

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

REFERENCES

1. Superplasticizing Admixtures in Concrete. Cement Admixtures Association and Cement and Concrete Association, London, England, Rept. 45.030, Jan. 1976, 30 pp.
2. V. M. Malhotra, E. E. Berry, and T. A. Wheat, eds. Superplasticizers in Concrete. Proc., International Symposium on Superplasticizers in Concrete, Ottawa, May 29-31, 1978, 801 pp.
3. M. M. Sprinkel. Super Water Reduced Concrete Pavements and Bridge Deck Overlays. Proc., International Symposium on Superplasticizers in Concrete, Ottawa, May 29-31, 1978, pp. 215-248.
4. V. M. Malhotra. Superplasticizers in Concrete. Department of Energy, Mines, and Resources, Ottawa, CanMET Rept. MRP/MSL 77-213 (J), Aug. 1977, 20 pp.
5. V. M. Malhotra. Effect of Repeated Dosages of Superplasticizers on Workability, Strength and Durability of Concrete. Department of Energy, Mines, and Resources, Ottawa, CanMET Rept. MRP/MSL 78-40 (OP&J), Feb. 1978, 34 pp.
6. R. C. Mielenz and J. H. Sprouse. High-Range, Water-Reducing Admixtures: Effect on the Air-Void System in Air-Entrained and Non-Air-Entrained Concrete. Proc., International Symposium on Superplasticizers in Concrete, Ottawa, May 29-31, 1978, pp. 347-378.
7. V. Ramakrishnan. Workability and Strength of Superplasticized Concrete. Proc., International Symposium on Superplasticizers in Concrete, Ottawa, May 29-31, 1978, pp. 481-514.
8. W. F. Perenchio, D. A. Whiting and D. L. Kantro. Water Reduction, Slump Loss and Entrained Air Void Systems as Influenced by Superplasticizers. Proc., International Symposium on Superplasticizers in Concrete, Ottawa, May 29-31, 1978, pp. 295-324.
9. B. Mather. Tests of High-Range Water-Reducing Admixtures. Proc., International Symposium on Superplasticizers in Concrete, Ottawa, May 29-31, 1978, pp. 325-346.
10. S. S. Pande, V. Ramakrishnan, and W. V. Coyle. Workability of Superplasticized Concrete. South Dakota School of Mines and Technology, Rapid City, Rept. SDSM&T-CCP7801, Feb. 1978, 71 pp.
11. D. Sadagopal, V. Ramakrishnan, and W. V. Coyle. Accelerated Methods of Estimating the Properties of Superplasticized Concrete. South Dakota School of Mines and Technology, Rapid City, Rept. SDSM&T-CC 7802, March 1978, 62 pp.
12. S. S. Pande, V. Ramakrishnan, and W. V. Coyle. Workability Studies on Retempered Normal and Superplasticized Concretes. South Dakota School of Mines and Technology, Rapid City, Rept. SDSM&T-CCP 7803, May 1978, 29 pp.
13. D. Ravina. Retémpering of Prolonged-Mixed Concrete with Admixtures in Hot Weather. Journal of the American Concrete Institute, Proc., Vol. 72, No. 6, June 1975, pp. 291-295.
14. M. J. Hawkins. Concrete Retémpering Studies. Journal of the American Concrete Institute, Proc., Vol. 59, No. 1, Jan. 1962, pp. 63-72.
15. F. W. Beaufait and P. G. Hoadley. Mix Time and Retémpering Studies on Ready-Mixed Concrete. Journal of the American Concrete Institute, Proc., Vol. 70, No. 12, Dec. 1973, pp. 810-813.
16. R. W. Previte. Concrete Slump Loss. Journal of the American Concrete Institute, Proc., Vol. 74, No. 8, Aug. 1977, pp. 361-367.
17. ASTM Standards—Concrete and Mineral Aggregates: Manual of Concrete Testing. ASTM, 1977.

Notice: The Transportation Research Board does not endorse products or manufacturers. Trade and manufacturers' names appear in this paper because they are considered essential to its object.

Super-Water-Reduced Concrete Pavements and Bridge Deck Overlays

Michael M. Sprinkel, Virginia Highway and Transportation Research Council, Charlottesville

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 work-

ability, 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 m³ (2 ft³), 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/in²) 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-m³ (8-yd³) batch was discharged directly from a mix truck positioned in the adjacent traffic lane. One internal vibrator, a wooden straight-edge, 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/in²) 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-m³ (6-yd³) 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 ≤ 0.37 was specified, but 0.39 was required to obtain a satisfactory initial consistency for the last batch, which contained only 2.3 m³ (3 yd³). 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-m³ (8-yd³) 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/m³ (2 gal/yd³) 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/in²) and 28-day strengths of 48.3 MPa (7000 lbf/in²), which may be attributed to the

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

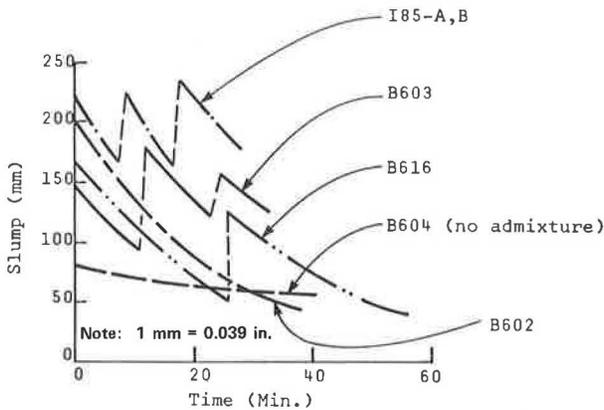


Figure 2. Liquid SWR admixture added to ready-mix truck.



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 m³ (8 yd³) to 4.6 m³ (6 yd³) 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-m³ (6-yd³) batch as was required to discharge the unmodified 6.1-m³ (8-yd³)

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.

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 5. Core showing segregation of fluid concrete.

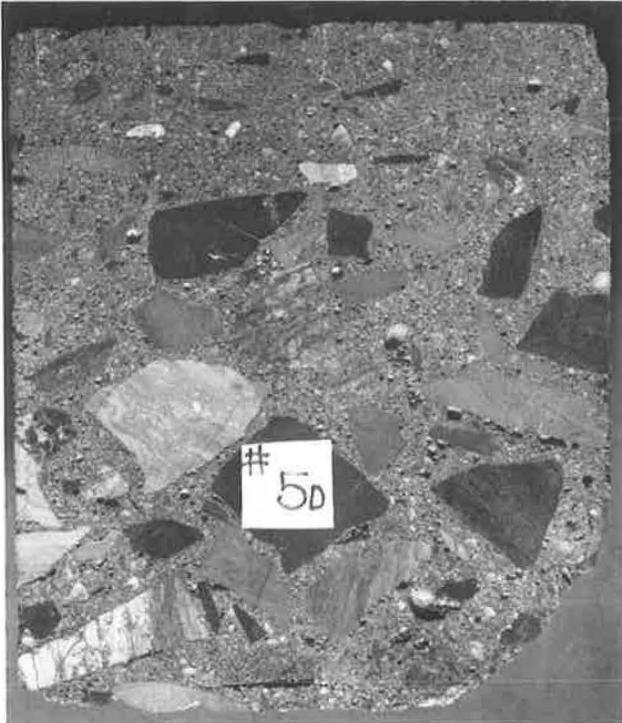


Figure 6. Core showing loss of cement mortar.

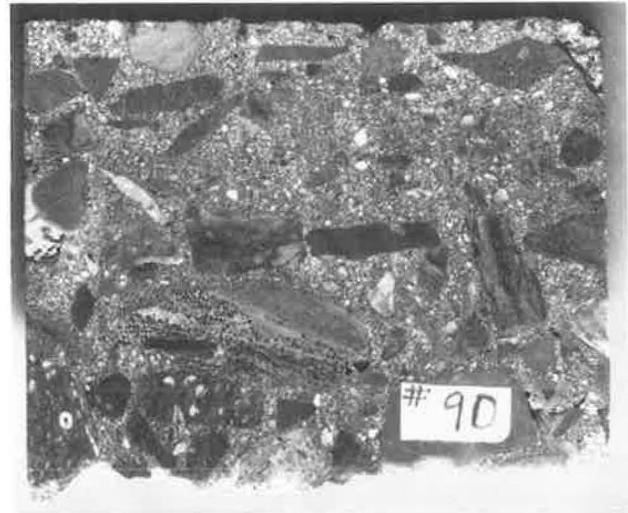


Table 1. Mixture proportions.

Location	SWR Admixture	Type 2 Cement Content (kg/m ³)	Coarse Aggregate		Content (kg/m ³)	Fine Aggregate Content (kg/m ³)	Maximum w/c	AEA* (ml/m ³)
			Nominal Maximum Size (mm)	Type				
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/m³ = 0.06 lb/yd³; 1 mm = 0.039 in; 1 ml/m³ = 0.02 oz/yd³.
*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/in²). 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

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.



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.

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-m³ (7-yd³) 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/in²).

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 place-

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



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



ment 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.

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/in²), 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 (%)				Slump (mm)			
		Design	Average	SD	Z*	Design	Average	SD	Z*
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.

*Percentage of data falling outside of design range.

Table 3. Cylinder strengths.

Location	SWR Admixture	Field-Cured Specimens (MPa)		Moist-Cured Specimens (MPa)			
		3-Day		14-Day		28-Day	
		Average	SD	Average	SD	Average	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		Percentage Weight Loss		RDF		RDF Percentage of Control
						Average	SD	Average	SD	Average	SD	
Laboratory	11/20/75	None	2	0.42	2 weeks, moist	1.5	-	1.1	-	100	-	100
	2/7/74	Melamine	3	0.32	1 week, laboratory	2.1	0.1	3.0	0.2	77	15	77
	8/10/76	Naphthalene*	3	0.35	2 weeks, moist 1 year, laboratory 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

*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.

Location	SWR Admixture	Measured Air Content (%)			Voids in Cores (%)									Voids in Specimens (%)								
					>1 mm			<1 mm			Total			>1 mm			<1 mm			Total		
		Design	\bar{X}	SD	Z	\bar{X}	SD	\bar{X}	SD	\bar{X}	SD	Z	\bar{X}	SD	\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 $1.1\text{-}2.7 \text{ m}^3$ ($1.4\text{-}3.6 \text{ yd}^3$) can be placed, consolidated, and screeded in 15 min; see the table below (1 mm = 0.039 in; 1 m = 3.3 ft; $1 \text{ m}^3 = 1.3 \text{ yd}^3$).

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 installa-

tions 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

This research was sponsored by the Virginia Highway and Transportation Research Council in cooperation with the Federal Highway Administration. The opinions, findings, and conclusions expressed in this paper are mine and not necessarily those of the sponsoring agencies.

REFERENCES

1. S. S. Tyson. Partial-Depth Repair of Jointed PCC Pavements. Virginia Highway and Transportation Research Council, Charlottesville, Rept. VHTRC 77-R37, Jan. 1977.
2. W. O. Tynes. Investigation of Proprietary Admixtures. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Rept. USAE WEST TR C-77-1, April 1977. NTIS AD A039612.
3. H. H. Newlon. Comparison of the Properties of Fresh and Hardened Concrete in Bridge Decks. Virginia Highway and Transportation Research Council, Charlottesville, Rept. VHTRC 70-R56, June 1971.
4. R. C. Mielenz and others. The Air Void System in Job Concrete. Journal of the American Concrete Institute, Vol. 4, No. 30, Oct. 1958, pp. 507-517.

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

V. M. Malhotra, Canada Centre for Mineral and Energy Technology,
Canada Department of Energy, Mines, and Resources, Ottawa

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/m³ (415 lb/yd³). 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 m²/kg, sulfate content of 3.24 percent, and C₃A 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/m³ (74.9 lb/ft³) 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