alaska, Delaware, New Jersey, New York, and Rhode Island, highway-user revenues are placed in the state's general fund, from which the state's highway appropriations are taken."

Effects of Superplasticizers on Properties of Fresh and Hardened Concrete

C. D. Johnston and B. R. Gamble, Department of Civil Engineering,
University of Calgary, Alberta
V. M. Malhotra, Construction Materials Section, Canada Department
of Energy, Mines, and Resources, Ottawa

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).

	Content (kg/m^3)	
Ingredient	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.

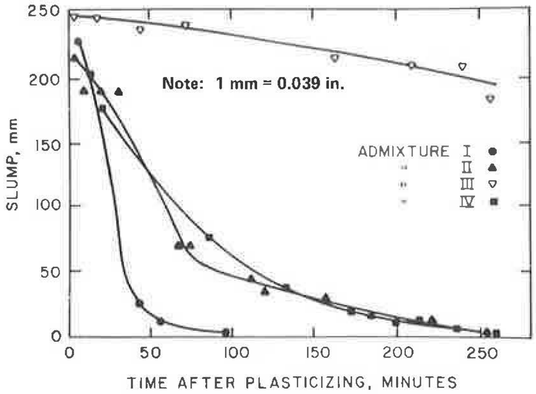
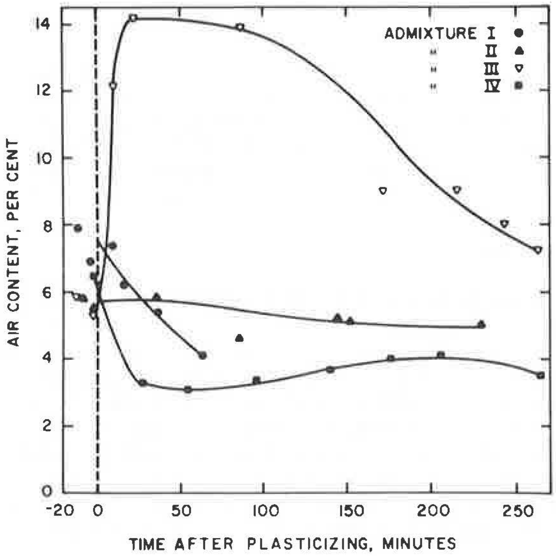


Figure 2. Changes in air content after addition of admixtures.



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 content 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.

	Air Content (%)		
Mix	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.

Mix	Initial Setting Time (min)	Initial Setting Increase (%)	Final Setting Time (min)	Final Setting 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.

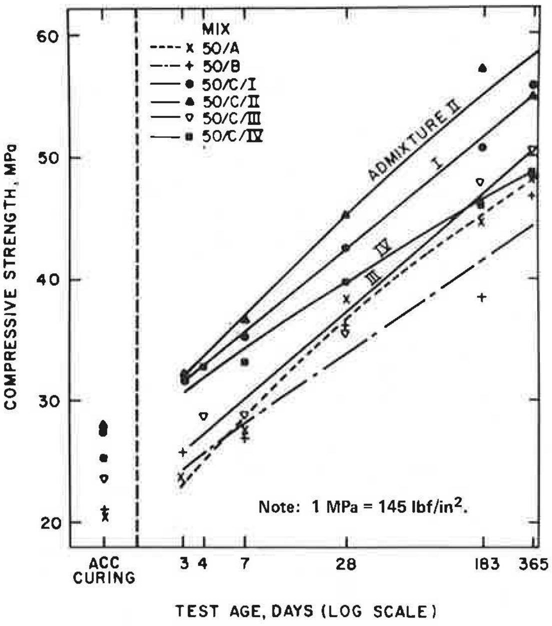


Table 2. Increases in compressive strength compared to mix 50/A.

Mix	Increase in Strength with Curing (%): Accelerated	Normal Moist (no. of days): 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.

Mix	Increase in Strength with Curing (%): Accelerated	Normal Moist (no. of days): 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

[a] 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 degee 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.

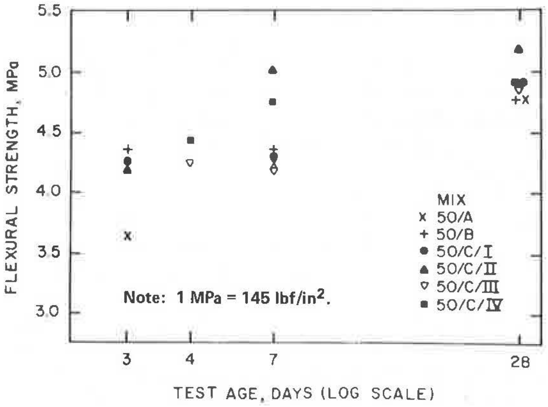
Flexural Strength

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.



Note: 1 MPa = 145 lbf/in².

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

$$\epsilon_{tot} = \epsilon_s + \epsilon_{bc} + \epsilon_{dc} \tag{1}$$

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.

Figure 5. Comparative drying creep with and without admixtures.

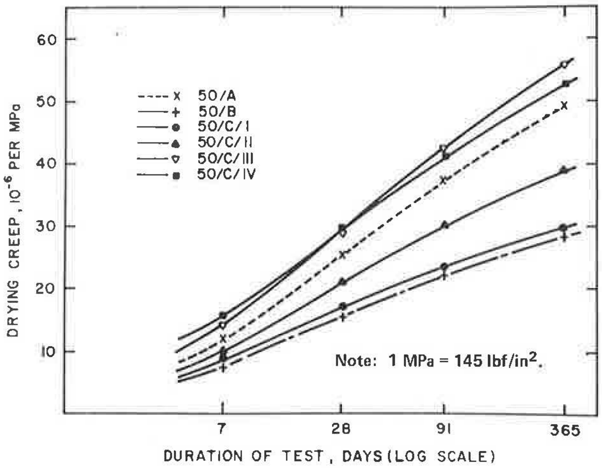


Table 6. Estimated total creep coefficients for specimens loaded and dried from age 28 days at 58 percent relative humidity.

	Creep Coefficients			
	Duration of Loading and/or Drying (days)			
Mix	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

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

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 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 naphthalene-sulfonated 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.

	Percentage of Composition	
Compound	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.

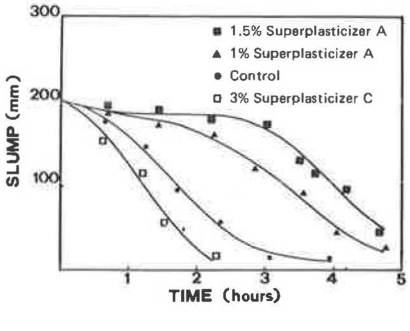
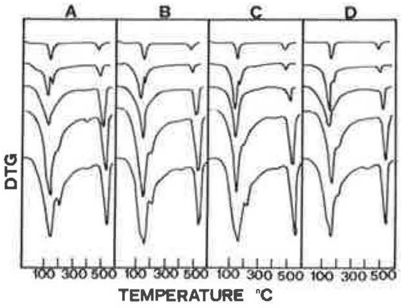


Figure 2. DTG curves for type 1 cement.



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.

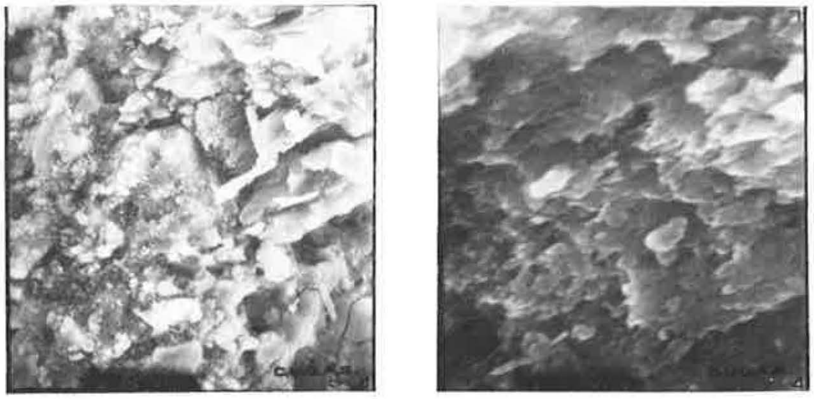


Figure 3. SEM micrographs of type 5 cement paste with superplasticizer at seven days (left = X 1000, right = X 10 000).

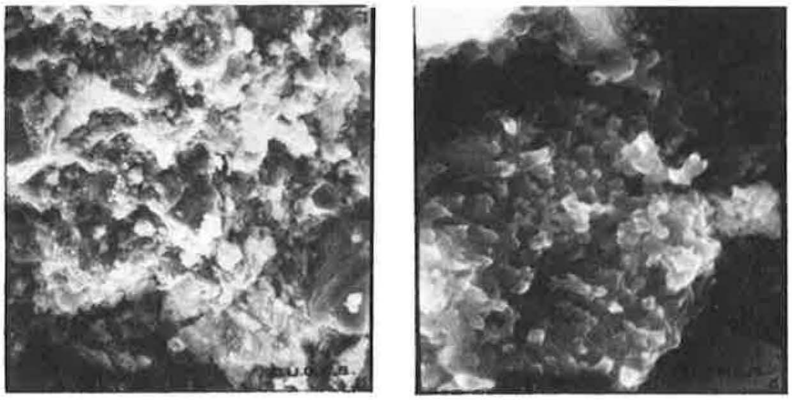


Figure 4. SEM micrographs of type 5 cement paste without superplasticizer at seven days (left = X 1000, right = X 10 000).

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.

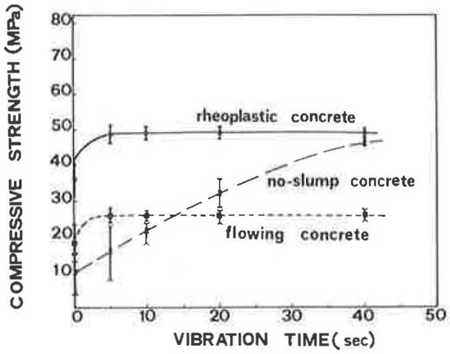


Figure 6. Compressive strength of rheoplastic concrete with 1.5 percent superplasticizer.

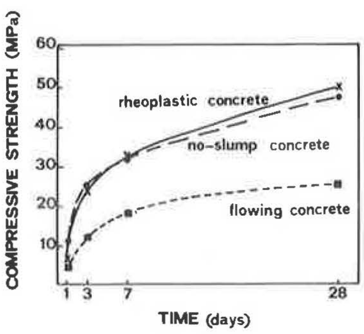
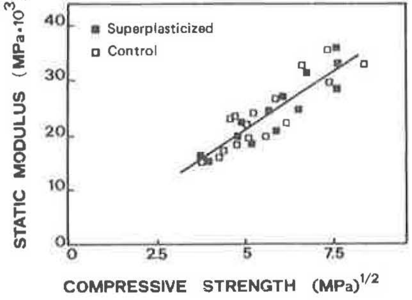


Figure 7. Static modulus of elasticity and compressive strength of concretes.



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.

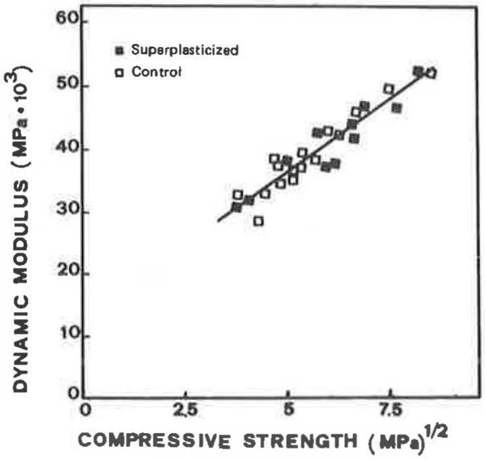


Figure 9. Shrinkage and creep for superplasticized concretes.

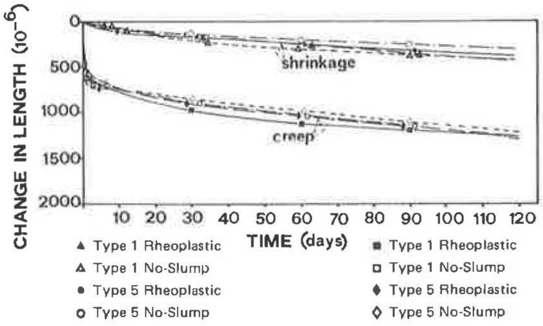


Table 2. Effect of superplasticizer A on freeze-thaw resistance of air-entrained concretes.

Cement Type	Cement Content (kg/m³)	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.

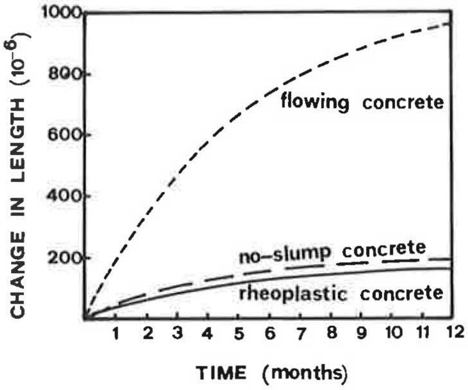


Figure 10. Changes in length caused by sulfate attack over time (type 1).

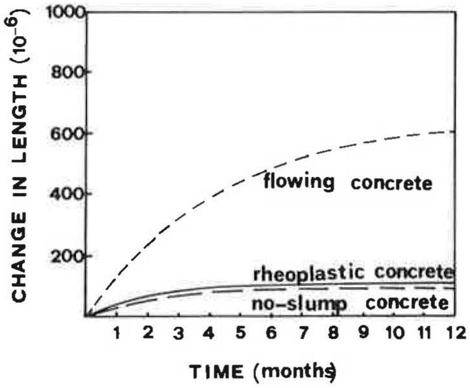


Figure 11. Changes in length caused by sulfate attack over time (type 5).

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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Workability and Strength of Retempered Superplasticized Concretes

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This paper presents the results of a comparative laboratory investigation of the workability of retempered concrete with and without superplasticizer. The effect of mixing time on the strength of superplasticized concrete is also discussed. Both superplasticizer and water were used as retempering agents, and the variables were type of superplasticizer and initial slump of the concrete. Fresh concrete was tested for slump, air content, and unit weight up to 150 min after initial mixing. The hardened concrete was tested for compressive strength and modulus of elasticity. The slump of retempered concrete both with and without superplasticizer decreased about equally with time. However, increased workability and subsequent slump loss depended on the type of superplasticizer used and the initial slump level. The results indicate that extended mixing time does not adversely affect the compressive strength of concrete. The large increases in slumps of superplasticized concretes can be maintained for several hours by retempering, which does not reduce the strength of the concrete. The properties of hardened retempered concrete are comparable to those of corresponding unretempered concretes.

Concrete that has desirable properties in the hardened state is normally made with a low water-to-cement (w/c) ratio and with the least possible amount of cement paste in the mix. Such a concrete usually has a low slump and requires the careful compaction needed for the high-density, low-slump concrete used in the Iowa method of bridge deck resurfacing.

In order to produce concrete of the same quality that requires less vibration, very effective plasticizers known as superplasticizers have been developed to make flowing and self-compacting concrete. Superplasticizers are added to concrete to greatly increase its workability or to allow a large reduction in mixing water and thus produce high-strength concrete (1, 2). Such a change in concrete properties would result in reduced placement costs or a reduction in the cement requirement. A well-designed mix with superplasticizer will have good flowability and sufficient cohesiveness and will not cause bleeding, segregation, or strength reduction during or after placement.

Though new to North America, superplasticizers have been successfully used in Japan since the late 1960s and in Germany since 1972 (1). The introduction of these superplasticizers has opened up new possibilities for the use of concrete in construction, particularly for resurfacing bridge decks and constructing other highway facilities. A few research establishments in the United States are performing laboratory studies on the use of these admixtures and are attempting to delineate their uses and limitations (3-9). Since 1976, investigations have been in progress at the Concrete Technology Research Center of the South Dakota School of Mines and Technology to determine the effects of superplasticizers on the properties of plastic and hardened concrete (7, 10-12).

Because slump loss is an inherent property of concrete even with the addition of superplasticizers, the high slumps of superplasticized concretes are not sustained over long periods. Hence delay in the discharge of concrete from the truck mixers could cause stiffening to the point of unworkability.

In actual field applications of superplasticizers, it may be necessary to add additional dosages—retempering—to maintain increased slump. The effects of extended mixing and of repeated dosages of superplasticizers to maintain a given slump need further study. Some retempering studies (13-16) investigated the effect of mixing time and retempering on conventional concrete by using water as the retempering agent. This paper presents the results of a comparative study of the workability and strength of retempered concretes with and without superplasticizer.

OBJECTIVES

The objectives of this research program are to study

1. Slump-loss characteristics for retempered superplasticized concretes,
2. The effect of retempering on the workability and strength of superplasticized concretes, and
3. The effect of mixing time on the workability and strength of superplasticized concretes.

RESEARCH PROGRAM

The research program consisted of three parts. First, water was used as the retempering agent, then superplasticizer was used, and finally the effect of mixing time on workability and strength was explored.

In part 1, water was used as the retempering agent for both control and superplasticized mixes. The control mixes were identical to the superplasticized mixes but lacked superplasticizers. Two control mixes, C1 and C2, were made, and 150 min after initial mixing, when the first workability study was over, these mixes were retempered with water. The retempered mixes were designated RC1 and RC2. Two corresponding superplasticized mixes, S1 and S2, were also retempered with water 150 min after initial mixing; these retempered mixes were designated RS1 and RS2.

The details of all eight mixes are given in Table 1. The same procedure was used for retempering all of them. When the first workability study was over, the concrete was weighed and put back in the mixer for 3 min. Retempering was done while the drum was rotating by adding a specific quantity of water according to judgment; the intent was to add enough to achieve a reasonably high initial slump.

In part 2 of the study, superplasticizer was used as the retempering agent. Two superplasticized mixes, PRS3 and PRS4, were made to study the effect of repeated dosages of superplasticizers on the workability and strength of concrete. Each mix was retempered three times, and the retempered mixes were designated PRS3-1, PRS3-2, and PRS3-3 and PRS4-1, PRS4-2,

Table 1. Properties of fresh and hardened concretes.

				Fresh Concrete				Hardened Concrete		
Mix	Dosage of Superplasticizer (%)	AEA[a] (%)	w/c Ratio	Temperature (°C)	Slump (mm)	Unit Weight (kg/m^3)	Air (%)	Unit Weight (kg/m^3)	Compressive Strength (MPa)	Modulus of Elasticity (MPa)
C1	-	0.12	0.65	22	172.7	2335.3	3.2	2365.8	23.16	31.92 × 10^3
RC1	-	0.12	0.80	20.5	107.9	-	-	2412.6[b]	25.00	32.95 × 10^3
								2448.3[c]	29.44	34.48 × 10^3
S1	Lomar-D 1.5	0.12	0.65	23	241.3	2374.90	3.6	2367.9	23.58	30.54 × 10^3
RS1	Lomar-D 1.5	0.12	0.77	18	193.0	2344.81	-	2379.7[b]	23.23	32.54 × 10^3
								2395.9[c]	25.23	33.16 × 10^3
C2	-	0.14	0.66	23	81.3	2301.44	5.0	2332.5	24.40	30.95 × 10^3
RC2	-	0.14	0.77	19	71.1	2342.41	-	2341.3[b]	24.61	31.51 × 10^3
								2462.0[c]	25.92	37.64 × 10^3
S2	Melment 1.5	0.14	0.66	25	233.7	2283.21	3.7	2360.2	25.23	32.13 × 10^3
RS2	Melment 1.5	0.14	0.86	20.5	195.6	2347.78	2.7	2357.6[b]	25.16	29.44 × 10^3
								2376.3[c]	26.54	31.64 × 10^3

Notes: t°C = (t°F - 32)/1.8; 1 mm = 0.039 in; 1 kg/m^3 = 0.062 lb/ft^3; 1 MPa = 145 lbf/in^2.

[a] AEA = air-entraining agent, Protex. [b] Molded 2.5 h after mixing. [c] Molded 5.0 h after mixing.

Table 2. Properties of fresh concretes.

Mix	Dosage of Superplasticizer (%)	AEA[a] (%)	w, c Ratio	Temperature (°C)	Slump (mm)	Unit Weight (kg/m^3)	Air Content (%)
TS1	Lomar-D 1.50	0.14	0.48	23	144.8	2266.8	-
TS2	Melment 1.50	0.14	0.48	23	119.4	2406.7	-
PS3	Melment 1.50	0.14	0.51	23	188.0	2395.6	5.0
PRS3-1	Melment 2.16	0.14	0.51	20	198.1	2413.5	3.8
PRS3-2	Melment 2.75	0.14	0.51	19.5	132.1	2448.5	1.6
PRS3-3	Melment 4.28	0.14	0.51	19	78.7	2434.2	1.6
PS4	Melment 1.50	0.14	0.49	22	165.1	2385.8	4.9
PRS4-1	Melment 2.62	0.14	0.49	20.5	129.5	2427.9	1.8
PRS4-2	Melment 3.15	0.14	0.49	19	0.0[b]	2440.0	2.0
PRS4-3	Melment 3.59	0.14	0.49	19	149.9	2432.8	1.7

Notes: t°C = (t°F - 32)/1.8; 1 mm = 0.039 in; 1 kg/m^3 = 0.062 lb/ft^3.

[a] AEA = air-entraining agent, Protex.

[b] This was not a true representative slump because all the mortar separated out from the aggregates.

and PRS4-3. Details for these eight mixes are given in Table 2.

Retempering was done when the slump was about 0-25 mm (0-1 in). The amount of superplasticizer added each time was again a matter of judgment; the intent was to add a sufficient quantity to increase the slump to a reasonable level. The remixing was done for 3 min at each retempering. After the initial mixing and at each interval, a known quantity of concrete was taken out for fresh concrete tests. Cylinders were cast after initial mixing and after each retempering.

In part 3, mixes TS1 and TS2 were used to study the effect of extended mixing time on the workability and strength of superplasticized concretes. The details of these mixes are given in Table 2. For these mixes, the concrete was left undisturbed and covered in the mixer for the entire period of testing. The fresh concrete tests were conducted, and specimens were cast immediately after initial mixing and after every elapsed hour.

MATERIALS, MIXES, SPECIMENS, AND TESTS

Materials

The materials used in the study are listed below.

1. Cement: The type 1 portland cement used satisfied ASTM C150-77 and was produced by the South Dakota State Cement Plant in Rapid City.
2. Aggregate: The fine aggregate was natural stone with a fineness modulus of 2.95, water absorption coefficient of 1.6 percent, and a saturated surface-dry specific gravity of 2.62; the coarse aggregate used was crushed limestone with a water-absorption coefficient of 0.45 percent and a saturated surface-dry specific gravity of 2.69.
3. Water: The water used was from the municipal water supply.
4. Air-entraining agent: The admixture Protex was used in constant dosage to entrain air.
5. Superplasticizers: Two types of superplasticizers were used: (a) Lomar-D, a high-molecular-weight condensed naphthalene sulfonate that meets all ASTM C494, type A admixture standards and (b) Melment L10, a 20 percent aqueous solution, clear to slightly milky to dark yellowish, with a density of 1.1 g/cm^3 (0.53 oz/in^3). Melment is a modified polycondensation product of melamine and formaldehyde. It contains no calcium chloride or other accelerating salts. Melment conforms to ASTM C494, type A standards.

Mixes

The same mix proportions were used for all mixes with an aggregate-to-cement ratio of 7.3 by weight. The different w/c ratios used are reported in Tables 1 and 2. The total initial mixing time was 8 min for all mixes: 3-min mixing, 3-min rest, and then 2-min mixing (ASTM C192-76).

Lomar-D was added along with water, and Melment was added during the last 2-min mixing. The first dosage of superplasticizer was added at the recommended rate given in Tables 1 and 2.

Specimens and Tests

The fresh concrete was tested for slump, air content, and unit weight. The temperature and slump of the concretes were recorded at fixed time intervals up to 150 min after initial mixing. Similar tests were carried out on fresh retempered concrete. For all the mixes, the hardened concrete was tested for 28-day compressive strength, modulus of elasticity, and unit weight.

The test specimens, 150x300-mm (6x12-in) cylinders, were cast in steel molds, compacted, and cured for 28 days in lime-saturated water according to ASTM C192. When the slump was less than 38 mm (1.5 in), the concrete was compacted with an internal vibrator.

ANALYSIS AND DISCUSSION OF TEST RESULTS

The results are discussed in three different parts corresponding to the three parts of the study undertaken in this investigation.

Part 1: Using Water as a Retempering Agent

Fresh Concrete

The slump and temperature measurements taken at 30-min intervals for eight mixes are given in Table 3. The slump-loss-with-time curves for control concrete, retempered control concrete, superplasticized concrete, and retempered superplasticized concrete are shown in Figures 1 and 2. As expected, there is a considerable increase in the slump of superplasticized concrete at recommended dosage. The slumps reached 229 mm (9 in), and even at these high slumps the concretes did not show any sign of segregation or excessive bleeding. This was true for both the superplasticizers, Lomar-D and Melment.

At the given w/c ratio and the dosage of air-entraining agent, the air content of both the control and the superplasticized concrete (with Lomar-D) was almost the same. The plastic unit weights were slightly higher for superplasticized concretes. For the concrete superplasticized with Melment, the air content was less than the corresponding control concrete.

The loss in slump in percentage-versus-time curves for one mix is plotted in Figure 3 and was calculated with respect to the initial slump. The slump-loss values are recorded elsewhere (12). In general, it was found that there was normal slump loss with time for all mixes. The slump of retempered control concretes reduced to a zero slump in about 90 min regardless of the initial level of slump for the control concretes. The initial temperature for these two control concretes was almost the same. For a higher initial slump of control concrete, the corresponding superplasticized concrete and the retempered superplasticized concrete took about 45-60 min to return to the initial slump of control concrete. As against this, for a lower initial slump of control concrete, the corresponding superplasticized concrete and retempered superplasticized concrete took longer, about 150 min, to come back to the initial slump of control concrete.

The results indicate that for all the mixes studied, the slump is lost in proportion to the initial slump level; the higher the initial slump, the higher the slump loss.

Table 3. Slump and temperature at various time intervals.

	Time After Initial Mixing and Retempering (min)					
Mix	0	30	60	90	120	150
C1						
Temperature (°C)	22	21.5	21	20.5	19.5	19.5
Slump (mm)	172.7	107.9	81.3	69.9	50.8	12.7
RC1						
Temperature (°C)	20.5	18.5	18	18	17	16.5
Slump (mm)	107.9	57.2	12.7	0	0	0
S1						
Temperature (°C)	23	22	21	20.5	19.5	19
Slump (mm)	241.3	190.5	133.4	101.6	73.7	68.6
RS1						
Temperature (°C)	18	17	16.5	16.5	15.5	15.5
Slump (mm)	193.0	146.1	134.6	94.0	76.2	58.4
C2						
Temperature (°C)	23	21	20	17	16.5	16.5
Slump (mm)	81.3	66.0	33.0	27.9	22.9	12.7
RC2						
Temperature (°C)	19	18.5	18	18	18	18
Slump (mm)	71.1	30.5	7.6	0	0	0
S2						
Temperature (°C)	25	23	21.5	20.5	20	19.5
Slump (mm)	233.7	193.0	170.2	114.3	91.4	50.8
RS2						
Temperature (°C)	20.5	19	17.5	15	14	14
Slump (mm)	195.6	180.3	114.3	88.9	81.3	61.0

Notes: t°C = (t°F - 32)/1.8; 1 mm = 0.039 in.

Figure 1. Slump versus time for S1, RS1, C1, and RC1.

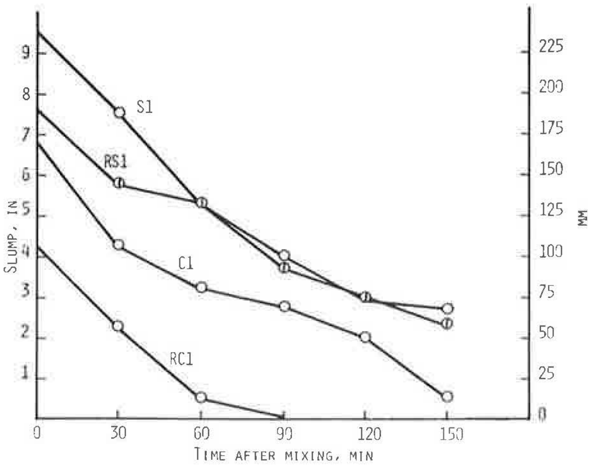


Figure 2. Slump versus time for S2, RS2, C2, and RC2.

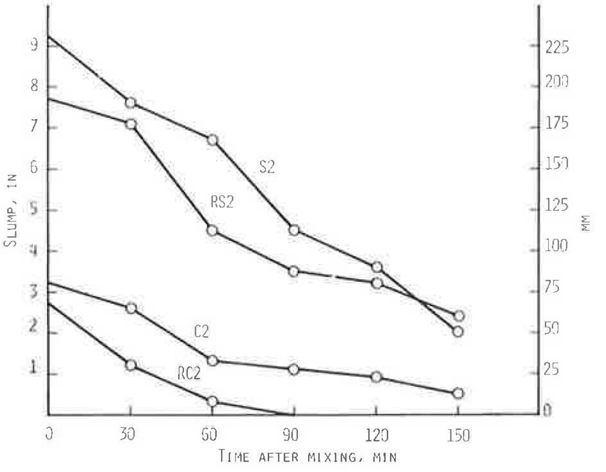
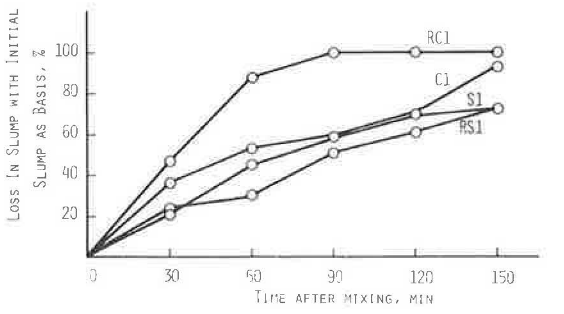


Figure 3. Loss in slump versus time for RC1, C1, S1, and RS1.

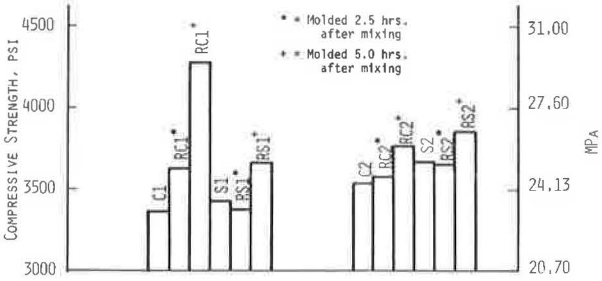


The same conclusion was drawn from the study by Previte (16).

The superplasticized concretes have less slump loss than the control concretes at all time intervals. The difference in the slump loss for control and retempered control concrete was maximum between 60-90 min, during which most of the slump was lost. The rate of slump loss for retempered control concrete was more than that of the control mix. However, the rate of slump loss is almost the same for both superplasticized and retempered superplasticized concretes.

The initial temperature of retempered mixes was always less than that of the corresponding control mixes. The amount of reduction in the temperature of fresh concrete during the 150-min period does not show any definite trend, but it was the same for both control and superplasticized concretes.

Figure 4. Comparison of compressive strength at 28 days for all mixes.



Hardened Concrete

Compressive strengths at 28 days are compared in Table 1 and Figure 4. In general, the compressive strengths of retempered concretes are equal to or greater than those of corresponding control concretes. This agrees with the results reported by Hawkins (14). The compressive strengths of cylinders cast from retempered concrete and molded 2.5 and 5.0 h after mixing are about 5 and 13 percent more than those of the respective control concretes. However, the cylinders cast from retempered superplasticized concretes and molded 5.0 h after mixing have shown an increase of 6 percent in the compressive strength, compared to the compressive strength of superplasticized concretes for both types of superplasticizers. A similar trend is shown in regard to dry unit weights.

The test results for modulus of elasticity are given in Table 1. In general it can be stated that retempering concrete does not adversely affect its modulus of elasticity. Also, the modulus of elasticity of retempered concrete cylinders molded 5 h after mixing is higher than that of those molded 2.5 h after.

Part 2: Repeated Dosages of Superplasticizer

Fresh Concrete

The slump, temperature, unit weight, and air content for the superplasticized and retempered superplasticized concrete mixes are reported in Table 4. A few typical slump-versus-time curves are plotted in Figures 5, 6, and 7, where it is clear that, regardless of the initial slump of the superplasticized concretes, the subsequent

Table 4. Temperature, slump, unit weight, and air content at various time intervals.

	Time After Initial Mixing and Retemperings (min)					
Mix	0	30	60	90	120	150
PS4						
Temperature (°C)	22	21	21	20	-	-
Slump (mm)	165.1	76.2	38.1	0	-	-
Unit weight (kg/m^3)	2385.8	2362.9	2387.6	2383.4	-	-
Air content (%)	4.9	5.0	5.0	-	-	-
PRS4-1						
Temperature (°C)	20.5	19.5	19.5	19	-	-
Slump (mm)	129.5	68.6	28.0	0	-	-
Unit weight (kg/m^3)	2427.9	2436.3	2413.0	2373.5	-	-
Air content (%)	1.8	2.0	2.0	-	-	-
PRS4-2						
Temperature (°C)	19	19	-	-	-	-
Slump (mm)	0[a]	12.7	-	-	-	-
Unit weight (kg/m^3)	2440.0	2425.8	-	-	-	-
Air content (%)	2.0	-	-	-	-	-
PRS4-3						
Temperature (°C)	19	19	-	-	-	-
Slump (mm)	149.9	0	-	-	-	-
Unit weight (kg/m^3)	2432.8	2427.9	-	-	-	-
Air content (%)	1.7	-	-	-	-	-
S3						
Temperature (°C)	23	22	21.5	21	20.5	20
Slump (mm)	188.0	162.6	111.8	101.6	50.8	33.0
Unit weight (kg/m^3)	2395.6	2331.8	2338.9	2352.7	2386.2	2382.7
Air content (%)	5.0	4.8	4.8	4.8	4.4	3.7
PRS3-1						
Temperature (°C)	20	19.5	19.5	-	-	-
Slump (mm)	198.1	48.3	22.9	-	-	-
Unit weight (kg/m^3)	2413.5	2408.4	2422.9	-	-	-
Air content (%)	3.8	2.8	-	-	-	-
PRS3-2						
Temperature (°C)	19.5	-	19	-	-	-
Slump (mm)	132.1	-	12.7	-	-	-
Unit weight (kg/m^3)	2448.5	-	2401.0	-	-	-
Air content (%)	1.6	-	-	-	-	-
PRS3-3						
Temperature (°C)	19	18.5	-	-	-	-
Slump (mm)	78.7	0	-	-	-	-
Unit weight (kg/m^3)	2434.2	-	-	-	-	-
Air content (%)	1.6	-	-	-	-	-

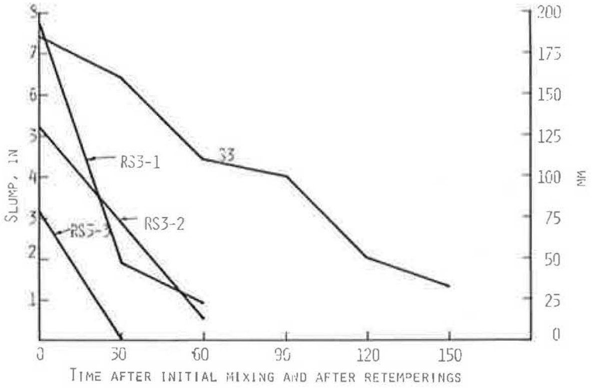
Notes: t°C = (t°F - 32)/1.8; 1 mm = 0.039 in; 1 kg/m^3 = 0.062 lb/ft^3.

[a] This was not a true representative slump because all the mortar separated out from the aggregates.

retemperings yield concrete that is workable for about 25-45 min.

The rate of loss of slump for the retempered concrete is considerably greater compared to the superplasticized concrete. Almost all the slump of retempered superplasticized concrete is lost in 30-60 min after retempering (Figure 6). For mix PS3, of high initial slump, the first retempering is done at 175 min after initial mixing; the second, third, and fourth retemperings are done after 80, 60, and 40 min, respectively. Thus the time between two successive retemperings shortens as the number of retemperings increases.

Figure 5. Slump versus time for S3, RS3-1, RS3-2, and RS3-3.



The amount of superplasticizer added at each retempering is recorded in Table 2, from which, with Figure 6, it is clear that the capacity of superplasticizer to make the concrete workable decreases as the number of retemperings increases. From Table 4, it is observed that the repeated addition of superplasticizer results in loss of entrained air. This results in a gain in plastic unit weight. There is a progressive decrease in temperature at each retempering.

It is very interesting to note that, when retempered with higher precentages of Melment (more than 3 percent), the concrete segregated immediately and the slump could not be measured properly. The cylinder cast with such a segregated concrete yielded a honeycombed specimen.

Figure 6. Loss in slump versus time for S3, RS3-1, RS3-2, and RS3-3.

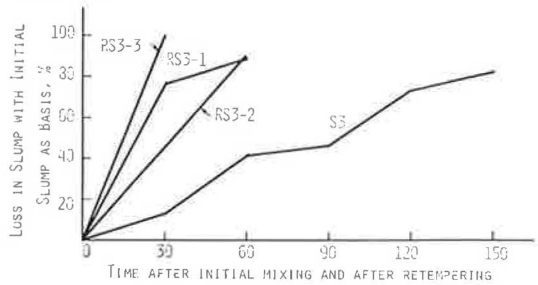


Figure 7. Slump-time retempering study for mix S3.

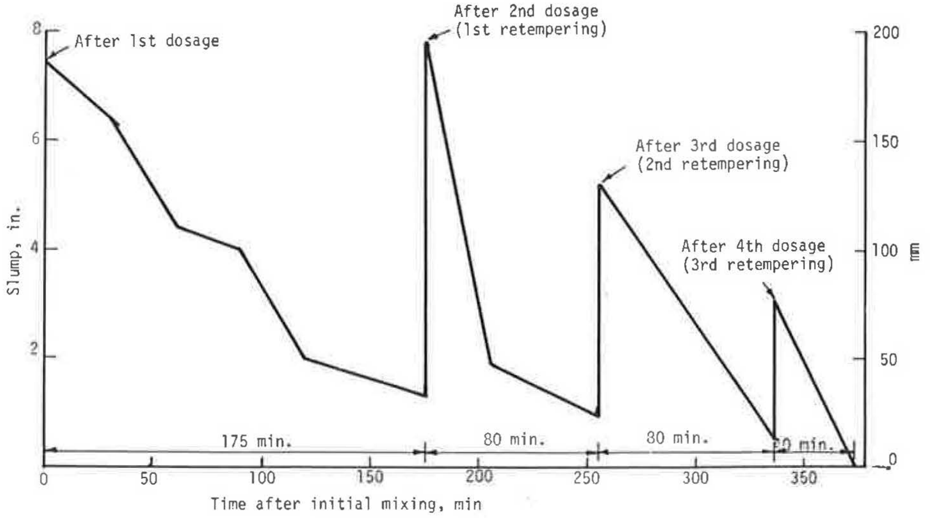
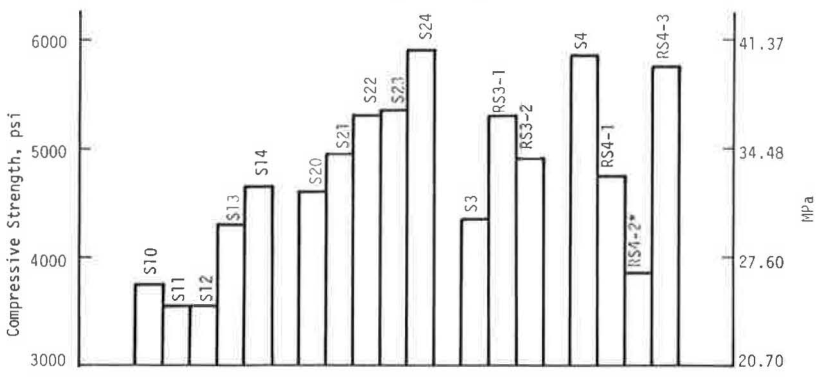


Figure 8. Comparison of compressive strength at 28 days.



*Honeycombed specimen

Table 5. Properties of hardened concrete.

Mix[a]	w/c Ratio	Unit Weight (kg/m^3)	Compressive Strength (MPa)	Modulus of Elasticity (MPa × 10^3)	Ratio $E_c/f'_c \times 10^3$[b]
TS10	0.48	2326.1	25.78	32.0	1.24
TS11	0.48	2322.9	24.54	30.5	1.24
TS12	0.48	2340.5	24.54	29.2	1.19
TS13	0.48	2403.0	29.79	32.8	1.10
TS14	0.48	2431.8	31.92	34.3	1.07
TS20	0.48	2436.6	31.85	34.4	1.08
TS21	0.48	2435.0	34.00	37.2	1.09
TS22	0.48	2438.2	36.61	40.6	1.10
TS23	0.48	2449.5	36.75	36.6	1.00
TS24	0.48	2451.1	40.75	34.5	0.85
PS3	0.51	2441.4	29.92	35.8	1.20
PRS3-1	0.51	2447.8	36.41	36.1	1.00
PRS3-2	0.51	2508.7	33.72	41.4	1.23
PRS3-3	0.51	2461.1	19.31[c]	-	-
PS4	0.49	2441.9	40.47	40.1	1.00
PRS4-1	0.49	2521.7	32.60	39.9	1.22
PRS4-2	0.49	2470.2	26.61	31.9	1.20
PRS4-3	0.49	2527.6	39.65	42.8	1.08

Notes: 1 kg/m^3 = 0.062 lb/ft^3; 1 MPa = 145 psi.

[a] TS14 is superplasticized mix 1 at 4 h after initial mixing; PRS4-3 is retempered superplasticized mix 4 at third retempering.

[b] E_c = modulus of elasticity and f'_c = 28-day compressive strength.

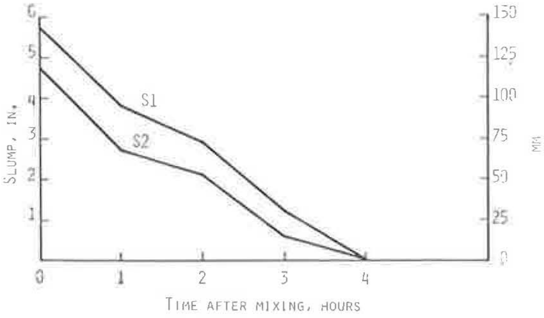
[c] Honeycombed specimen.

Table 6. Temperature, slump, and unit weight at various time intervals.

	Time After Initial Mixing (h)				
Mix	0	1	2	3	4
TS1					
Temperature (°C)	23	21.5	21	21	21
Slump (mm)	144.8	96.5	73.7	30.5	0
Unit weight (kg/m^3)	2266.8	2273.9	2290.0	2325.0	2282.0
TS2					
Temperature (°C)	23	23	23	23	23
Slump (mm)	119.4	68.6	53.3	15.2	0
Unit weight (kg/m^3)	2406.7	2409.1	2407.4	2401.7	-

Notes: $t°C = (t°F - 32)/1.8$; 1 mm = 0.039 in; 1 kg/m^3 = 0.062 lb/ft^3.

Figure 9. Slump versus time for S1 and S2.



Hardened Concrete

The comparison of compressive strengths at 28 days is shown in Table 5 and Figure 8. In general, the compressive strengths of retempered superplasticized concretes are equal to or greater than the strengths of superplasticized concretes. This is attributed mainly to the loss of entrained air from concrete. Similar results have also been reported by Hawkins (14) and Beaufait and Hoadley (15). Modulus of elasticity of concrete is not adversely affected by retempering.

Part 3: Time-Strength Study

Fresh Concrete

The temperature, slump, and unit weight measurements at 1-h intervals for mixes TS1 and TS2 are given in Table 6. After the initial mixing, the concrete was left undisturbed and covered in the mixer for the entire period of testing to prevent evaporation of water. A specific quantity of concrete was taken from the drum every hour until the concrete could no longer be either worked or removed from the drum without adding water. The slump-versus-time curves for both mixes are shown in Figure 9.

Under the experimental conditions, both superplasticized concretes behaved identically and reached zero slump in about 4 h. However, the concrete became very difficult to work after approximately 3 h. The temperature loss for superplasticized concrete with Lomar-D was more than that for the one with Melment. From Table 6 it is observed that the plastic unit weight increases at first and then, when compaction becomes difficult, it decreases.

Hardened Concrete

The results of the tests conducted to study the effect of mixing time on the compressive strength are presented in Figure 8, and Table 5. In general, mixing time did not adversely affect the strength, and concrete gained strength (25 percent) up to 4 h after mixing time. A similar gain was also reported by Hawkins (14) when water was used as the retempering agent.

The test results for modulus of elasticity are given in Table 5. The modulus of elasticity has not been influenced by extended mixing time. Table 5 gives the ratio of modulus of elasticity (E_c) to 28-day compressive strength (f'_c); it shows a definite trend. The ratio of E_c/f'_c decreases as the mixing time increases. The compressive strength might have been increased by a reduction in the air content, whereas the modulus of elasticity of concrete does not change after prolonged mixing; hence, the ratio E_c/f'_c decreases.

CONCLUSIONS

Based on the analysis of experimental results, the following conclusions are drawn.

1. There is a normal loss of slump with time for all the mixes, including control mix, superplasticized mix, and the corresponding retempered concrete mixes. However, high slumps of superplasticized concretes can be maintained for several hours by retempering.
2. The slump loss is proportional to the initial slump level for all the mixes; the higher the initial slump, the higher the slump loss. However, the total time span during which concrete could be kept workable is longer for concrete with higher initial slump.
3. About 60-80 percent of the slump of control and retempered control concrete is lost in 60-90 min.
4. The capacity of the superplasticizer to keep the concrete workable is reduced as the number of retemperings is increased. Higher dosages of superplasticizer lead to segregation. The rate of slump loss is higher for retempered concretes.
5. Repeated dosages of superplasticizer cause a loss in entrained air.
6. An extended period of mixing does not have an adverse effect on the strength of superplasticized concrete; however, extended mixing time does affect the workability of the mix.
7. The properties of hardened retempered concrete such as compressive strength, dry unit weight, and modulus of elasticity are not adversely affected for both the mixes with and without the addition of the super-

plasticizer. This is true when water or different dosages of superplasticizer are used for retempering.

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Super-Water-Reduced Concrete Pavements and Bridge Deck Overlays

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In order to obtain mixtures that have (a) a consistency that would permit use of conventional placement equipment and (b) a water-to-cement ratio of 0.33-0.37, melamine- and naphthalene-sulfonated polymer admixtures were used in the concrete placed in two experimental pavements and four bridge deck overlays. With one exception, ready-mix trucks were used to mix the concrete, and placement methods included direct discharge, buggy, crane and bucket, and pump. Internal vibration was used for consolidation, and the screeding equipment included a wooden straightedge, an oscillating screed, a rotating-drum screed, and a metal vibrating straightedge. Compression-tested specimens from the projects showed significantly higher early and 28-day strengths than specimens without the admixture, and petrographic examinations of cores taken from the overlays indicated that, on the average, the concrete was properly consolidated and controlled. However, because of the extreme variability of the concrete, many portions of the completed structures exhibited inadequate consolidation, segregated mixture components, improperly entrained air, shrinkage cracks, and poor finishes. Also, specimens from freeze-thaw tests showed low durability factors that were attributed to an unsatisfactory air-voids system.

Super-water-reducing (SWR) admixtures were used experimentally by the Virginia Department of Highways and Transportation on a number of construction jobs between May 1974 and June 1977. The melamine- (M) and naphthalene-sulfonated (N) polymer admixtures were used to produce concrete of a water-to-cement (w/c) ratio of 0.33-0.37. This resulted in concrete that had high early and 28-day strengths.

On these jobs an effort was made to maintain a workability that would allow the concrete to be placed with conventional equipment. Concrete of conventional workability, i.e., one having a slump of 50-100 mm (2-4 in) as measured by the slump cone (ASTM C 143), was sought on the first job, but mixtures of slumps ranging from 0 to 267 mm (0 to 10.5 in) were placed during the three-year period.

The basic problem was the inability of construction personnel to maintain a workability that allowed the concrete to be placed, consolidated, and finished with conventional equipment. In addition, it was difficult to control the gradation and the moisture content of the fine aggregate with the accuracy necessary to prevent significant fluctuations in slump between batches. The rapid loss in workability was best accommodated by keeping batch size small, shortening the length of the screed span, and adding the SWR admixture at the project site before discharge and periodically during discharge. However, 76x102x406-mm (3x4x16-in) prismatic specimens, made at the job sites and tested in accordance with ASTM C 666, procedure A (modified by using 2 percent sodium chloride by weight in water), showed low durability factors compared to conventional concrete of a w/c ratio of 0.43 and a consistency of 51-102 mm (2-4 in).

The use of SWR concrete in construction has now been terminated by the department until (a) satisfactory guidelines can be developed for batching, placing, consolidating, and finishing the concrete; (b) a satisfactory specification can be prepared to allow for field acceptance; and (c) the durability of the concrete can be improved.

FIELD INSTALLATIONS

State maintenance forces used concrete containing an SWR admixture on a partial-depth pavement-repair operation in May 1974 and for the construction of a full-depth turning lane in November 1974. Between July 1976 and May 1977, three contractors constructed SWR concrete overlays on four bridges by using four installation techniques and five mixture proportions.

One or more trial batches were made before placing each of the seven mixtures containing the SWR admixtures. Conventional ready-mix trucks were used to mix and deliver all the concrete except that used in the partial-depth pavement-repair operation, which involved site batching. Haul time for the concrete was 25-35 min except for that used on the full-depth turning lane, which required a 5-min haul time.

Partial-Depth Pavement Repair with Site-Batched Concrete

Maintenance forces installed the first SWR concrete in Virginia in the form of 15 small, partial-depth pavement patches on the Norfolk and Virginia Beach Expressway (1). A trial batch was made to determine the quantities of ingredients needed to consistently produce a concrete of an initial consistency of 51-102 mm (2-4 in). A paddle-type mixer, capacity 0.057 m^3 (2 ft^3), was used on the job.

Before the coarse aggregate was added, the M-SWR admixture was added in powder form at a recommended dosage of 1 percent of the weight of the cement, which provided a workable concrete of a w/c ratio of 0.35. No problems were encountered, and the maximum time required to batch, place, consolidate, finish, and apply the liquid-membrane-curing compound for any one patch was about 15 min.

Standard 152x305-mm (6x12-in) field specimens tested in accordance with ASTM C 39 provided strengths of 13.8 MPa (2000 lbf/in^2) at 16 h, at which time the patched lane was opened to traffic. The patches appear to be in good condition after having been subjected to 4.5 years of heavy traffic and a very modest number of freeze-thaw cycles.

Full-Depth Pavement with Short-Haul Directly Discharged Concrete

Maintenance forces used SWR concrete to construct a full-depth 230-mm (9-in) turning lane approximately 61 m (200 ft) long and 3.4 m (11 ft) wide on a four-lane divided highway. The M-SWR admixture was added to the ready-mix truck in powder form with the fine aggregate at the batch plant, located about 5 min from the project. Each 6.3-m^3 (8-yd^3) batch was discharged directly from a mix truck positioned in the adjacent traffic lane. One internal vibrator, a wooden straightedge, and a broom were used to consolidate, finish, and texture the concrete, which had an initial slump of 76-178 mm (3-7 in) and a w/c ratio of 0.35. The concrete was placed and finished in a few minutes without any noticeable problems, and a liquid-membrane-curing compound was applied. Cylinder strengths averaged 35.2 MPa (5100 lbf/in^2) after three days of field curing at temperatures near freezing.

This pavement appears to be in satisfactory condition after having been subjected to four years of moderate traffic and a fair number of freeze-thaw cycles. Several major transverse cracks are visible, and much of the surface has scaled moderately; coarse aggregate is visible in many areas. An examination of cores recently removed from the pavement indicated that some of the concrete was poorly consolidated.

Deck Overlay with Directly Discharged Concrete

The M-SWR admixture for the first deck overlay, placed on a bridge (B616) at Charlottesville, was blended in powder form with the fine aggregate before placement in the ready-mix truck at the batch plant.

The 4.6-m^3 (6-yd^3) batches were tested for consistency and air content at the bridge site before they were discharged directly into the 11x8-m (36.0x 26.4-ft) area to be overlaid. The contractor used internal vibrators and an oscillating longitudinal screed. The fact that the batch plant was located about 25 min from the job site made it necessary to add water to maintain an initial consistency of 102-178 mm (4-7 in) (Figure 1). A w/c ratio of $\leq$0.37 was specified, but 0.39 was required to obtain a satisfactory initial consistency for the last batch, which contained only 2.3 m^3 (3 yd^3). A total of 57 min elapsed between the time the last truck was batched and discharge began at the job site. Slump measurements confirmed that the workability of the concrete decreased by 50 percent in 15 min, which had not been anticipated and was therefore not properly covered by the batching technique and the direct-discharge placement method.

Petrographic examination of cores removed from the 102-mm (4-in) thick overlay showed that the concrete was much too permeable because of inadequate consolidation. After just one winter of freeze-thaw and heavy traffic, the concrete had deteriorated to the point of needing replacement. Obviously the concrete was inferior because the contractor failed to place, consolidate, and finish it before it lost satisfactory workability.

Deck Overlays with Crane-and-Bucket-Placed Concrete

In placing overlays on two two-lane three-span bridges, B602 and B603, a crane and bucket were used to move SWR concrete from 6.1-m^3 (8-yd^3) capacity ready-mix trucks onto the decks.

On the first of the six 12.8-m (42-ft) spans to be overlaid, the N-SWR admixture was added to the ready-mix truck at the batch plant, which was located about 25 min from the project. Approximately 7.5 L (2 gal) of water was used to wash the liquid admixture into the mix truck, and water was added at the bridge site to produce concrete of a workability of 51-102 mm (2-4 in). Because of the rapid loss of workability, the contractor was unable to properly consolidate and finish the concrete.

After the first span of B602 was completed, it was decided that on the next two spans the liquid admixture would be added at the bridge site (Figure 2). The ready-mix trucks were batched as usual, except that the admixture and 9.9 L/m^3 (2 gal/yd^3) of the water was withheld and mixing was restricted to 10 revolutions until the contractor was prepared to receive the concrete on the bridge deck.

Before discharging, most of the water that had been withheld was added and the ingredients were mixed for 70 revolutions, which produced concrete of zero slump. The liquid N-SWR admixture was then added at a recommended dosage of 1.2 percent of the weight of cement and was washed into the truck with the remainder of the previously withheld water. The ingredients were mixed for 30 revolutions, and a small amount was discharged for testing. By adding the N-SWR admixture at the bridge site rather than at the batch plant, initial slumps ranging from 165 to 242 mm (6.5 to 9.5 in) were obtained.

It took an average of 39 min to mix and place the concrete from each truck. During this interval the consistency of the concrete dropped to as low as 51 mm (2 in), a slump loss of 50 percent in about 20 min. In addition, slight changes in the gradation and moisture content of the fine aggregates caused significant fluctuations in slump between batches.

Because of the nonuniform consistency of the concrete, the contractor had considerable difficulty in properly consolidating, screeding, and finishing the 102-mm (4-in) thick overlay (see Figures 3 and 4). Areas of the overlay containing concrete placed at a high slump bled considerably and flowed behind the screed, even though the finish grade was only 2 percent.

Areas containing concrete placed at a low slump could not be properly consolidated or finished. Segregation was obvious in some of the concrete placed at a consistency above 203 mm (8 in) (see Figures 5 and 6). However, field specimens tested in accordance with ASTM C 39 provided average three-day strengths of 23.8 MPa (3455 lbf/in^2) and 28-day strengths of 48.3 MPa (7000 lbf/in^2), which may be attributed to the

Figure 1. Typical curves for slump versus time after adding initial SWR admixture.

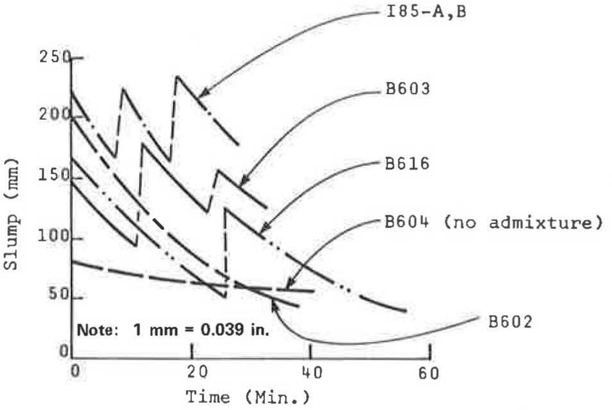


Figure 2. Liquid SWR admixture added to ready-mix truck.

Figure 3. SWR overlay on B602.

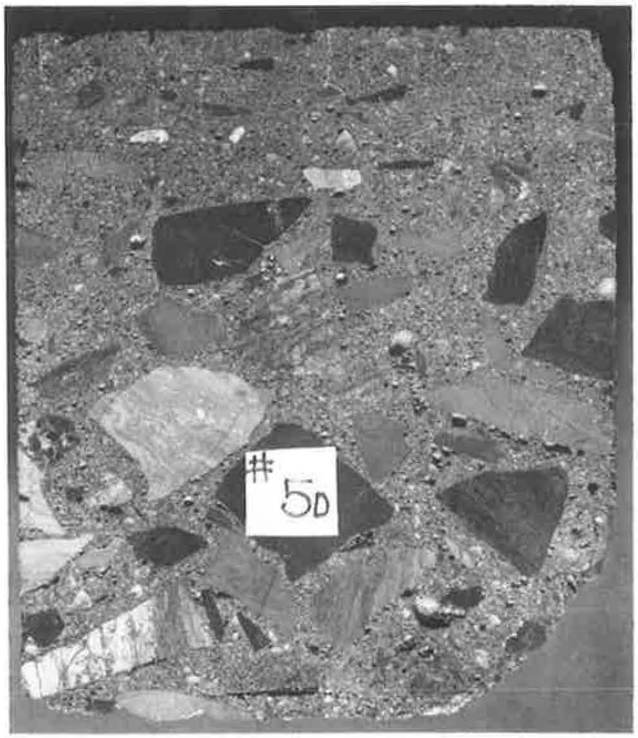
Figure 4. Variable concrete pulling in lower part and flowing in upper part.

0.34 w/c ratio required by the specified mixture proportions.

The manufacturer of the N-SWR admixture suggested that segregation might not occur if the fine aggregate content of the mixture were increased. So, before the overlay on the three spans of B603 was placed, the mixture proportions were changed to provide a 7.5 percent increase in the fine aggregate content and a 5.0 percent decrease in the coarse aggregate (Table 1). Also, the batch size was reduced from 6.1 m^3 (8 yd^3) to 4.6 m^3 (6 yd^3) and the addition of the N-SWR admixture several times during discharge was permitted.

In overlaying these three spans, the N-SWR admixture was added to the ready-mix trucks two or three times (Figure 1), but the same consolidating and finishing problems were encountered. Segregation was not apparent, but slumps did not exceed 203 mm (8 in) for concrete placed on B603; for the same dosage of SWR admixture, the slump of the concrete on B603 was generally lower than on B602. Because mixing additional admixture requires several minutes, as much time was required to discharge the 4.6-m^3 (6-yd^3) batch as was required to discharge the unmodified 6.1-m^3 (8-yd^3) batches. On one span the overlay was covered with a considerable amount of bleed water after screeding (see Figure 7), and on another it was stiff enough to walk on before screeding was complete. Field records indicate that there were no differences in the concretes used in these two spans, except that the N-SWR admixture was added in the amount of 1.5 percent by weight of the cement for the former and 1.2 percent for the latter and the dosage of air-entraining admixture was 25 percent greater for the latter.

Figure 5. Core showing segregation of fluid concrete.



It was apparent in placing the overlays on B602 and B603 that the N-SWR admixture was not properly mixed with the concrete at all times. Occasionally after the addition of the admixture the consistency of the concrete did not change, but at other times the first concrete discharged after mixing was very fluid but was followed by concrete that was very stiff. Concrete that was extremely fluid on the initial discharge was returned to the truck and mixed again. When the air content of the concrete was below the specified minimum of 5 percent, additional air-entraining admixture was added to the batch and mixed for 2 min. At times, the air content increased to 12 percent and the workability increased significantly; at other times the air content did not change and the workability decreased. Obviously, quality concrete is difficult to achieve when admixtures are added to ready-mix trucks at the job site.

Before the SWR overlays were placed on B602 and B603, the contractor had successfully placed a conventional A4-concrete overlay on a similar three-span bridge (B604) with the same crew and equipment. The

Figure 6. Core showing loss of cement mortar.

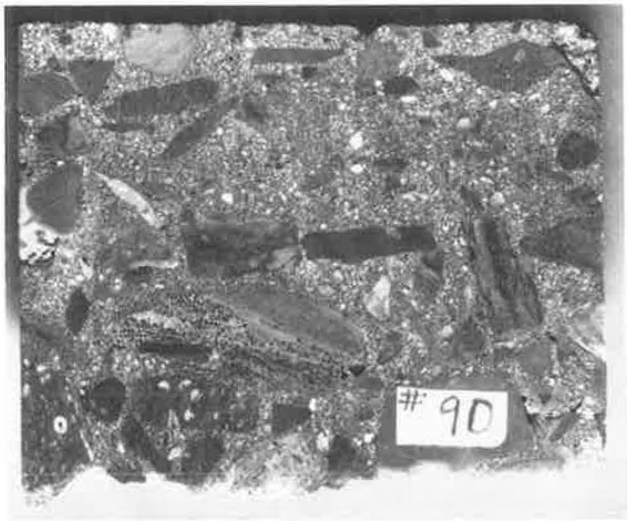


Table 1. Mixture proportions.

Location	SWR Admixture	Type 2 Cement Content (kg/m^3)	Coarse Aggregate			Fine Aggregate Content (kg/m^3)	Maximum w/c	AEA[a] (ml/m^3)
			Nominal Maximum Size (mm)	Type	Content (kg/m^3)			
B616	Melamine	390	13	No. 7 crushed stone	831	963	0.37	170
B604	None	376	25	No. 57 crushed stone	1063	674	0.44	274-276
B602	Naphthalene	376	25	No. 57 crushed stone	1090	745	0.34	217-296
B603	Naphthalene	376	25	No. 57 crushed stone	1036	801	0.34	296-395
B639	None	376	25	No. 57 crushed stone	1073	699	0.44	276
I-85A	Naphthalene	418	13	No. 7 gravel	983	720	0.35	316-395
I-85B	Naphthalene	390	13	No. 7 gravel	983	769	0.35	395
I-85C	None	418	13	No. 7 crushed stone	869	767	0.42	253

Notes: 1 kg/m^3 = 0.06 lb/yd^3; 1 mm = 0.039 in; 1 ml/m^3 = 0.02 oz/yd^3.

[a] Vinsol resin.

w/c ratio used for the conventional overlay was 0.43, so the 28-day cylinder strengths averaged only 41.2 MPa (5980 lbf/in^2). A longitudinal oscillating screed and several internal vibrators were used on both the SWR and the conventional installations. A belt texture was applied to the conventional decks but hand finishing and some broom texturing were used on the SWR overlays. A liquid-membrane-curing compound was applied to all the decks as the sheen disappeared from the surface.

Figure 7. Excess bleed water remaining after screeding and finishing overlay on B603.

Figure 8. SWR concrete being pumped into place on I-85A.

Figure 9. Poor finish resulting from a rapid loss in workability.

Deck Overlay with Pumped Concrete

In only 5 h a contractor placed a 102-mm (4-in) thick overlay on three bridge spans 21.3x9.1 m (70x30 ft) wide on I-85 (I-85A). The concrete was pumped into place so rapidly that the ready-mix producer had difficulty keeping the pump supplied.

The same technique for plant batching and site mixing used on B603 was also used here, and the admixture was added at an initial dosage of 1.5 percent by weight of the cement. Additional dosages were administered at 10-20 percent of the initial dosage. The liquid was added to the 5.4-m^3 (7-yd^3) capacity ready-mix truck several times as the concrete was being discharged into the pump at a consistency above 203 mm (6 in) at all times. The average consistency of the concrete was 216 mm (8.5 in), but slumps as high as 267 mm (10.5 in) were recorded. One mix truck was positioned on each side of the pump; while one was being unloaded another was being modified with the liquid N-SWR admixture. A truck could be unloaded in about 30 min from the time mixing began at the bridge site.

A double-drum screed that rolled over the 9.1-m (30-ft) wide deck surface between the parapets was used to level the concrete, which previously had been consolidated with internal vibrators as it was discharged from the pump. Operating from the work bridge, kept about 4.6 m (15 ft) behind the screed, laborers applied a hand finish, a broom texture, and a membrane-curing compound. The entire operation was well organized and moved in a very systematic manner (Figure 8). An earlier attempt to pump the concrete had failed because concrete having an initial consistency of only 76 mm (3 in) was discharged into the pump and in a matter of minutes clogged the line. The initial dosage of the N-SWR admixture was increased from 1.2 to 1.5 percent by weight of the cement to provide the consistency necessary for pumping.

Although the operation was well organized, the finished product was less than desirable. More than half of the surface area was very rough, and there were numerous highly porous areas in the top 6.4 mm (0.25 in) of the overlay, both of which may be attributed to the fact that the contractor was unable to properly level and finish the concrete before it lost its workability (Figure 9). Sufficient surface mortar to provide a satisfactory finish could be obtained only if the concrete was finished before it lost its workability. The overlay also had numerous shrinkage cracks that probably formed because the contractor did not apply the curing compound as soon as the sheen disappeared. The 19-mm (0.75-in) maximum size of the coarse aggregate, the high cement content, and the high slump may have contributed to the incidence of shrinkage cracking. Most of the cracks, both full and partial depth, were oriented in the transverse direction and were spaced about 0.6-1.2 m (2-4 ft) apart. Some were randomly oriented. The fluid concrete was virtually self-leveling and self-consolidating, but to obtain a satisfactory finish and to prevent shrinkage cracks it was necessary to screed, texture, and apply the curing compound within about 20 min of placing the concrete. The contractor decided that he could not speed up his operation sufficiently to provide a satisfactory finish and chose to abandon the pumping operation. Cylinders obtained from the project had average 28-day strengths of 54.8 MPa (7947 lbf/in^2).

Deck Overlays with Buggy-Placed Concrete

On subsequent SWR deck installations on I-85 (I-85B) the contractor chose to bring his placement operations under control by dividing the 9.1-m (30-ft) roadway width into two 4.6-m (15-ft) wide sections and replacing the drum-type screed with a custom-made vibrating screed. The screed consisted of a vibrator attached to the midspan of several 51x254-mm (2x10-in) timbers and two metal angles attached to the bottom of the timbers.

The concrete was mixed at the site as was done with the pumping operation, and buggies were used to transport the concrete from the trucks to the deck. The screed spanned a distance of only 4.6 m (15 ft), so the contractor was able to consolidate, screed finish, and apply the curing compound in a very short time after the concrete was placed (Figure 10). Also, the forward travel of the vibrating screed could be adjusted to suit the consistency of the concrete and thereby impart a satisfactory finish regardless of whether the concrete was fluid or very stiff. Considerable vibration is needed to consolidate and finish stiff concrete, whereas a fluid concrete can tolerate very little vibration when it is being consolidated and finished.

Although buggies do not provide for a rapid placement operation, the short-span vibrating screed did give a satisfactory finish. Two spans were overlaid with SWR concrete by using this technique. It was readily apparent from the previous installations that the water content and the gradation of the fine aggregate must be precisely determined if a product that will be given an SWR admixture is to have the desired consistency. The consistency cannot be checked by the slump-cone method before the SWR admixture is added because the slump is essentially zero for the mixture proportions used in Virginia. Consequently, if a standard percentage of admixture is added to two batches of slightly different water contents, a mix with good workability may be obtained in one case and a fluid mix as shown in Figure 11 in the other.

Figure 10. Satisfactory finish obtained with a vibrating straightedge and rapid placement operation.

Figure 11. Super-water-reduced concrete flowing out of control.

Because of the poor freeze-thaw performance of field specimens made during the installations on B602 and B603, it was decided that the remaining spans on I-85 (I-85C) would be overlaid with A4 concrete. The average 28-day cylinder strength for the A4 concrete was 38.6 MPa (5600 lbf/in^2), which is 79 percent of the strength attained with the SWR concrete used on I-85A and I-85B.

PRELIMINARY EVALUATIONS OF THE SUPER-WATER-REDUCED CONCRETE

Preliminary evaluations of the SWR concretes placed in Virginia are based on (a) field observations and data collected at the time the concretes were placed, (b) laboratory tests of 152x305-mm (6x12-in) cylindrical compression test specimens and 76x102x406-mm (3x4x16-in) prismatic freeze-thaw test specimens made from random samples of the concretes, and (c) petrographic examinations of 102-mm (4-in) diameter cores removed from the structures and of portions of selected 152x305-mm (6x12-in) cylindrical specimens made from random samples of the concretes.

The scope of this paper does not make it practical to report detailed information for each of the SWR concrete installations. Therefore, selected data are reported. Information on several A4 concrete deck overlay installations (B604, B639, and I-85C) involving similar construction circumstances are reported to help clarify the significance of some of the data reported for the SWR concrete. The concrete mixture proportions to be considered are given in Table 1.

Concrete Properties

The ASTM C 231 pressure method was used to measure air content of all the study concretes; consistency was determined in accordance with ASTM C143. Air-content measurements of the SWR concrete made by the Chace method were always very low and were therefore considered inaccurate. The characteristics of the SWR concretes changed as the mixtures were placed, so air content and consistency measurements were made several times as a batch was being discharged. Also, at times no measurements were made on the SWR concrete because delays caused by checking the concrete properties impeded the contractor's operations. The air-content and slump-test results are summarized in Table 2.

It is immediately apparent from the magnitudes of the standard deviations in Table 2 that one significant difference between SWR concrete and conventional concrete is the variability in the properties of the plastic concrete. Assuming a normal distribution of data, approximately 35 percent of the SWR concrete had an air content and 40 percent of it had a slump outside of the design range, compared to only approximately 5 and

Table 2. Properties of plastic concrete.

Location	SWR Admixture	Air Content (%) Design	Air Content (%) Average	Air Content (%) SD	Air Content (%) Z[a]	Slump (mm) Design	Slump (mm) Average	Slump (mm) SD	Slump (mm) Z[a]
B604	None	5.0-8.0	6.8	0.9	11	51-102	71	15	11
B602	Naphthalene	5.0-8.0	5.4	1.9	50	102-203	145	71	48
B603	Naphthalene	5.0-8.0	6.1	1.4	30	102-203	122	58	45
B639	None	5.0-8.0	6.8	0.8	8	51-102	97	13	34
I-85A	Naphthalene	5.0-9.0	6.5	1.6	23	152-267	208	36	11
I-85B	Naphthalene	5.0-9.0	5.5	1.7	41	152-267	208	71	42
I-85C	None	5.0-9.0	6.7	0.4	0	51-127	119	5	6

Note: 1 mm = 0.039 in.

[a] Percentage of data falling outside of design range.

Table 3. Cylinder strengths.

Location	SWR Admixture	Field-Cured Specimens (MPa) 3-Day Average	Field-Cured Specimens (MPa) 3-Day SD	Moist-Cured Specimens (MPa) 14-Day Average	Moist-Cured Specimens (MPa) 14-Day SD	Moist-Cured Specimens (MPa) 28-Day Average	Moist-Cured Specimens (MPa) 28-Day SD
B604	None	17.4	1.2	29.0	1.1	41.2	1.9
B602	Naphthalene	23.8	1.1	40.5	4.5	48.3	5.7
B603	Naphthalene	15.4	4.5	55.6	1.2	61.3	2.8
B639	None	-	-	22.0	-	25.4	1.7
I-85A	Naphthalene	-	-	-	-	54.8	2.0
I-85B	Naphthalene	32.2	4.1	-	-	43.3	3.1
I-85C	None	-	-	-	-	38.6	1.8

Note: 1 MPa = 145 lbf/in².

Table 4. Freeze-thaw performance for 300 cycles.

Location	Date Cast	SWR Admixture	No. of Specimens	w/c Ratio	Type of Cure	Surface Rating Average	Surface Rating SD	Percentage Weight Loss Average	Percentage Weight Loss SD	RDF Average	RDF SD	RDF Percentage of Control
Laboratory	11/20/75	None	2	0.42	2 weeks, moist 1 week, laboratory	1.5	-	1.1	-	100	-	100
	2/7/74	Melamine	3	0.32	2 weeks, moist 1 year, laboratory	2.1	0.1	3.0	0.2	77	15	77
	8/10/76	Naphthalene[a]	3	0.35	2 weeks, moist 3 weeks, laboratory	2.1	0.1	0.4	0.5	94	9	94
B604	8/30 and 9/11/76	None	8	0.43	3-7 months, field	1.9	0.4	1.1	0.5	90	7	100
B602	10/11 and 15/76	Naphthalene	13	0.34	2-6 months, field	2.1	0.9	1.6	1.6	70	23	78
B639	10/27 and 28/76	None	4	0.43	1 month, field	2.3	0.2	3.2	0.9	98	1	100
I-85A	4/29/77	Naphthalene	3	0.35	1 month, field	2.5	1.4	4.7	3.3	62	42	63
I-85B	5/27/77	Naphthalene	3	0.35	1 month, field	4.8	2.3	19.8	17.8	47	38	48
I-85C	6/14/77	None	3	0.42	2 weeks, moist	2.3	0.1	5.1	1.6	97	2	100
I-85A	4/29/77	Naphthalene	3	0.35	2 weeks, moist	5.3	1.2	2.3	4.0	8	6	8
I-85B	5/20/77	Naphthalene	4	0.35	1 month, moist	4.4	1.5	10.1	4.4	19	8	20
B603	3/8 and 10/77	Naphthalene	9	0.34	1 month, moist	2.7	0.9	1.8	2.5	44	19	45

[a] Retarded version.

15 percent, respectively, for the conventional concrete.

The large variability in the measured properties of the SWR concrete was caused by the rapid change in the consistency and subsequent retempering to achieve a more uniform consistency. It was common for the slump to decrease by 50 percent in 10-20 min. An effort was made to use high-slump concrete because of the rapid loss in slump, but segregation occurred on B602 when the slump exceeded 203 mm (8 in). Adequate consolidation was difficult to achieve when the SWR concrete was placed with a slump of 102 mm (4 in) or less. A satisfactory screed finish was almost impossible to achieve because of the variability in the consistency of the concretes.

Cylinder Strengths

Standard 152x305-mm (6x12-in) specimens made from random samples of the concretes were tested in accordance with ASTM C 39. As indicated in Table 3, the SWR concrete attained significantly higher early and 28-day strengths than the concrete without the admixture but also exhibited the largest variation in strength among cylinders.

Freeze-Thaw Tests

Standard 76x102x406-mm (3x4x16-in) freeze-thaw beams made from random samples of the concrete were subjected to 300 cycles of freezing and thawing in accordance with ASTM C 666, procedure A, modified by using 2 percent sodium chloride by weight in the water; the results are shown in Table 4.

Before testing, the beams were either field cured or moist cured as indicated in the table. Beams cured in a similar manner are grouped together. The freeze-thaw specimens were evaluated periodically throughout the 300-cycle test with respect to surface appearance, weight loss, and durability factor.

Prior experience at the Virginia Research Council has suggested that, for beams made in the laboratory, moist cured for two weeks, and laboratory air cured for one week, a surface rating less than 3.0 and a weight loss less than 7 percent are indications of good performance for 300 cycles. Low durability factors are an indication of internal cracking, and values above 70 are an indication of satisfactory performance for 300 cycles. The results of tests on three sets of A4-concrete beams made in the laboratory are included in Table 4 for comparison.

From Table 4 it is also apparent that, on the average, most of the field specimens performed satisfactorily with respect to surface rating and weight loss. Some of the SWR specimens scaled severely and lost a considerable amount of weight, but others performed as well as the conventional concrete specimens with respect to scaling and weight loss. The durability factors were significantly lower for the SWR concrete. Low durability factors for this type of concrete have been reported by Tynes (2). It is felt that the results in Table 4 are representative of the performances to be expected of the concretes in the study structures.

It appears that the durability factors were influenced by the curing method and the curing period; the lowest values were found for moist-cured beams tested two weeks after batching. But regardless of the curing method and period, in no case were the durability factors better for the SWR concrete than for the conventional concrete when both were cured in like manner. Assuming that the conventional A4-concrete specimens had a durability of 100, Table 4 clearly shows the low relative durability factors for the similarly cured SWR specimens.

Petrographic Examinations

Petrographic examinations were conducted to determine the quantity, size, and spacing of voids in 102-mm (4-in) diameter cores removed from the overlays and in 152x305-mm (6x12-in) cylindrical specimens made from random samples of the study concretes. The voids data are shown in Table 5.

Research has shown that concrete that is properly batched and consolidated will exhibit a void content in the hardened concrete that is approximately equal to the air content of the fresh concrete (3). When the void contents of 152x305-mm (6x12-in) cylindrical test specimens are higher than the measured air contents of the fresh concrete, the difference may be attributed to water voids. When the void contents of cores removed from a structure differ from the void contents of 152x305-mm (6x12-in) cylindrical test specimens, the difference may be attributed to a difference in the degree of consolidation.

Close agreement between the void contents of cores and the measured air contents of the fresh concrete is often an indication of adequate consolidation and a minimum of water voids. However, overconsolidation and high water content may also produce hardened concrete with a void content equal to the measured air content. Water voids and entrapped voids are less than 1 mm (0.04 in) in diameter, and entrained air voids are greater than 1 mm in diameter. The size of the voids as well as the void content must be known before an accurate analysis of the concrete can be made.

From Table 5 it can be seen that there is agreement, within the range of 1 standard deviation, between the average of the measured air contents and the average of the total void contents of the cores and the 152x305-mm (6x12-in) specimens for all the concretes except the mixture pumped into place on I-85A. Therefore, it can be concluded that, on the average, the SWR concrete was properly batched and consolidated.

However, because the magnitudes of the standard deviations are much greater for the SWR concrete than for the conventional concrete, it is apparent that approximately 50 percent of the SWR concrete was either inadequately consolidated or extremely over- or under-entrained with air. The void data for the cores suggest that, in general, the concrete in B602 has a low entrained-air content, the concrete in B603 has a high entrapped-air content, and the concrete in I-85A has a high entrained-air content. The high entrained-air contents may have been caused by the combined entraining effect of the air-entraining admixture and the SWR admixture. The low entrained-air contents were probably caused by a loss of air during the highly fluid state and during the mixing and the placing of the concrete. The relatively high fine-aggregate content specified for B603 likely hindered consolidation efforts and resulted in a high entrapped-air content.

Air-Void Spacing Factor

An air-void spacing factor, $\bar{L}$, of 0.2 mm (0.008 in) or less is needed for satisfactory freeze-thaw durability in conventional bridge deck concrete (4). Values of $\bar{L}$ were calculated for the study concretes and are reported in Table 6, from which it can be seen that there is good agreement between the $\bar{L}$ values as determined from the cores and those as determined from the 152x305-mm (6x12-in) specimens made of fresh concrete. The greatest difference is associated with the SWR concrete mixes; the higher values are found in the cores and probably reflect a consolidation problem.

Satisfactory spacing factors were obtained for the conventional A4 overlay concretes. Values of $\bar{L}$ for the SWR overlays were about twice as large on the average as those for the conventional concrete. The large values of $\bar{L}$ are associated with low air content and low specific surface. The air content of some of the SWR concrete was lower than anticipated, but high

Table 5. Void contents of cores and field specimens.

		Measured Air Content (%)				Voids in Cores (%)							Voids in Specimens (%)						
						>1 mm		<1 mm		Total			>1 mm		<1 mm		Total		
Location	SWR Admixture	Design	$\bar{X}$	SD	Z	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	Z	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	Z
B604	None	5-8	6.8	0.9	11	2.8	0.7	3.7	0.3	6.5	0.5	0	1.5	0.5	4.6	1.5	6.1	1.4	30
B602	Naphthalene	5-8	5.4	1.9	50	2.5	1.2	2.9	1.6	5.3	2.2	55	2.2	0.8	5.3	2.9	7.5	3.4	67
B603	Naphthalene	5-8	6.1	1.4	30	3.4	1.2	4.2	1.4	7.5	2.4	57	2.0	0.7	4.4	1.0	6.3	1.6	35
I-85A	Naphthalene	5-9	6.5	1.6	23	2.3	1.3	8.7	3.0	11.0	2.0	50	2.1	1.1	3.0	1.0	5.2	1.9	48

Notes: 1 mm = 0.039 in.
Z = percentage outside design range.

Table 6. Air-void spacing factors.

Location	SWR Admixture	Spacing in Cores (mm)		Spacing in Field Specimens (mm)	
		Average	SD	Average	SD
Pavement patch	Melamine	0.23	-	-	-
Full-depth pavement	Melamine	0.34	-	-	-
B616	Melamine	0.52	0.22	-	-
B602	Naphthalene	0.34	0.10	0.26	0.08
B603	Naphthalene	0.28	0.11	0.25	0.05
I-85A	Naphthalene	0.16	0.07	0.31	0.03
I-85B	Naphthalene	0.55	0.10	0.36	0.01
B604	None	0.19	0.01	0.20	0.06
B639	None	-	-	0.12	0.05

Note: 1 mm = 0.039 in.

enough to provide a satisfactory $\bar{L}$ in conventional concrete. Unfortunately, specimens of SWR concrete that had a high air content also failed the freeze-thaw test. Petrographic examinations indicated that, in general, the entrained voids were larger in the SWR concrete than in conventional concrete. The large diameter of the entrained voids in the former provided the poor air-voids distribution that was responsible for the poor freeze-thaw durability.

DISCUSSION OF RESULTS

The rapid slump loss associated with SWR concrete is an established phenomenon. Data recorded during the field installations in Virginia clearly indicate that the workability of the SWR concrete decreases by about 50 percent in 15-20 min. If conventional equipment is to be used with SWR concrete, the placement operations must be completed before the workability of the concrete falls below 51 mm (2 in). A batch of concrete of an initial slump of 102 mm (4 in) must be consolidated and screeded within 15-20 min of this initial slump measurement. Likewise, a batch of an initial slump of 204 mm (8 in) must be screeded within 30-40 min.

It is believed that SWR concrete can be satisfactorily placed by properly coordinating the batch size to the site conditions, the construction personnel and equipment, the geometry of the form, and the consistency of the mix. Batches 6.1 m^3 (8 yd^3) or larger could probably be properly placed in the forms for bridge beams or similar structural members in 15-20 min. On the other hand, data collected on numerous bridge deck installations in Virginia show that only about 1.1-2.7 m^3 (1.4-3.6 yd^3) can be placed, consolidated, and screeded in 15 min; see the table below (1 mm = 0.039 in; 1 m = 3.3 ft; 1 m^3 = 1.3 yd^3).

Placement Depth (mm)	Screed Span (m)	Time Required (per m^3, min)	Volume Placed and Screeded in 15 min (m^3)
216	15.0	13.8	1.1
152	11.4	11.3	1.3
51	11.4	12.4	1.2
132	12.6	10.0	1.5
102	9.0	5.5	2.7
102	4.5	7.4	2.0

Additional SWR admixture must be periodically added to larger-sized batches to maintain a satisfactory consistency. Because of the rapidly changing consistency of the SWR concrete and the problems associated with adding further admixture to a large batch, conventional field acceptance tests are often impractical.

It was encouraging to note during the field installations that the consistency of the SWR concrete appeared to be altered by the same factors that alter conventional concrete. For example, it was observed that, for a fixed SWR admixture content and a w/c ratio of 0.34-0.35, the slump decreased as mixing time, temperature, and fine-aggregate content increased; the entrained-air content decreased; and rounded gravel was replaced with crushed stone. The slump also decreased as the SWR admixture content decreased. Unfortunately, because of the rapid slump loss and the high initial slumps that were used, the effects were much more pronounced than for conventional concrete, which probably explains some of the high variability in the data for the SWR concrete.

Experience in Virginia indicates that, whereas it is difficult to produce durable SWR concrete in the laboratory, it is almost impossible, when using conventional equipment, to consistently install durable SWR concrete in flatwork such as a bridge deck overlay where the plastic concrete is typically subjected to long-haul distances and prolonged installation time and where a majority of the concrete is readily exposed to fluctuations in wind velocity, humidity, and temperature. Site batching with portable concrete mixers would probably improve quality control, because the batching would be similar to that done in the laboratory. However, a considerable amount of research must be devoted to the development of guidelines for batching, placing, and accepting SWR concrete if it is to be successfully used in bridge decks or pavements that must withstand numerous freeze-thaw cycles while wet.

CONCLUSIONS

On the average, the SWR concrete placed in Virginia was adequately batched and consolidated with conventional equipment. Also, compression-test specimens provided extremely high early and 28-day strengths. However, because of the variability of the concrete, many portions of the completed structures exhibited inadequate consolidation, segregation, improperly entrained air, shrinkage cracks, and poor finishes. Furthermore, freeze-thaw specimens provided low durability factors because of an unsatisfactory air-voids system.

The rapid slump loss associated with SWR concrete can be remedied by properly matching the batch size to the placement rate and by adding the SWR admixture immediately before discharging the concrete. For the mixture proportions considered in this paper, it is believed that quality control can be maintained by specifying a batch size equal to the quantity of concrete that can be batched, placed, and finished in a 20-min interval. Mixture proportions should be specified that provide a slump greater than zero before addition of SWR so that fluctuations in gradation and moisture content can be accommodated by adjusting the dosage.

The concrete should not be placed where freeze-thaw durability is important. Further research is needed to develop a satisfactory specification for batching, placing, and accepting the concrete.

ACKNOWLEDGMENT

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Performance of Superplasticized Concretes That Have High Water-to-Cement Ratios

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This study presents results of laboratory investigations into superplasticized concretes that have high water-to-cement (w/c) ratios. Two series of concrete mixes totaling 18 were made at a w/c ratio of 0.65 and a slump of 50 mm (2 in). Various dosages of different superplasticizers were added to the mixes after completion of the initial mixing and then mixed for 2 min. Initial setting times, increases in slump, and subsequent slump loss with time were recorded. A number of test specimens were cast to determine mechanical strength and freeze-thaw durability. The incorporation of superplasticizers in concrete did not significantly affect initial setting time. The large increases in the slump of superplasticized concrete and its loss with time were found to be functions of the dosage rate of the superplasticizer used. At the recommended dosage rates, the 28-day compressive strengths of the test specimens cast with and without vibration were comparable to or greater than those of the control specimens. In the superplasticized concretes, the bubble-spacing factor ranged from 0.254 to 0.432 mm (0.01 to 0.017 in), compared to 0.254 mm for the control. In spite of the increased bubble spacing, the freeze-thaw durability of test prisms cast from the air-entrained superplasticized concretes at the end of 300 freeze-thaw cycles compared favorably with those cast from the air-entrained control mix.

Superplasticizers, although relatively new, are finding increasing acceptance in the concrete industry in North America and offer considerable potential for energy saving in the precast-concrete industry and for the use of marginal aggregates in construction (1,2).

In 1976, the Canada Centre for Mineral and Energy Technology (CanMET) initiated laboratory investigations to determine the effect of superplasticizers on the mechanical properties and freeze-thaw durability of concrete. Earlier reports had discussed the use of superplasticizers in high-strength concrete with a water-to-cement (w/c) ratio of 0.42 and the effect of repeated dosages of superplasticizers on the workability, strength, and durability of concrete (3-5). This study deals with performance of superplasticizers in concretes having a w/c ratio of 0.65.

SCOPE OF INVESTIGATION

In this study, two series of concrete mixes were made with a w/c ratio of 0.65 and a cement content of 246 kg/m^3 (415 lb/yd^3). Four commonly available superplasticizers were incorporated into the mixes at dosages varying from 0.5 to 3.0 percent by weight of cement. The properties of the fresh concrete were determined. For mixes of series A, a number of 100x200-mm (4x8-in) cylinders were cast with and without vibration for compression testing at 28 days. Test prisms were also cast for determining flexural strength and resistance to freeze-thaw cycles. Air-void parameters of the hardened concrete were determined. For mixes of series B a large number of 200x300-mm (6x12-in) cylinders were cast to establish strength-versus-age relationships.

CONCRETE MIXES

The mixes were made in the CanMET laboratory during April and May 1977. Initial mixing time for each batch was 6 min. The properties of the fresh concretes were determined immediately following mixing, after which the required dosage of the superplasticizer was added and the concrete was mixed for 2 min.

Normal portland cement ASTM type I was used. It had a fineness of 373 m^2/kg, sulfate content of 3.24 percent, and C_3A content of 8.27 percent. Minus 19-mm (0.75-in) crushed limestone was used as the coarse aggregate and local sand as the fine aggregate. To keep the grading uniform for each mix, the sand was separated into different size fractions that were combined to a specified grading. A sulfonated-hydrocarbon air-entraining agent was used in all the concrete mixes except the non-air-entrained control mix.

Superplasticizers

The following three types of superplasticizers were used in the concrete mixes:

1. Sulfonated naphthalene formaldehyde condensates: Superplasticizers A and C fall in this category. Superplasticizer A is of U.S. origin. It is usually available as a soluble powder or as a 34 percent aqueous solution with a density of 1200 kg/m^3 (74.9 lb/ft^3) and is dark brown. The chloride content is negligible. Superplasticizer C is of Japanese origin. It is usually available as a 42 percent aqueous solution that also has a density of

1200 kg/m^3 and is dark brown. The chloride content is also negligible.

2. Sulfonated melamine formaldehyde condensates: Superplasticizer B belongs to this category and is of German origin. It is usually available as a 20 percent aqueous solution with a density of 1000 kg/m^3 (62.4 lb/ft^3) and is limpid (clear) to slightly turbid (milky) in appearance. The chloride content is 0.005 percent.

3. Modified lignosulfonates: Superplasticizer D falls in this category. It is of French origin but is now being manufactured in Montreal. It is usually available as a 20 percent aqueous solution, has a density of 1100 kg/m^3 (68.6 lb/ft^3), and is light brown in appearance. It contains no chlorides.

Mix Proportioning

The graded coarse and fine aggregates were weighed in the room-dry condition. The coarse aggregate was then immersed in water for 24 h. The excess water was decanted and the water retained by the aggregate was determined by weight difference. A predetermined amount of water was added to the fine aggregate, which was then allowed to stand for 24 h.

A standard mix with a w/c ratio of 0.65, aggregate-to-cement (a/c) ratio of 7.76, and cement content of 246 kg/m^3 (15 lb/ft^3) was used. The dosage of the air-entraining agent was kept constant, but the type and dosage of superplasticizers were varied.

Properties of Fresh Concrete

The properties of the fresh concrete—temperature, slump, unit weight, and air content—were determined after the initial mixing time of 6 min and again after addition of the superplasticizers and further mixing for 2 min (Table 1). Also, measurements were taken frequently to determine the rate of slump loss.

Initial Time of Set of Fresh Concrete

To determine whether the superplasticizers retarded the set of the concrete, initial times of set were determined in accordance with ASTM standard C403-70 (1976) for the time of setting of concrete mixtures by penetration resistance.

PREPARATION AND CASTING OF TEST SPECIMENS

Series A: Concrete Mixes 1-14

Nine 100x200-mm (4x8-in) cylinders and six 90x100x400-mm (3.5x4x16-in) prisms were cast from each mix. The only exception was the non-air-entrained control mix, for which only three cylinders and five prisms were cast. All test specimens except the control mixes 1 and 2 were cast after adding superplasticizers. Three cylinders were compacted by using a vibrating table; three cylinders were not subjected to any vibration; and the remaining three cylinders were cast (compacted on a vibrating table) after the slump had turned to its original value. The prisms were cast by filling brass molds and compacting them on a vibrating table. After casting, all the molded specimens were covered with water-saturated burlap and left in the casting room at 24 ± 1°C (75 ± 2°F) and 50 percent relative humidity for 24 h. They were then unmolded and transferred to the moist-curing room until they were required for testing.

Series B: Concrete Mixes 15-18

Ten 200x300-mm (6x12-in) cylinders were cast from each of the four mixes. All cylinders except that for control mix 15 were cast after superplasticizers were added. The cylinders were compacted by using an internal vibrator. After casting, all the molded specimens were covered with water-saturated burlap and left in the casting room at 24 ±1°C and 50 percent relative humidity for 24 h. They were then unmolded and transferred to the moist-curing room until required for testing.

TESTING OF SPECIMENS

Series A: Concrete Mixes 1-14

The test cylinders from control mix 1 were tested at 28 days only, whereas the cylinders from control mix 2 were tested at both 7 and 28 days. All cylinders of mixes

Table 1. Properties of fresh concrete.

	Superplasticizer		After Initial 6-Min Mixing				After Addition of Superplasticizer and 2-Min Mixing		
Mix No.	Type	Dosage (%)	Temperature (°C)	Slump^a (mm)	Unit Weight (kg/m^3)	Air Content (%)	Slump^a (mm)	Weight (kg/m^3)	Air Content (%)
1	Control without AEA		23	50	2371	2.8	-	-	-
2	Control with AEA		21	50	2333	5.0	-	-	-
3	A	1.0	20	80	2290	5.7	220	2345	3.6
4		1.5	17	80	2270	6.7	210	4360	3.0
5		2.0	19	100	2270	7.2	230	2430	1.5
6	B	1.0	21	50	2340	5.0	90	2345	4.5
7		2.0	21	50	2310	5.0	210	2380	3.5
8		3.0	21	70	2340	4.6	250	2365	3.5
9	C	0.5	25	50	2320	5.4	100	2350	3.9
10		1.0	23	50	2320	5.8	210	2380	3.4
11		1.5	24	50	2310	5.8	250	2390	2.6
12	D	1.0	23	50	2330	5.0	80	2310	5.8
13		2.0	23	50	2330	5.0	200	2330	4.8
14		3.0	23	50	2330	5.0	250	2345	4.6
15	Control with AEA		24	70	2310	6.4	-	-	-
16	B	2.0	22	50	2330	5.0	210	2360	4.2
17	C	1.0	22	50	2320	5.5	210	2370	3.4
18	D	2.0	23	50	2320	6.0	200	2325	5.2

Notes: AEA = air-entraining agent; t°C = (t°F - 32)/1.8; 1 mm = 0.039 in; 1 kg/m^3 = 0.06 lb/ft^3.

^{a}Slumps were read nearest to 10 mm for cases when slump was below 150 mm; they were read to nearest 20 mm when they were greater than 150 mm.

3-14 were tested at 28 days only. Before testing, the cylinders were removed from the moist-curing room and capped with a sulfur and flint mixture. A 272 160-kg (600 000-lb) capacity machine was used for compression testing.

Two test prisms from each of the 14 mixes were removed from the moist-curing room after 14 days and tested in flexure according to ASTM standard C78-75 by using a third-point loading.

Series B: Concrete Mixes 15-18

The test cylinders from each mix of series B were tested at 1, 7, 28, and 91 days. As in series A, the cylinders were removed from the moist-curing room immediately before testing and were capped with a sulfur and flint mixture before testing.

DURABILITY STUDIES

In this investigation, test prisms were exposed to repeated cycles of freezing in air and thawing in water according to ASTM standard C666-75. During this investigation the freeze-thaw unit did not fully meet the temperature requirements of the ASTM standard and fluctuated between -15 and -11.7°C (5 and 11°F) during freeze cycles.

The freeze-thaw test specimens were visually ex-

Figure 1. Loss of slump with time for superplasticizer A.

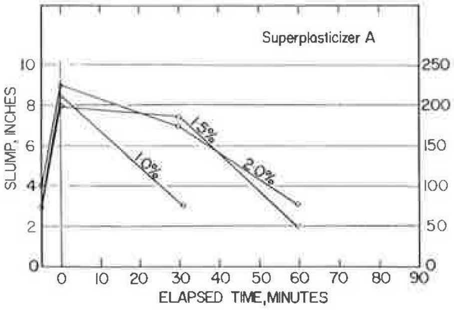


Figure 2. Loss of slump with time for superplasticizer B.

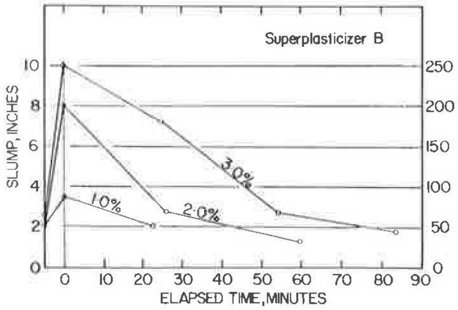


Figure 3. Loss of slump with time for superplasticizer C.

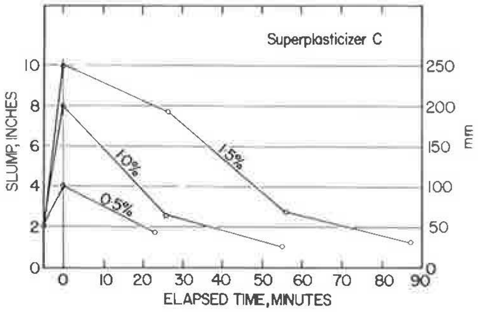


Figure 4. Loss of slump with time for superplasticizer D.

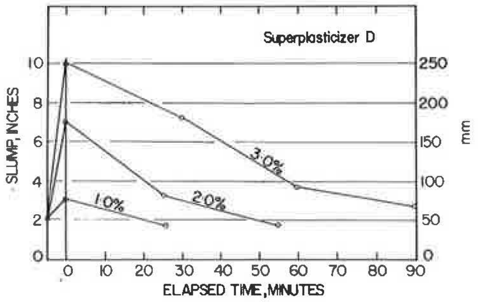


Table 2. Summary of compressive strengths after 7 and 28 days.

			Compressive Strength of 100x200-mm Cylinders[a]			
	Superplasticizer		After 7 Days,	After 28 Days		
Mix No.	Type	Dosage (%)	Vibrated (MPa)	Not Vibrated (MPa)	Vibrated (MPa)	Vibrated[b] (MPa)
1	Control without AEA		-	-	26.6	-
2	Control with AEA		19.2	-	24.4	-
3	A	1.0	-	24.8	23.6	25.8
4		1.5	-	18.8	20.3	25.9
5		2.0	-	11.7	12.1	27.4
6	B	1.0	-	25.4	26.9	26.8
7		2.0	-	25.5	27.9	27.2
8		3.0	-	25.5	23.8	27.1
9	C	0.5	-	24.1	26.5	24.9
10		1.0	-	24.2	27.1	25.3
11		1.5	-	24.0	27.0	27.2
12	D	1.0	-	23.8	25.0	26.5
13		2.0	-	24.0	23.0	24.5
14		3.0	-	24.4	23.9	24.6

Notes: 1 mm = 0.039 in; 1 MPa = 145 lbf/in².

[a] Compressive strength of control mix with AEA at 28 days is the average of six test results; the remainder are averages of three test results.

[b] These cylinders were cast after the slump had reverted to the original value.

Table 3. Summary of compressive strengths after 1, 7, 28, and 91 days.

	Superplasticizer		Compressive Strength of 100x200-mm Cylinders[a]			
Mix No.	Type	Dosage (%)	After 1 Day (MPa)	After 7 Days (MPa)	After 28 Days (MPa)	After 91 Days (MPa)
15	Control with AEA		8.8	18.8	22.5	24.6
16	B	2	8.9	18.3	23.4	25.4
17	C	1	8.3	-	21.2	24.1
18	D	2	7.8	16.6	20.3	22.0

Notes: 1 mm = 0.039 in; 1 MPa = 145 lbf/in².

[a] Compressive strength of test specimens of control mix with AEA is the average of three test results. Compressive strengths of test specimens of the other mixes at 1, 7, 28, and 91 days are the averages of three, two, three, and two results, respectively.

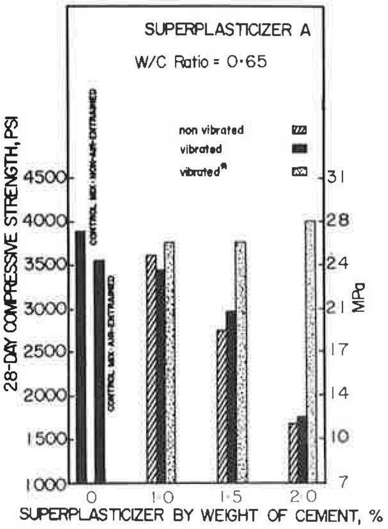
Table 4. Summary of flexural strength test results.

	Superplasticizer		
Mix No.	Type	Dosage (%)	Strength of Moist-Cured Prisms After 14 Days[a] (MPa)
1	Control without AEA		5.8
2	Control with AEA		5.2
3	A	1.0	5.4
4		1.5	4.3
5		2.0	3.3
6	B	1.0	5.1
7		2.0	4.9
8		3.0	4.9
9	C	0.5	5.4
10		1.0	5.1
11		1.5	4.8
12	D	1.0	5.1
13		2.0	5.1
14		3.0	5.2

Note: 1 MPa = 145 lbf/in².

[a] Each result is a mean of tests on two prisms; testing was done at third-point loading.

Figure 5. Compressive strength of test cylinders at 28 days for superplasticizer A.



amined at the end of every 50-cycle interval. At approximately every 100-cycle interval, their lengths were measured and they were weighed and tested by resonant frequency and by the ultrasonic pulse method. The freeze-thaw tests should be continued until the end of 1000 cycles if possible, so both freeze-thaw and reference prisms will be tested in flexure.

Another useful index for determining the durability of concrete exposed to freeze-thaw cycling is the bubble-spacing factor, an index related to the maximum distance in millimeters of any point in the cement paste from the periphery of an air void. The spacing factor for concrete under investigation was determined in accordance with ASTM standard C457-71 by using the modified point-count method.

TEST RESULTS AND ANALYSIS

Altogether 169 cylinders and 83 prisms were tested in this investigation. The loss of slump with time is shown in Figures 1-4. A summary of the compressive and flexural strength is given in Tables 2-4 and the data are illustrated in Figures 5-9. Changes in weight, length, pulse velocity, and resonant frequencies of reference prisms and prisms subjected to freeze-thaw cycles are shown in Table 5. The results of the air-void analyses of the hardened concrete test specimens are given in Table 6.

DISCUSSION OF RESULTS

Initial Time of Set of Concrete

Studies were performed only for superplasticizers B, C, and D, and in each case there was some retarding effect on the time of set. However, this was not significant from a practical point of view because maximum retardation was only 42 min (superplasticizer D). These results are similar to the data for concretes with a w/c ratio of 0.42 reported in 1977 (3).

Segregation of Superplasticized Concrete

When examined visually, the superplasticized concretes did show segregation that ranged from insignificant for concrete incorporating superplasticizer C to considerable for concrete incorporating superplasticizer A. In the latter case there was almost complete separation of the mortar fraction. This degree of segregation is unacceptable for field application.

The excessive segregation problem may be overcome by increasing the amount of fines in the mix, such as fly ash or the amount of 50- to 100-mesh fraction of the fine aggregate.

Slump Increases and Losses with Time

Superplasticized concretes exhibited large increases in slump at the recommended dosages. The slumps reached 175 mm (7 in) or more within minutes of adding the superplasticizers, and 50- to 75-mm (2- to 3-in) slump concretes became flowing concretes. And, except for concrete made with superplasticizer A, even at these high slumps there was no significant segregation. The concretes maintained the initial slump for about 5 min, after which there was rapid slump loss. Concrete incorporating superplasticizer A lost slump more rapidly than the other concretes.

Figure 6. Compressive strength of test cylinders at 28 days for superplasticizer B.

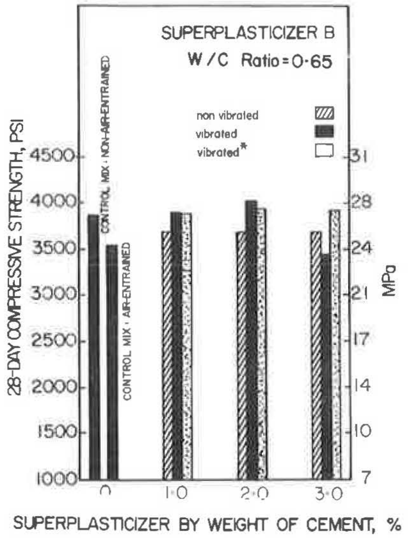
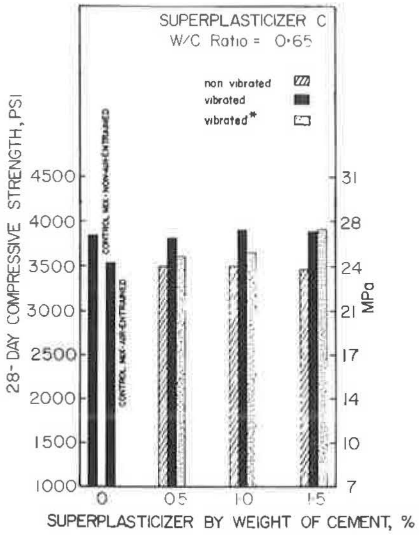


Figure 7. Compressive strength of test cylinders at 28 days for superplasticizer C.



Generally the concretes had reverted to about 50-mm (2-in) slumps in 40 ± 10 min, under laboratory temperature and humidity conditions. At maximum recommended dosages of superplasticizer A = 2.0 percent, superplasticizer B = 3.0 percent, superplasticizer C = 1.5 percent, and superplasticizer D = 3.0 percent, the superplasticized concrete lost slump at a slower rate. At the elapsed time of about 70 min, concretes incorporating superplasticizers A, B, and C had residual slumps of 50 mm (2 in). The corresponding value for

Figure 8. Compressive strength of test cylinders at 91 days for superplasticizer D.

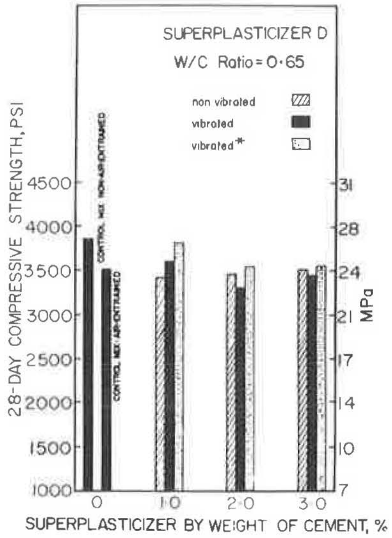


Figure 9. Compressive strength versus age relationship for control and superplasticized concretes.

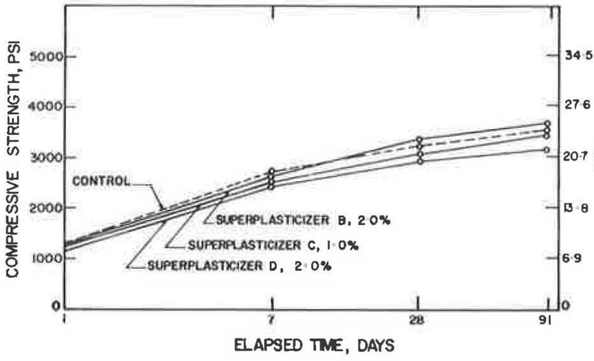


Table 5. Summary of freeze-thaw test results.

Superplasticizer		Summary of Freeze-Thaw Test Results							
		At 0 Cycles				At Completion of 300 Cycles			
Type	Dosage (%)	Weight (kg)	Length* (mm)	Longitudinal Resonant Frequency (Hz)	Pulse Velocity (m/s)	Weight (kg)	Length (mm)	Longitudinal Resonant Frequency (Hz)	Pulse Velocity (m/s)
Control without AEA		8.75	3.48	4950	4661	Prisms completely disintegrated at 45 cycles			
Control with AEA		8.46	3.06	4960	4520	8.48	3.49	4880	4467
A	1	8.16	3.65	4990	4611	8.63	3.28	4770	4402
B	2	8.63	3.67	5030	4530	8.66	2.53	4990	4488
C	1	8.71	3.93	5040	4617	8.74	3.27	4960	4541
D	2	8.58	2.71	5000	4557	8.54	3.26	4930	4472

Notes: 1 kg = 2.2 lb; 1 mm = 0.039 in; 1 m/s = 3.28 ft/s.

*Gauge length = 345 mm.

Table 6. Summary of air-void determination in hardened concrete.

Superplasticizer		Paste Content[a]	Voids in Concrete	Void-Spacing Factor
Type	Dosage (%)	(%)	(%)	(mm)
Control without AEA		27.9	2.2	1.27
Control with AEA		24.0	6.5	0.25
B	1.0	24.0	5.2	0.25
	2.0	24.0	4.9	0.36
	3.0	24.0	3.6	0.43
C	0.5	24.0	4.8	0.33
	1.0	24.0	3.0	0.41
	1.5	24.0	3.3	0.33
D	1.0	24.0	5.6	0.31
	2.0	24.0	4.8	0.28
	3.0	24.0	5.0	0.31

Note: 1 mm = 0.039 in.

[a] Calculated from mix proportions.

concrete incorporating superplasticizer D was 85 mm (3.5 in).

It appears that concretes having high w/c ratios can be superplasticized, which offers opportunities for placing flowing concretes in basement walls and other similar structures. The principal advantage of the superplasticizers under these conditions would be the savings from reduced labor needs for handling, placing, and compacting of concrete.

Compressive Strength Development

Compressive Strength at 28 Days

The compressive strength results are shown in Table 2 and in Figures 5-8. The following general observations can be made.

1. At the recommended dosage rates
   a. The compressive strength of cylinders cast by vibration was between 2 and 10 percent higher than the strength of cylinders cast from the air-entrained control mix (the only exception was concrete incorporating superplasticizer A, where there was a very slight decrease in the strength that is of little practical significance);
   b. The compressive strength of cylinders cast without vibration was comparable to that of the cylinders cast from the air-entrained control mix; and
   c. The compressive strength of cylinders cast with vibration from concrete after it had reverted to the original slump was between 2 and 10 percent higher than the strength of cylinders cast from the air-entrained control mix. This is even true for concrete incorporating superplasticizer A.
2. At the maximum recommended dosage rates
   a. The compressive strengths of superplasticized cylinders, cast with and without vibration, were comparable to strengths of cylinders cast from the air-entrained control mix, although there were exceptions: The cylinders cast from concrete incorporating superplasticizer A showed about 50 percent loss in strength compared to the control cylinders, which was probably due to the excessive segregation of the mix, while the strength of cylinders cast from concrete incorporating superplasticizer C was about 11 percent higher than the strength of the control cylinders;
   b. The strengths of the superplasticized cylinders cast from concretes after the slump had returned to the original value of about 50 mm (2 in) were comparable to or about 11 percent higher than the strength of the control cylinders. This is probably due to the loss of moisture from the fresh concrete.

Compressive Strength Versus Age

The compressive-strength-versus-age test results are shown in Table 3 and Figure 9.

It will be seen from the data that, at the recommended dosage rates, the compressive strengths of cylinders cast from concrete incorporating superplasticizers B and C were comparable to the strength of the control cylinders at all ages. However, the compressive strength of cylinders cast from concrete incorporating superplasticizer D was consistently lower than the strength of the control cylinders at all ages. At 91 days the difference was about 9 percent. The lower strengths were probably due to the high amounts of entrained air retained by the concrete after the superplasticizer had been added. These results agree with data reported earlier for low w/c ratio concrete (3).

Flexural Strength

In general, the 14-day flexural strengths of test prisms (Table 4) cast from the concretes superplasticized at the recommended dosage rates showed no significant change from the strengths of the control prisms. The strength values were of the order of 5 MPa (725 lbf/in^2). However, the prisms cast from concrete incorporating superplasticizers A, B, and C showed a steady drop in strength with increased dosage rate. For example, at the maximum recommended dosage rates the 14-day strength values were 3.27, 4.92, and 4.76 MPa (475, 715, and 690 lbf/in^2), respectively. The prisms cast from concrete incorporating superplasticizer D, to the contrary, showed a very slight increase in strength with increased dosage rates; at the maximum recommended dosage rate, the 14-day strengths reached a value of 5.24 MPa (760 lbf/in^2).

DURABILITY OF CONCRETE PRISMS EXPOSED TO REPEATED FREEZE-THAW CYCLES

Durability of concrete prisms exposed to repeated cycles of freezing and thawing was determined by measuring weight, length, resonant frequency, and pulse velocity of test prisms before and after exposure to freeze-thaw cycles and then comparing these with corresponding values of the reference prisms. The test prisms had been cured for 13 days in a moist-curing room before being subjected to freezing and thawing.

The non-air-entrained control prisms had shown considerable distress after about 30 freeze-thaw cycles. The tests were discontinued after 45 freeze-thaw cycles, at the end of which the residual flexural strength of the prisms was only 3.8 percent.

In general, there were no significant changes in the test prisms cast from air-entrained superplasticized concrete at the end of 300 cycles (Table 5). Tests are being continued and the performance of the prisms up to the end of 1000 cycles will be reported at a later date.

Test results have indicated that all prisms performed just about equally well, at least up to 300 cycles. This was also confirmed by the results of flexural strength tests of the prisms. However, there are indications that test prisms incorporating superplasticizer A may not last much beyond 400 freeze-thaw cycles.

The freeze-thaw tests were performed using ASTM standard C666-76 and employing procedure B, rapid freezing in air and thawing in water. ASTM standard C494-71, chemical admixtures, specifies the use of procedure A, rapid freezing and thawing in water, for evaluating concrete that incorporates chemical admixtures. Nevertheless, the reported freeze-thaw data are still considered valid because the freeze-thaw is a comparative test carried out with the specimens cast from the control mixes. For this investigation, the test prisms cast from the non-air-entrained control mix had disintegrated at less than 45 freeze-thaw cycles. Data published by others (7) indicate that superplasticized concrete prisms perform satisfactorily when exposed to rapid freezing and thawing in water in accordance with procedure A.

AIR-VOID DETERMINATION OF HARDENED CONCRETE

The microscopic determination of air-void content and parameters of the air-void system in hardened concrete was made according to ASTM standard C457-71. It has been found that for satisfactory durability the cement paste should be protected with air bubbles (4). Adequate protection required that the spacing factor, an index related to the maximum distance of any point in the cement paste from the periphery of an air void, not exceed 0.20 mm (0.008 in).

In this investigation the air-entrained concrete had a void-spacing factor of 0.254 mm (0.01 in) but performed satisfactorily in freeze-thaw cycling (Table 6). The superplasticized concretes investigated for air-void determination had bubble-spacing factors that ranged from 0.254 to 0.432 mm (0.01 to 0.017 in). In spite of the increased bubble spacing, the durability of concretes incorporating superplasticizers B and D was not impaired. It appears that bubble-spacing factor limitations stipulated for air-entrained concrete may not be valid for concretes incorporating superplasticizers. Further research is needed on how these parameters can be correlated with the performance of concrete under freeze-thaw cycles.

CONCLUSIONS

At the recommended dosage rates there was no significant segregation of concrete except for the mix incorporating one of the naphthalene-based superplasticizers. High dosages of superplasticizers are not recommended because of the tendency of the concrete to segregate. This is particularly true of superplasticizer A.

All superplasticizers investigated had only insignificant retarding effects on the time of initial set of concrete.

When superplasticizers are added to concrete at the manufacturers' recommended dosage rates, the 28-day compressive strengths of test cylinders cast from superplasticized concrete are comparable to or greater than the corresponding strengths of cylinders cast from the reference mix. The strengths are comparable when the cylinders from the superplasticized concrete are cast without compaction by vibration and greater when cast with compaction by vibration.

For recommended dosage rates, the freeze-thaw durability of the test prisms cast from the air-entrained superplasticized concretes compared favorably with those cast from the air-entrained control mix at the end of 300 freeze-thaw cycles. The nature of the relationship between the durability of superplasticized concrete and the value of its bubble-spacing factor needs further research.

Superplasticizers are more expensive than ordinary water-reducing admixtures and therefore may or may not be economical for use in concrete of a high w/c ratio. This aspect will have to be considered for each job situation.

The results reported here were obtained with concrete of a w/c ratio of 0.65 and made with ASTM type I cement. The superplasticizers may or may not perform as reported in concrete made with other w/c ratios and with different types of cements and aggregates.

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Optimum Mix Proportions for Flowing Concrete

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The optimum mix proportions for flowing concrete were investigated statistically by examining the effects of cement, water, fine aggregate, and superplasticizer on the properties of concrete. The properties considered were slump, slump flow, DIN flow, three kinds of workability, air content, segregation, bleeding, compressive strength, tensile strength, Young's modulus, drying shrinkage, moisture loss, crack, and cost. It was shown that these can be controlled by varying the level of each factor. The above characteristic properties were combined into three parameters indicating flowability, physical properties of hardened concrete, and workability. By using these parameters, the flowing concrete was classified into three categories: mixes exhibiting excellent properties in all respects and suitable for commodity-type high-grade concrete, mixes giving hardened concrete with excellent properties and suitable for reduced-crack or water-tight concrete, and mixes having improved flowability and workability and suitable for extensively steel-reinforced buildings. The optimum mix proportions for these uses have been demonstrated to be achievable.

The "Fliessbeton" or flowing concrete technology developed in West Germany a few years ago has been in practical use in Japan since 1975; 900 000 m^3 of flowing concrete have been placed since then. However, little has been reported on the mix proportioning of flowing concrete, and most of the mix proportions now being used are determined from preliminary tests on dosages for conventional high-slump concrete, which do not always meet the requirements for optimum properties.

In this investigation, the optimum mix proportioning for flowing concrete for general building construction was investigated by statistical analysis of the interrelations between the mix proportions of flowing concrete prepared with naphthalene superplasticizer and its characteristic properties, including those of hardened concrete.

METHOD

Materials

Onoda ordinary portland cement was used, and the fine aggregate was Kinokawa river sand [ρ (specific gravity) = 2.58, fineness modulus (FM) = 2.91]; the coarse aggregate was crushed stone from Takarazuka combined with gravel from Hidaka-gawa River (ρ = 2.62, FM = 6.76). The admixture for the base concrete was a commercial air-entraining agent, while the superplasticizer was Mighty FD naphthalene, manufactured by the Kao Company.

Procedure

The scheme for the optimum mix proportioning is given in Figure 1. The variable factors, mix conditions, and the characteristic properties of concrete are summarized in Table 1. Four factors varied at five levels were allocated in an orthogonal matrix. Fifty batches of fresh concrete were mixed with the 25 kinds of mix proportions, and 15 properties were determined for each mix. The variation range of the level for each factor was determined by referring to the practical construction data. Those properties with no standard for testing were determined by the following methods.

Workability

According to Fukuchi (1), a specially designed test apparatus was employed. The box test apparatus is equipped with a vertical half plate that separates the upper room of the box so that the fresh concrete entering from one opening can flow to another through the bottom opening. The box is mounted on a flow table. By using the apparatus it was possible to determine the workability, the mobility of concrete at placing, the flow rate on vibration, and the number of vibrations required to complete compaction.

The degree of separation of aggregate was determined from the weight ratio of segregated coarse aggregate to the placed concrete, and the rate of crack formation expressed in days was determined by observation of the outset of crack formation onto the stressed specimen.

Figure 1. Scheme for selecting optimum mix proportioning.

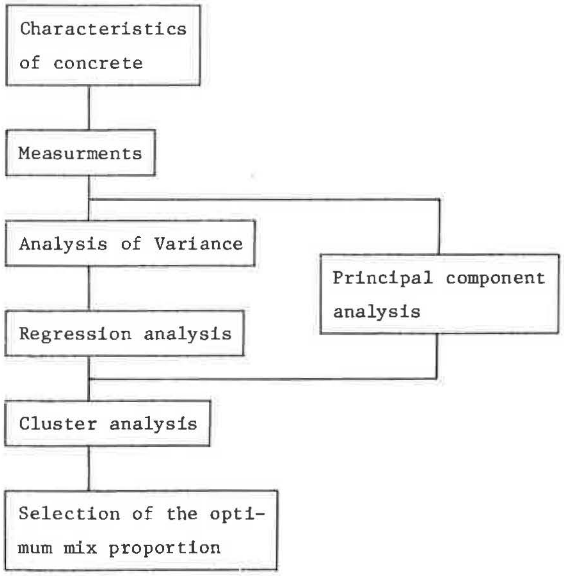


Table 1. Summary of experiment.

	Level				
Factor	-2	-1	0	1	2
Cement content (kg/m^3)	280	290	300	310	320
Water content (kg/m^3)	170	175	180	185	190
Sand (%)	42	44	46	48	50
Dosage of superplasticizer (%)	0.4	0.5	0.6	0.7	0.8

Table 2. Analysis of variance and analysis of principal components.

	Analysis of Variance						Analysis of Principal Components			
	Rate of Contribution[a]						Factor Loading			
Property	C	W	S	SP	Interaction	Total	Z1	Z2	Z3	Contribution
Slump	-	23	-	23	-	46	0.90	-0.14	0.23	88.2
Slump flow	-	15	19	49	-	83	0.95	0.20	-0.05	95.1
DIN flow	-	11	11	56	-	78	0.94	0.09	-0.09	90.3
Workability 1	49	13	-	11	-	73	0.78	0.20	0.55	94.6
Workability 2	-	46	-	-	WxSP:14	60	0.62	-0.09	0.66	82.5
Workability 3	38	14	-	-	-	52	0.64	0.04	0.71	91.4
Air content	-	24	40	12	WxSP:8	84	-0.74	-0.17	0.51	84.3
Segregation	17	-	42	-	-	59	0.74	-0.22	-0.36	72.7
Bleeding	-	56	13	-	-	69	0.70	0.12	-0.60	86.4
Compressive	37	34	-	10	WxSP:5	86	-0.54	0.62	0.50	91.5
Tensile strength	29	8	32	-	CxW:8 CxSP:6	83	-0.02	0.89	0.05	79.9
Young's modulus	13	18	23	9	WxSP:12	75	-0.23	0.72	-0.15	60.0
Drying shrinkage	-	47	27	-	CxW:5 WxSP:3	82	-0.09	-0.76	0.13	60.0
Moisture loss	23	34	30	-	-	87	0.01	-0.94	-0.16	90.5
Crack	-	-	-	-	CxW:35	35	0.17	0.79	-0.31	74.6
Eigen value							5.96	3.98	2.47	
Cumulation							40	66	83	

[a] C = cement content; W = water content; S = percentage sand; SP = dosage of superplasticizer.

Table 3. Qualitative relations between mix proportions and characteristic properties of concrete.

	Ingredient			
Property	Cement	Water	Sand	Mighty FD
Slump	-	I	-	I
Slump flow	-	I	D	I
DIN flow	-	I	D	I
Workability 1	I	I	-	I
Workability 2	-	I	-	I
Workability 3	I	I	-	-
Air content	-	D	I	D
Segregation	D	-	D	-
Bleeding	-	-	D	-
Compressive strength	I	-	-	-
Tensile strength	I	D	D	-
Young's modulus	I	D	D	-
Drying shrinkage	-	I	I	-
Moisture loss	D	I	I	-
Crack	D	I	-	-
Parameter Z1	-	I	-	I
Parameter Z2	I	D	D	-
Parameter Z3	I	-	I	-

Note: I = increasing; D = decreasing.

DISCUSSION OF RESULTS

Statistical Test on the Effects of Variable Factors

The analysis of variance was made on the results of 15 properties. The effect of each factor was tested statistically. In Table 2 are shown the contributions of significant factors by F-test. From this table one can see that these factors greatly affected each property. The results also indicate that the properties of flowing concrete can be controlled by varying mix levels of cement, water, fine aggregate, and superplasticizer.

Determination of Response Function

The value of each characteristic property was approximated by using the following response function, where Xi (i = 1-4) denotes the level of each factor and where the first five terms are linear, the next four terms are quadratic, and the final six terms are interaction terms.

$$\begin{aligned} Y = {} & a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 \\ & + a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + a_{44}x_4^2 \\ & + a_{12}x_1x_2 + a_{13}x_1x_3 + a_{14}x_1x_4 \\ & + a_{23}x_2x_3 + a_{24}x_2x_4 + a_{34}x_3x_4 \end{aligned} \tag{1}$$

The qualitative relations among mix formulations and properties of concrete indicated by the response function are summarized in Table 3. For instance, increasing water or superplasticizer seems to increase the slump value. Also indicated is that drying shrinkage can be reduced by reserving water or fine aggregate. Generally, increasing cement or superplasticizer gives better results, whereas increasing water or fine aggregate does not always do so. Results differ depending on the property being considered.

Combined Parameters Summarizing Fifteen Properties

Because of the difficulty in grasping 15 characteristic values at once intuitively, these values have been combined into three values by using principal-component analysis. The results are shown in Table 2. The principal component Z1 interrelates significantly with slump, slump flow, and DIN flow values and is regarded as a combined characteristic parameter controlling the flow property of fresh concrete. The principal component Z2, on the contrary, relates to the moisture loss by drying and tensile strength and can be regarded as a combined characteristic parameter controlling the property of hardened concrete. Finally, the principal component Z3 relates to flowability -1, -2, and -3 and to the degree of segregation of aggregate and can be related as a combined parameter to the workability or ease of placement of fresh concrete. The sum of the contribution rates of the three principal components reaches 83 percent, which indicates that the 15 properties of flowing concrete can be summarized into three combined parameters that provide all but 17 percent of the needed information. Based on these results, the three parameters were employed as criteria for selecting the optimum proportion of flowing concrete.

Selection of the Optimum Mix Proportion

Mix proportions of 625 kinds allocated in four factors by five levels were made. The 15 characteristic properties were simulated by using the response function, from which the mix proportions with desirable properties were selected.

For the first step, the mix proportions that displayed a particular dominant character were selected. Figure 2 is an illustration of this type expressed in chart form and showing the mix formulation and the corresponding characteristic values for the mix with high slump value. In this particular case, the advantage of higher flowability is cancelled out by the disadvantages of higher bleeding and aggregate segregation.

In the chart, the three combined parameters—Z1, Z2, and Z3—are shown in the inner circle, whereas the 15 characteristic properties and material costs of concrete are shown clockwise. The mix proportions are shown in the upper left of the chart.

Each characteristic property except mix formulation tends toward optimum as it extends to the outer circle. The average value is shown by an intermediate circle. The spacing between circles represents a threefold standard deviation (3σ). The proportions of the triangle form a criterion for the total characterization of the flowing concrete.

Another example of mix proportion for high tensile strength is shown in Figure 3; an example of lower bleeding is shown in Figure 4. From Figures 2 to 4, it is obvious that, as a rule, the improvement of certain properties is counterbalanced by the worsening of others. Therefore, it is difficult to establish an ideal mix proportion that has excellent characteristics in all respects.

Figure 2. Mix proportion for high-slump flowing concrete.

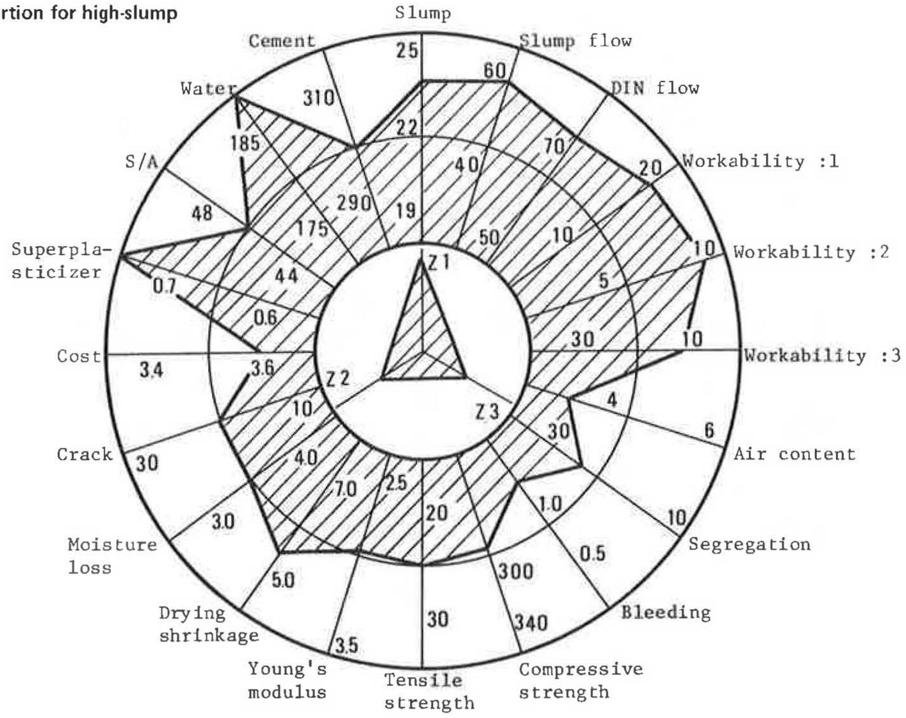
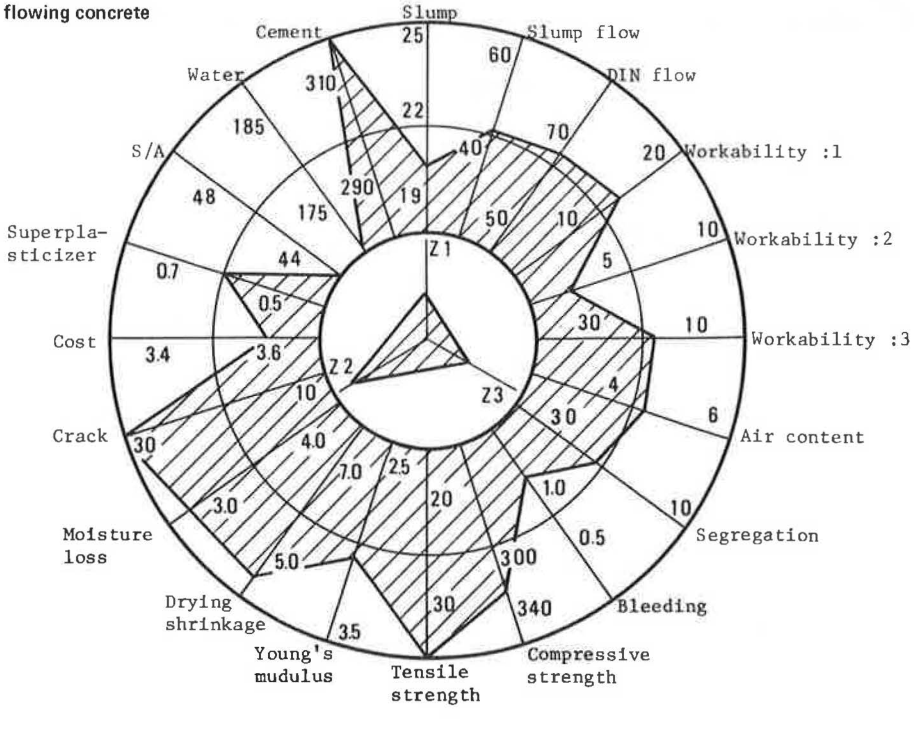


Figure 3. Mix proportion for flowing concrete of high tensile strength.



For the second step, the three combined parameters were taken into account to select the optimum mix proportion. In doing this, those mix proportions that had above-average parameter values (top 10 percent) were selected; thus, 65 mixes were selected out of 625. By further cluster analysis, these 65 mixes were classified into three categories: Those belonging to the first category exhibit excellent properties in all respects, a mix of the second category gives a hardened concrete with excellent properties, and a mix of the third category has an improved flowability and workability.

In Figures 5-7 are illustrated the typical patterns for each category. Of these, Figure 5 is an illustration for a mix that has outstanding performance and is above average in all respects and can be regarded as an example of the optimum mix proportion for high-grade ready-mixed concrete of commodity type. On the other hand, Figure 6 illustrates the mix proportion for hardened concrete with improved properties that is regarded as the most reasonable mix proportion for re-

Figure 4. Mix proportion for flowing concrete with lower bleeding.

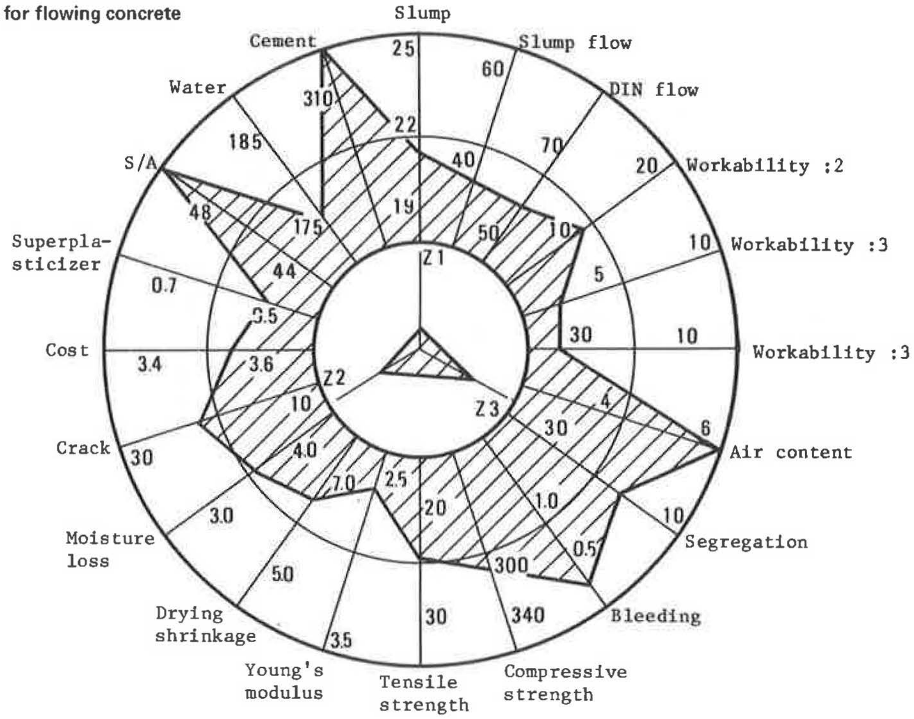


Figure 5. Mix proportion for flowing concrete exhibiting excellent properties in all respects.

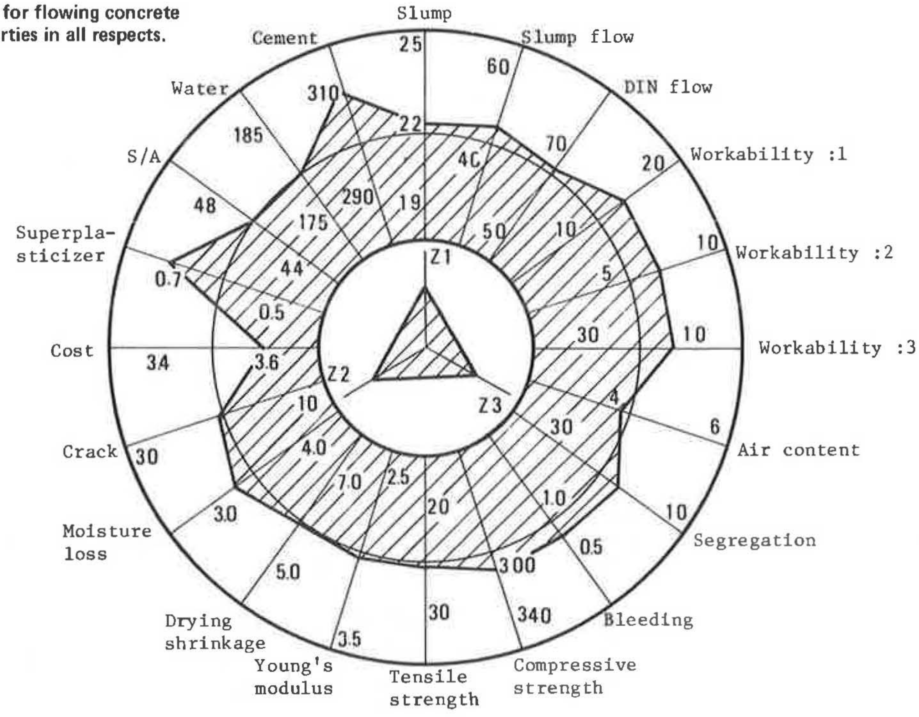


Figure 6. Mix proportion for flowing concrete giving hardened concrete with excellent properties.

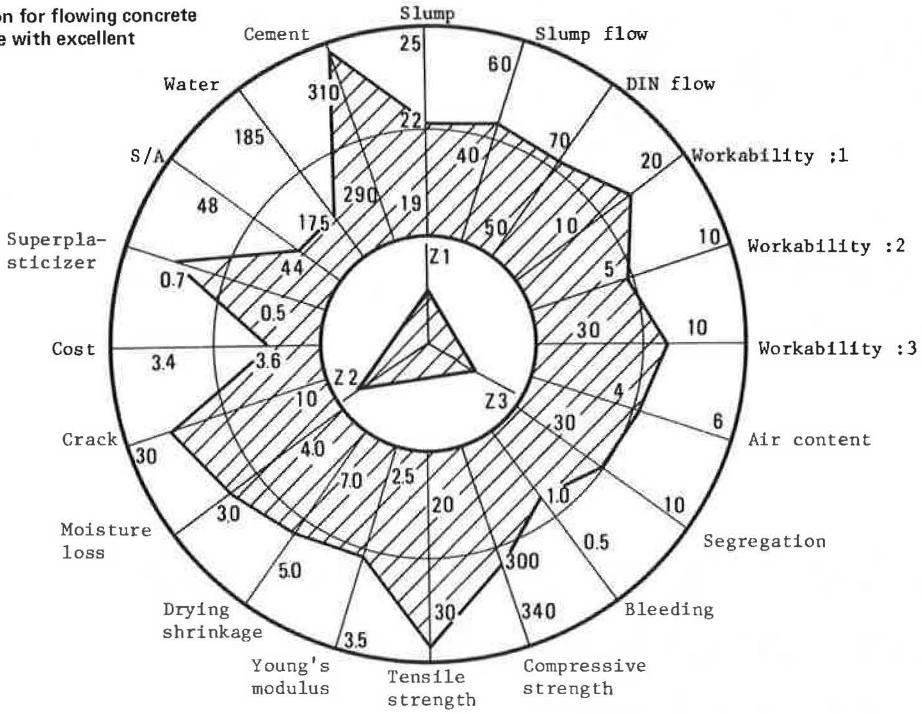


Figure 7. Mix proportion for flowing concrete that has improved flowability and workability.

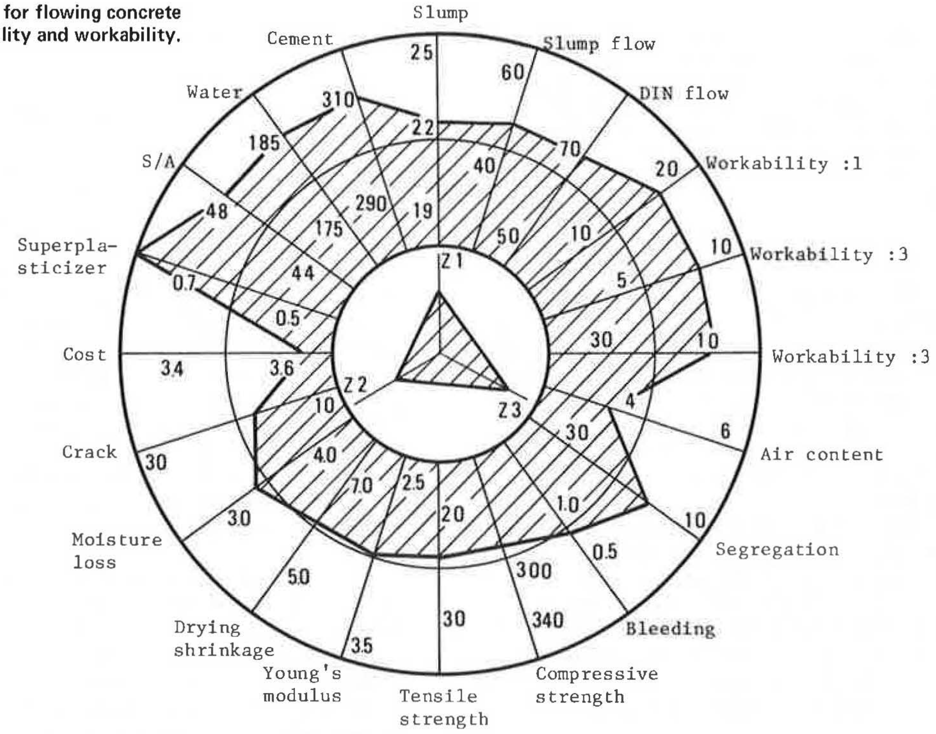


Table 4. Fundamental mix proportions of flowing concrete for various purposes.

	Base Concrete				Flowing Concrete		
Purpose	Slump (cm)	S/A (%)	Cement Content kg/m^3	Base Admixture	Slump (cm)	Air Content (%)	Super-plasticizer (%)
High-grade ready-mixed concrete (above average in all properties)	12	46	300	AEA	22	4.0	0.6
Water-tight concrete with reduced cracking (good properties in hardened stage)	8	44	320	AEA or DA	21	3.5	0.7
Built-in tiling process, highly reinforced (good flowability and workability)	15	48	310	AEA	23	4.5	0.5

duced cracking and water-tight concrete. In contrast, Figure 7 is an example of the optimum mix proportion for improved flowability as well as workability; it is suitable for built-in tiling or highly steel-reinforced building structure. In Table 4 the fundamental mix proportions of flowing concrete for various purposes are summarized.

ACKNOWLEDGMENT

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Cement-Content Measurements with the Rapid-Analysis Machine

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The rapid-analysis machine (RAM) is a relatively new apparatus developed by the Cement and Concrete Association of England. RAM determines the cement content of fresh concrete by a wet-analysis process through a series of automatically controlled devices. This paper gives details of experience with this machine under controlled laboratory and normal field conditions. It was noted that the machine is capable of carrying out routine testing of fresh concrete efficiently under field conditions.

The traditional way of determining the satisfactory characteristics of concrete delivered to a site is to cast standard cylinders and to test these after curing at an age of 28 days. As techniques have advanced, certain accelerated test methods have come into vogue, and these enable the quality of the concrete to be predicted by tests at ages of only one or two days. However, even a day after a faulty concrete has been placed in a structure, the concrete has set, is hard, and will be expensive to replace.

Recognition of the advantages of being able to determine properties of the plastic concrete before it is placed into the structure is therefore growing. The rapid-analysis machine (RAM), although it does not produce all the required answers, does determine one of the critical characteristics of the concrete mix: its cement content. By using the equipment now available it is possible to make the test within 5 min of taking a sample.

OBJECTIVE

In addition to a brief description of RAM, the objective of this paper is to describe our experience with using this machine on concretes mixed under the various conditions below:

1. In the laboratory,
2. Ready mixed in a few selected highway contracts, and
3. As a part of the normal quality control tool on a nuclear power station site and a major airfield paving contract.

DESCRIPTION OF THE MACHINE

RAM, shown in Figure 1, is a floor-mounted automatic unit approximately 1 m^2 (3 ft^2) in plan and 1.5 m (5 ft) high and about 160 kg (360 lb) in weight. About an 8-kg (17-lb) sample of fresh concrete is fed into a hollow cylindrical elutriation column. Water pumped from a reservoir in the machine up through the elutriation column liquefies the sample, and the cement along with some sand particles are lifted off as a slurry. At the top of the column is a sampling head where a tenth of the slurry is collected by weirs and directed into a 150-μm (no. 100) sieve, while the rest of the slurry is being carried to a waste container.

On the sieve the slurry sample is vibrated and washed by a water spray into a conical conditioning vessel where it is stirred and dosed with flocculating agents.

The base of the conditioning vessel is a detachable collecting pot or constant volume vessel (CVV) in which the solids are precipitated. The water in the conditioning vessel is syphoned off to a constant level within the CVV. The weight of the CVV containing solids and water is proportional to the weight of materials of cement fineness (apparent cement content) in the original mix. From a calibration curve (Figure 2) prepared for the machine, this apparent cement content can be obtained, and now a correction factor (Figure 3) for silt (finer than 150-μm sieve) present in the aggregate can be applied to get the true cement content of the mix.

It has been reported (1) that in a sand stockpile the ratio of weights of material passing the 150-μm sieve to materials held on this sieve but passing the 300-μm (no. 50) sieve is fairly constant. This relationship can be established from the proportional weight of the CVV with sand retained on the 150-μm sieve screened through a 600-μm (no. 30) sieve for a nominal mix.

This estimated silt-correction curve (Figure 3) would remain valid unless a significant variation in the sand grading or mix proportion were to occur. The exact procedure for calibration and establishing the silt-correction curve is given in the machine manual.

Figure 1. Rapid-analysis machine.

PERFORMANCE UNDER LABORATORY CONDITIONS WITH KNOWN CEMENT CONTENT

Several batches of 0.0283-m^3 (1.0-ft^3) air-entrained concrete containing various amounts of cement were made in the laboratory (2). After initial mixing and tests for slump, unit weight, and air content were completed, five samples of approximately 6-8 kg (13-17 lb) each were taken from the pan mixer. A sixth sample was also collected from the remaining portion of the concrete after remixing for about 1 min. All these samples were weighed and de-entrained with a dosage of tributylphosphate before they were run through the machine.

Appropriate silt-correction factors were applied to each test result, and the actual cement content was determined. The cement content as determined by the machine was then compared with the actual cement factor used in the original mix, and the percentage error was calculated.

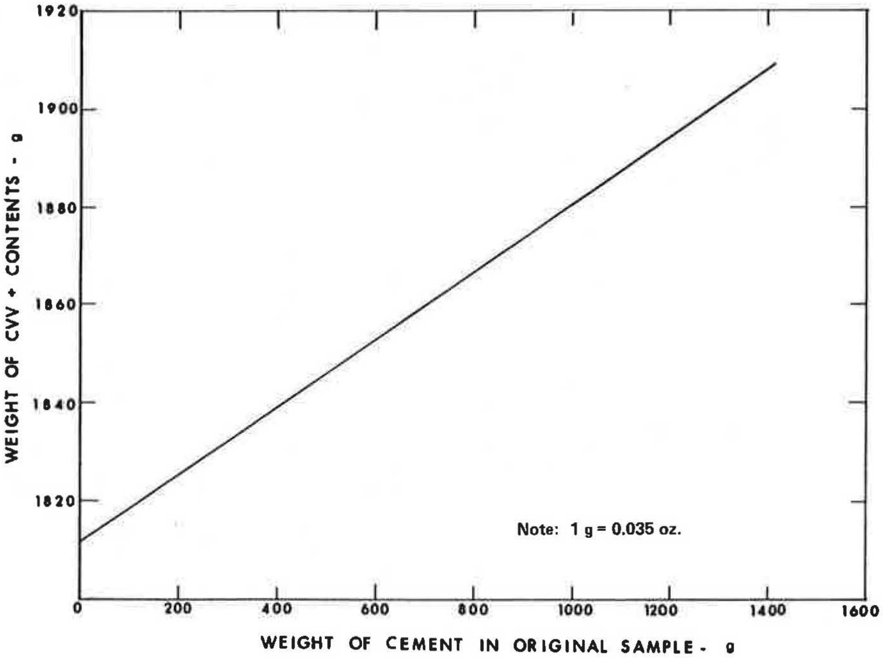
Table 1 summarizes these results. The laboratory standard sand used in these tests conformed to ASTM C33 requirements and contained about 6 percent pass 150-μm particles. The average corrections required for silt in the first and second, third and fourth, and fifth and sixth test mixes (Table 1) were about 8.5, 4.0, and 2.5 percent of the actual cement content, respectively. The overall variations between the actual cement content and the results obtained by the machine after applying the silt corrections were between +5.4 and -7.5 percent, the average being +1.3 to -3.8 percent.

SELECTED HIGHWAY CONTRACTS

RAM was mounted in a 2.7-t (3-ton) closed motorized vehicle with a 455-L (100-gal) water tank, and a 50-A, 120-V generator was installed in it. Four contracts were visited during this trial period, and the concrete for them was sampled from the ready-mix trucks.

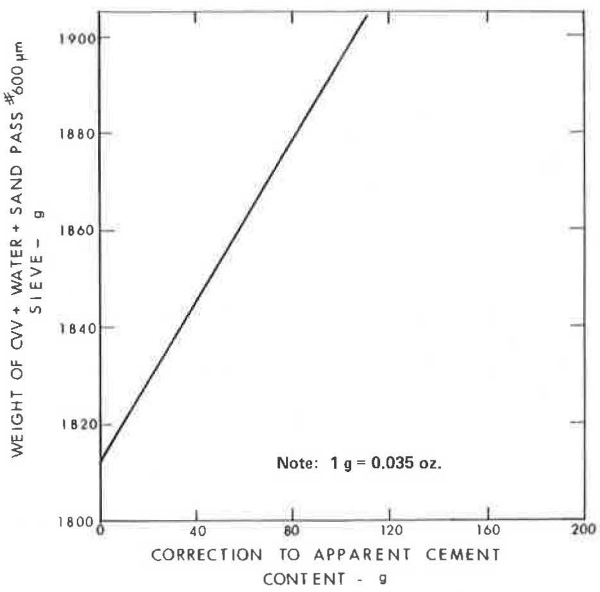
After an initial discharge of about 0.4-0.8 m^3 (0.5-1.0 yd^3) of concrete, three samples each weighing about

Figure 2. Calibration curve.



Note: 1 g = 0.035 oz.

Figure 3. Silt-correction curve.



Note: 1 g = 0.035 oz.

7 kg (15 lb) were scooped from the chute of the ready-mix truck and collected in small plastic buckets. The first sample was collected at the beginning, the second was somewhere near the middle, and the third was toward the end of the discharge. A fourth sample was also collected from the middle of the discharge for air content and unit-weight tests. This sample was discarded after the two tests were completed.

The current trials were designed to evaluate the performance of the RAM mobile unit, so it was felt necessary to carry out as many test runs as possible within a short period of time. No attempt was therefore made at this stage to test one representative sample by combining the three samples collected from one truckload. The procedure followed also gave an opportunity to see the mixing efficiency of a ready-mix truck. The average of three test results was taken as the cement content of the load.

The time taken to complete a set of three tests from one truckload was between 1 and 2 h. This included time taken to complete tests for unit weight and air content and to carry out normal calculations as shown in Table 2. A well-trained technician and a helper were required to carry out all necessary field operations.

Table 1. Summary of laboratory test results.

	Actual Cement Content (kg/m³)											
	313		314		366		368		416		419	
Sample	CC	%	CC	%	CC	%	CC	%	CC	%	CC	%
A	310	-0.9	314	+0.0	355	-3.0	361	-1.9	390	-6.3	426	+1.7
B	330	+5.4	315	+0.3	363	-0.8	374	+1.6	392	-5.8	-[a]	-[a]
C	317	+1.3	316	+0.6	370	+1.1	364	-1.1	385	-7.5	412	-1.7
D	316	+1.0	315	+0.3	350	-4.4	376	+2.2	-[a]	-[a]	416	-0.7
E	318	+1.6	315	+0.3	349	-4.6	349	-5.1	416	0.0	418	-0.2
F	313	+0.0	322	+2.5	375	+2.5	366	-0.5	415	-0.2	422	+0.7
Average	317	+1.3	316	+0.7	360	-1.6	365	-0.8	400	-3.8	419	+0.0

Notes: 1 kg/m³ = 0.06 lb/ft³.
CC = cement content determined by RAM in kg/m³; % = percentage difference from the actual amount of cement used.

[a] Minor mechanical problem with the machine.

Table 2. Field test results.

			Tests on Concrete			Tests in RAM			Calculations from Graphs					
Truck No. and Mix No.	Sample Time of Sampling	Sample Location in Truck	Slump (mm)	Air (%)	Unit Weight (kg/m³)	Weight of Sample (g)	Weight of CVV + Cement + Silt (g)	Weight of CVV + Sand Passing 600 µm Sieve (g)	Apparent Cement Content (g)	Silt Correction (g)	Actual Cement in Sample (12 - 13) (g)	Cement Factor [(14/9) × 8 kg/m³]	Average Cement Content (kg/m³)	% Difference from Specified Content
317			64	3.6	2417								374	-3.0
1	7:35	B				7672.5	1900	1864.3	1270	63	1207	380		
2	7:40	M				7672.9	1900.7	1866.2	1275	65	1210	380		
3	8:00	E				7671.9	1895.7	1865.0	1210	64	1146	361		
317			NT	6.0	2347								357	-1.7
1	9:15	B				7672.2	1893.9	1864.3	1190	63	1127	345		
2	9:25	M				7672.1	1896.8	1864.5	1235	63	1172	359		
3	9:35	E				7672.8	1899.2	1864.9	1265	64	1201	367		
318			NT	5.0	2372								377	+3.9
1	11:40	B				7672.8	1902.1	1867.5	1310	67	1243	384		
2	11:47	M				7671.9	1898.2	1865.5	1250	65	1185	366		
3	11:55	E				7672.1	1900.9	1861.5	1295	59	1236	382		
408			NT	6.8	2321								339	-6.6
1	1:25	B				7671.2	1899.8	1871.4	1265	71	1194	361		
2	1:35	M				7670.5	1894.7	1869.3	1190	69	1121	339		
3	1:40	E				7673.1	1899.2	1868.6	1120	68	1052	318		
318			NT	4.8	2385								375	+3.3
1	2:26	B				7671.6	1900.9	1872.5	1290	73	1217	378		
2	2:28	M				7671.2	1905.8	1875.6	1355	76	1279	398		
3	2:35	E				7672.5	1895.0	1872.0	1200	74	1126	350		

Notes: 1 mm = 0.039 in; kg/m³ = 0.06 lb/ft³; 1 g = 0.03 oz; 1 µm = 0.0039 in.
B = beginning of the discharge; M = middle of discharge; E = end of discharge; NT = not tested.

Table 3. Summary of field test results.

Item	Job No. 1	2	3	3	4
Specified cement content (kg/m^3)	474	337	337	363	363
No. of tests	13	6	30	22	15
Average cement content by RAM (kg/m^3)	468	326	330	356	365
Average difference from specified (%)	-1.4	-3.4	-2.3	-2.0	+0.5
Range of difference from specified (%)	-0.8 to -1.9	-2.3 to -4.5	+2.5 to -7.5	+0.6 to -5.7	+4.0 to -6.6
Average air content (%)	4.5	4.5	4.9	4.9	5.2
Average unit weight (kg/m^3)	2473	2406	2353	2387	2368

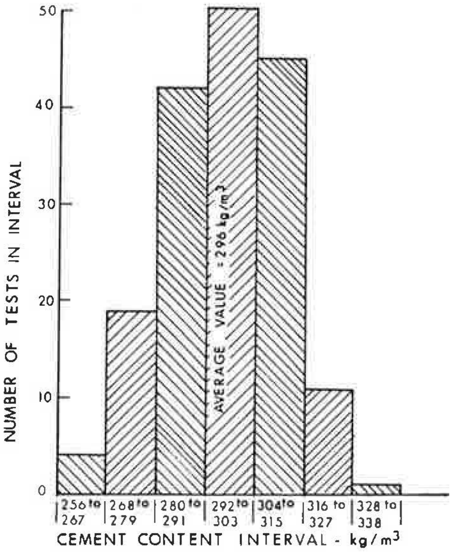
Note: 1 kg/m^3 = 0.06 lb/ft^3.

Table 4. Statistical analysis of test data from two contracts.

Contract	Specified Cement Content (kg/m^3)	No. of Tests	Mean Cement Content by RAM (kg/m^3)	Standard Deviation (kg/m^3)	Coefficient of Variation (%)
A					
With fly ash	234	119	233	15.6	6.7
Without fly ash	234	134	239	12.7	5.3
B	288	172	296	14.5	4.9

Note: 1 kg/m^3 = 0.06 lb/ft^3.

Figure 4. Test results of airfield paving contract.



Note: 1 kg/m^3 = 0.06 lb/ft^3.

A typical field data sheet is shown in Table 2, and a summary of the results of all the tests carried out during this phase of the evaluation is included in Table 3. It may be noted that the maximum variation in the cement content of job 3 was between +2.5 and -7.5 percent of the specified cement factor, based on the air content and the unit weight as measured before test runs. Other jobs showed smaller variations.

The following points were noted during the field operations.

1. The water tank needed refilling from a mobile tanker after every five or six tests. This was a time-consuming process. A constant source of water supply would be an advantage.
2. It was necessary to clean the machine after every five or six tests with diluted muriatic acid.
3. The shelf life of the flocculating agents was about two months.
4. No significant shift in calibration was noticed during these trials.
5. A periodic check on the grading of aggregates is required to make any adjustment of the silt-correction curve. Also, if the mix proportions are changed significantly, the curve should be reestablished.
6. The overall electromechanical function of the machine was satisfactory, although some problem was encountered with the solenoid valves. These were replaced easily.
7. The mobile laboratory vehicle required a reasonably level parking spot. This sometimes created a problem.

NORMAL QUALITY-CONTROL TOOL IN A NUCLEAR POWER STATION SITE AND AN AIRFIELD PAVING CONTRACT

RAM was used on two major contracts in Ontario. The first one was on a nuclear power station construction site and the second one was on an airfield paving contract (3).

During the initial stage of the operation it was found that the sampling technique was critical. After several trials, a sampling technique was developed that allowed a sample to be taken for testing in RAM without significantly delaying the other routine tests such as air content, slump, unit weight, and cylinder casting.

Four or five buckets of concrete were taken from a truck and spread out in a mixing tray, and a representative sample of about 7-9 kg (17-20 lb) was taken for RAM by random increments from the overall sample. The remaining concrete was used to carry out the other usual tests. The sample was processed through the machine and, after applying the proper corrections, the cement content was determined.

First Contract

The concrete for the nuclear project was used either with or without fly ash in the mix and had a cement content of 234 kg/m^3 (14 lb/ft^3). The appropriate corrections to be made were determined following the method described by Forrester, Black, and Lee (1). A periodic check on the calibration and the correction factor was carried out. The aggregate size was up to a maximum of 76 mm (3 in). However, aggregates larger than 38 mm (1.5 in) were removed after weighing but before processing the sample in the machine. The cement paste on these large particles was washed off into the test sample without causing any significant error in the final result. A total of 252 test results were analyzed in this contract.

Second Contract

The specified cement content in the airfield paving contract was 288 kg/m^3 (17 lb/ft^3), and the maximum nominal aggregate size was 38-mm crushed limestone. A total of 172 tests were carried out in this contract. The sampling and testing procedures were similar to the method described above.

Test Results

In both the above contracts the test results were well within the normal variations expected from a ready-mix truck. A statistical analysis of the test data was carried out; the standard deviations and coefficients of variation for each set of data are included in Table 4. Also, the distribution of the test data for the airfield paving contract is shown in Figure 4. A similar distribution was also noted for the other contract.

CONCLUSIONS

RAM is capable of carrying out a routine field testing of fresh concrete with good accuracy. The cement content of fresh concrete checked under field conditions usually varied within ±10 percent of the specified content. Any significant deviation from the specified cement content of a freshly mixed concrete can easily be detected by this test, and, if required, appropriate action can then be taken before the concrete has hardened.

ACKNOWLEDGMENT

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**P. K. Mukherjee was with the Ontario Ministry of Transportation and Communications when this work was done.*