Superplasticized Fiber-Reinforced Concretes for the Rehabilitation of Bridges and Pavements

V. RAMAKRISHNAN

ABSTRACT

The most critical problem facing the highway industry is the rehabilitation of its distressed structures, particularly concrete bridge decks and pavements. Various forms of distress have occurred in some of the surfaces and different rehabilitation procedures can be very costly. There is a need to determine the most effective and the most economically advantageous means to rehabilitate the damaged concrete bridge decks and pavements. An investigation sponsored by the U.S. Department of Transportation has been completed at the South Dakota School of Mines and Technology to develop a tough, high-strength, high-density, durable concrete for bridge deck construction; and a medium-strength, flowing, structural concrete through the use of superplasticizers and steel fibers. The study was conducted in two phases. The first investigated the basic properties of concrete made with superplasticizers through the use of experimental mixtures conforming to the requirements dictated by statistically valid factorial designs, so that analysis of variance can be used in the evaluation. The second phase extended the findings into an evaluation of superplasticized concrete containing steel fibers. The study has been completed and the significant results are presented in this paper. The addition of the special type of steel fibers (with deformed ends and glued together into bundles with a quick water soluble adhesive) to superplasticized concrete greatly increased its ductility, toughness, impact resistance, ultimate flexural strength, post-crack load-carrying capacity, and shock resistance. The fiber-reinforced superplasticized concrete also had higher freeze-thaw durability and lower permeability. These improvements were achieved without a reduction of workability or the usual balling of steel fibers in the plastic concrete. Therefore, the fiber-reinforced superplasticized concrete is an almost ideal material for the rehabilitation of bridge decks and highway pavements, and for construction of other concrete structures.

The causes of concrete deterioration are many and varied. In general, concrete not properly designed, prepared, installed, finished, or cured is more susceptible to those deleterious influences that cause the concrete to deteriorate and spall and the reinforcing to rust and lose section. This, in turn, reduces the structural sufficiency and ultimately results in failure. Corrosion of reinforcing steel is the major cause of deterioration in bridge decks, beams, caps, columns, abutments, wing walls, and underdecks. Due to increasing heavy traffic, use of de-icing salts, freeze-thaw cycles, studded tires, and various other fatigue, surface deterioration and failures are beginning to show up on the bridge decks and pavements. Rehabilitation of bridges is one of the most critical problems facing the highway industry. Therefore, there is a need to find the most effective and most advantageous methods to rehabilitate the distressed concrete bridge decks and pavements.

The author was given a contract by the U.S. Department of Transportation to develop a tough, high-strength, high-density, durable concrete for bridge deck construction and a medium-strength flowing structural concrete through the use of superplasticizers and steel fibers (1). The study was conducted in two phases. In the first phase, an extensive investigation of superplasticized concretes (both flowing concrete and high-strength concrete) was completed (2,3), and the second phase extended the findings into evaluation of superplasticized concretes with new types of steel fibers. Highlights of this research are presented in this paper.

SUPERPLASTICIZED CONCRETE

Concrete having desirable properties in the hardened state is normally made with a low water-cement ratio and with the least possible amount of cement paste in the mix. Such a concrete usually has a low slump and requires intensive and careful compaction such as the high-density, low-slump concrete used in the Iowa Method of bridge deck resurfacing. In order to produce concrete of the same quality but requiring less vibration, very effective plasticizers, known as superplasticizers, have been developed for making flowing and self-compacting concrete. Superplasticizers are added to concrete to cause a vast increase in its workability to allow a large reduction in mixing water, and thus produce high-strength concrete. Such a change in concrete properties would result in reduced placement costs or reduction in the cement requirement. A well-designed mix with superplasticizer will have good flowability and sufficient cohesiveness and would not cause bleeding or segregation or strength reduction either during or after placing of the concrete.

The introduction of superplasticizers has opened up new possibilities for the use of concrete in construction, particularly for bridge-deck repair and resurfacing, pavement rehabilitation, and construction of other highway facilities.

EFFECTS OF SUPERPLASTICIZERS ON FRESH CONCRETE

The results reported in this paper are based on the work done by the author using the following two types of superplasticizers: sulfonated naphthalene formaldehyde condensate and sulfonated melamine formaldehyde condensate. The results obtained have established certain real advantages, economical as well as technical, that can be gained by the controlled and proper use of these admixtures (1-4). Compared to the corresponding normal concrete, the concrete with the addition of superplasticizer has good flowability, excellent cohesiveness, less bleeding, no segregation, better pumpability, and lower pumping pressure. The entrained air content of fresh superplasticized concrete decreases with time.

Superplasticized concretes exhibit large increases in workability (slump). Because slump loss is an inherent property of concrete, this increase in slump is of short duration, and within 30 to 60 min, the concrete loses its increased workability. The rate of loss of slump depends on the type of superplasticizer, its dosage rate, temperature of the concrete, the humidity, and the type of cement. Figure 1 shows typical slump loss with time curves for a particular mix with different concrete temperatures. The increase in temperature increases the rate of slump loss. The mixes made at lower temperatures had higher initial air contents and high slumps whereas mixes made at higher temperatures had very low air contents and low slumps.

Although useful trends can be deduced from such visual examination of the slump loss curves, more quantitative parameters are needed. Two such parameters that have been found useful are "slump window" and "total working time." "Slump window" is defined as the time taken for the slump to decay from 76 mm to 25.4 mm and would be useful to those interested in slipform operations in which high slumps could not be tolerated. The "total working time" is defined as the time needed for the slump to go from the initial value to 25.4 mm. These two parameters are plotted in Figure 1.

The rapid loss of workability with time is considered a serious drawback. A delay in the discharge of concrete from truck mixer could cause stiffening to the point of unworkability and loss in air content thus affecting the desired air-void system. However, this disadvantage can be minimized or mitigated by retempering (adding additional dosages of superplasticizer and air entraining agent). The large increase in workability and the desired air content can be maintained for several hours by the addition of a second and third dosage as shown in Figure 2. The second and third dosages used were less than the initial dosage. The slump after initial mixing was 220 mm, whereas the slump after the first and the second retempering was 191 mm. The rate of slump loss was low and the time taken to reach a workable slump of 51 mm after each retempering was 3.5 hr. Overdosing of superplasticizer should be avoided because this can cause segregation.

EFFECT OF SUPERPLASTICIZERS ON THE PROPERTIES OF HARDENED CONCRETE

With the addition of superplasticizers, water reductions of up to 20 percent can be achieved in the manufacture of concrete. This causes an increase in mechanical properties such as compressive strength, flexural strength, and modulus of elasticity. This increase in strength is generally proportional to the reduction in the water-to-cement ratio. The ability of superplasticizers to reduce water and achieve very high strengths is of special importance for the concrete repair and rehabilitation work where high early strengths are needed. In some cases, the concretes with superplasticizers had shown higher strengths at earlier ages than the reference concretes, indicating an increased rate of strength development at early ages.

The study has shown that the shrinkage of superplasticized concrete is equal to or less than the shrinkage of reference concrete. The concrete with the superplasticizers has approximately the same creep as the reference concrete. The study has shown that the addition of superplasticizer does not affect the relationship between the accelerated strength and 28-day compressive strengths. The modified boiling test, ASTM C684, was the accelerated strength test used in the study.

In cold regions, the resistance of concrete to freeze-thaw cycling is important. Therefore, for concretes used in the cold regions, an air entraining admixture is added to entrain air bubbles of the required sizes. These air bubbles provide the satisfactory freeze-thaw durability of the concretes. An extensive investigation has shown that the concretes with superplasticizers have adequate freeze-thaw durability in spite of the larger bubble sizes found

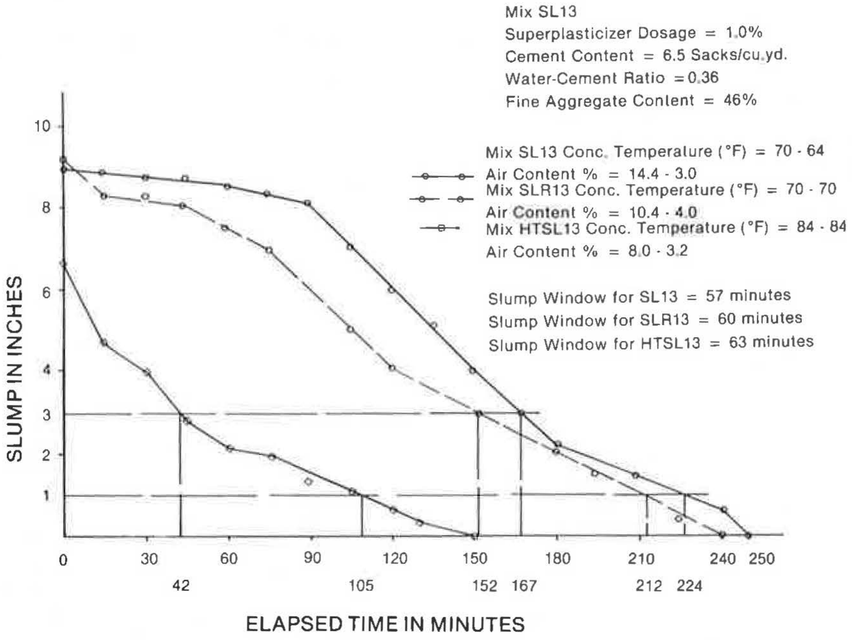

FIGURE 1 Slump versus time.

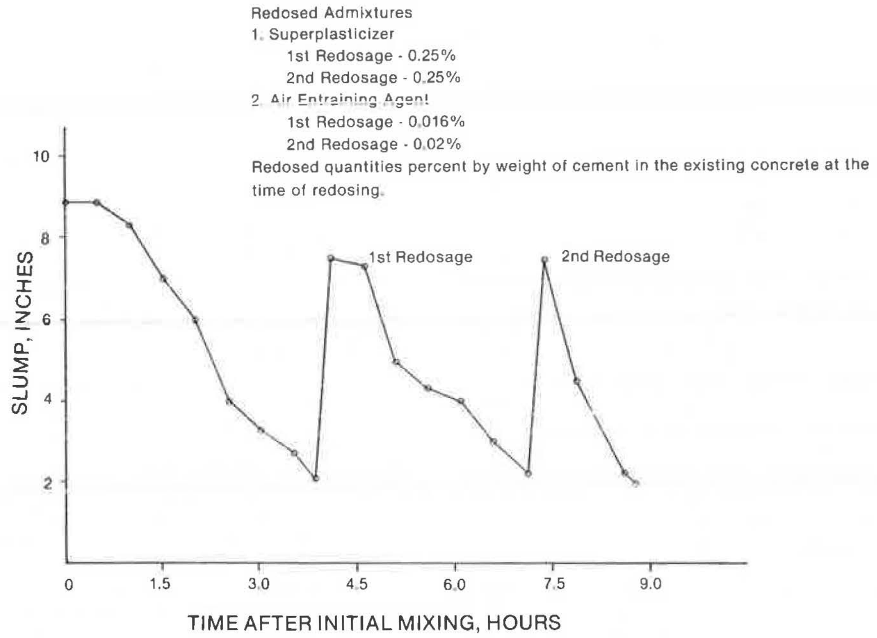

FIGURE 2 Slump-time-retempering study for Mix RTP13.

in some concretes. The superplasticized concretes had performed equally well in the de-icer scaling test recommended by ASTM.

In general, the study has shown that with the addition of superplasticizers, it is possible to produce a very highly workable concrete, which is known as flowing concrete, without any detrimental effects either in the plastic or in the hardened states. It is also possible to produce extra high-strength concretes (80 to 100 MPa) with a low water-cement ratio (0.25 to 0.28) and high workability.

SUPERPLASTICIZED FIBER-REINFORCED CONCRETE

High-strength concrete is being increasingly used in the repair and rehabilitation of bridges (particularly overlays), buildings, and other reinforced and prestressed concrete structures. One major drawback of high-strength concrete is that it is brittle and leads to a sudden and explosive type of failure. The failure will be catastrophic, particularly in structures that are subjected to earthquakes, blast, or suddenly applied loads. An ideal solution to overcome this serious disadvantage of high-strength concrete is to add steel fibers in the concrete. It is well-established (4-7) that the addition of steel fibers greatly increases the ductility, energy absorption capacity, and ultimate strain capacity of the concrete. Fiber reinforcement considerably increases the ultimate flexural strength, the post-crack load-carrying capacity, impact resistance, shear and torsional strength, fatigue strength, shock resistance, and failure toughness. However, the main problems associated with fiber concrete are fiber balling and inadequate workability. Balling of fibers in the mixer prevents uniform distribution and also causes problems when the concrete is placed. Fiber balling and consequent inadequate mix workability imposes an upper limit beyond which increase in strength and other properties are no longer realized when using conventional mixing procedures.

To remedy the problem of fiber balling, a new type of fiber (several fibers with hooked ends glued together side by side with water soluble adhesive) were used with successful results, and a superplasticizer was used to increase workability adequately. The addition of fibers and superplasticizers proved to be an ideal combination to produce high-strength ductile concrete.

The hooked fibers used in this project are glued together side by side into bundles with a water-soluble adhesive. These fibers are made from low carbon steel wires, and have a nominal length of 52 mm and a diameter of 0.5 mm. The bundling of fibers creates an artificial aspect ratio (the ratio of length to diameter of the wires) to approximately 30 when introduced to the mix. When the glue is dissolved by the water in the mix, the fibers will be separated as individual fibers with an aspect ratio of 100. These hooked fibers are commercially known as Dramix.

The basic properties of superplasticized fiber-reinforced concretes were investigated through the use of 47 experimental mixes conforming to the requirements dictated by statistically valid factorial design so that analysis of variance could be used in the evaluation. Using a statistical model (the central Rotatable Composite Factorial Design), four major factors--water-cement ratio, cement content, fiber content, and superplasticizer dosage--were investigated. The statistical analysis determined the effect of these factors and their mutual interactions on the different response variables workability (slump, vebe time, and flow table spread), plastic unit weight, compressive strength, and flexural strength. The developed prediction equations were used to construct a set of curves for a variety of levels of the four independent variables to readily obtain the estimate of compressive strength, flexural strength, slump, flow table spread, and vebe time (1).

For the same water-cement ratio, an increase in superplasticizer dosage caused considerable increase in slump and air content. With higher cement content (390 kg/m^3) and higher superplasticizer dosage (1.2 percent), it was possible to achieve up to 200 mm of slump at low water-cement ratios (0.30) without any segregation. The measured slumps for superplasticized fiber-reinforced concrete was slightly less when compared to the values of superplasticized concrete without fibers.

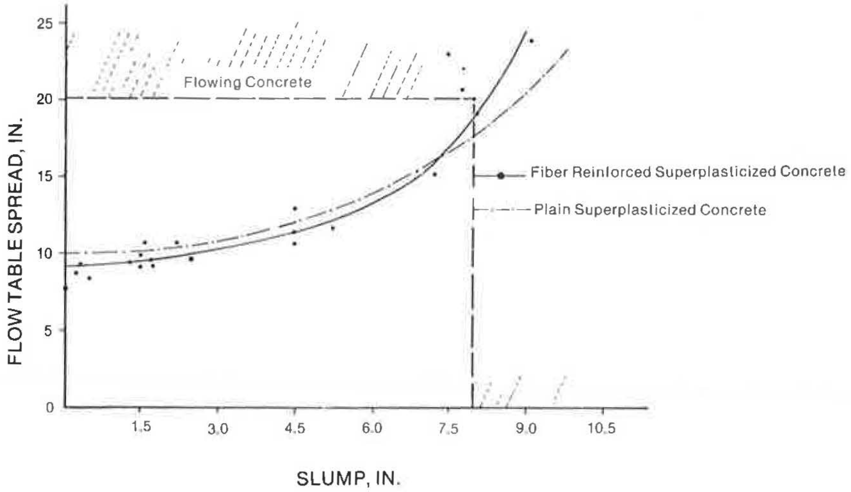

FIGURE 3 Relationship between slump and flow table spread.

The hooked fibers performed well during mixing because no balling occurred in almost all the mixes except for mixes with zero slumps and high fiber contents, even though the fibers were charged to the mixer all at one time along with the aggregates. This must be taken as the consequence of low aspect ratio created by the collating of the fibers. It took approximately 1.5 min for the glue to dissolve and for the fibers to separate. Of the workability tests commonly used, the slump test is the most sensitive indicator of change because the range covered is so large. However, the flow table test conditions are closer to the real placing situation and, consequently, a more realistic indicator of workability for flowing concrete than the slump test. The relationship between slump and flow table spread for plain and fiber-reinforced superplasticized concrete is shown in Figure 3. These two curves show only a small difference between them; the relationship between slump and flow table spread is approximately the same for both superplasticized concretes, with and without fibers.

Concrete with superplasticizer added and having a slump of 200 mm (7.9 in.) or greater and a flow table spread within the range 510 to 620 mm is classified as a flowing concrete. Flowing concrete should not exhibit excess bleeding or segregation. Other terms used to describe the flowing concrete are: self-compacting concrete; flocrete; soupcrete; and liquid, fluid, and collapsed-slump concrete. This study has shown that it is possible to produce flowing fiber-reinforced concrete.

Unlike those for plain superplasticized concretes, the measured vebe times were quite high for superplasticized fiber-reinforced concretes. For superplasticized fiber-reinforced concrete mixes with zero slumps, vebe times were approximately in the range of 10 to 28 sec, whereas for superplasticized concretes without fibers, they were in the range of 7 to 10 sec.

The increase in fiber content from 32.63 kg/m^3 to 56.36 kg/m^3 had negligible effect on the slump and flow table spread. However, an increase in fiber content caused an increase in vebe time. Slump and flow table tests are used to measure the workability of concrete based on the flowability character of concrete. Consequently, an increase or decrease in fiber content did not have much influence on the results attained from these tests. Vebe time is used to measure the workability of concrete, based on the energy needed to compact the concrete. The energy requirement for plain superplasticized concrete mixes is less than for superplasticized fiber-reinforced concrete. In the case of superplasticized fiber-reinforced concrete mixes, the energy needed appears to be proportional to the fiber content in the concrete.

The slump of the concrete had a greater influence on the air content than the air-entraining agent used. For concrete with zero slump, an increase in air-entraining agent from 0.2 percent to 0.8 percent caused no appreciable increase in air content. For zero slump concrete, it was never possible to achieve an air content of 6 percent, even with a very high dosage of air-entraining agent (0.8 percent by weight of cement).

Figure 4 shows that for a constant quantity of air-entraining agent (0.4 percent), the air content increases from 4.2 percent to 7.4 percent with an increase in slump from 0.0 mm to 38.0 mm. The same phenomenon is true for other dosages of air content. With a constant dosage of air-entraining agent (0.2-0.25 percent), the air content increased from 3.8 percent to 9.6 percent for an increase in slump from 0 mm to 152.4 mm, and for a constant dosage of from 0.1 percent to 0.15 percent, the air-content increased from 3.8 percent to 9.2 percent when the slump increased from 0 mm to 229 mm.

Based on the statistical analysis, two typical mixes, Mix 1 and Mix 26 were selected for intensive study. Mix 1 had a low water-cement ratio (0.3), high cement content (474 kg/m^3), and medium workability, and it will be suitable for bridge deck overlays and for constructions where high-strength and highly impermeable concretes are needed. Mix 26 had a medium water-cement ratio (0.4) medium cement content (363 kg/m^3), and high workability, and it will be suitable for general structural work and for construction of highway pavements. For these concretes, all the fresh concrete as well as the hardened concrete properties were determined (1).

The initial setting time for Mix 26 corresponding to a penetration resistance of 3.45 MPa was 8 hr 45 min and the final setting time corresponding to a penetration resistance of 27.5 MPa was 10 hr 50 min. The corresponding initial and final setting times for Mix 1 were 7 hr 59 min and 10 hr 36 min.

The slump loss study had shown that there was adequate total working time (0.5-1.5 hr) for fiber-reinforced superplasticized concretes. The retempering study had shown that after each stage of mixing, the concrete had good workability and maintained it for more than an hour (depending on the superplasticizer dosage), especially after first retempering.

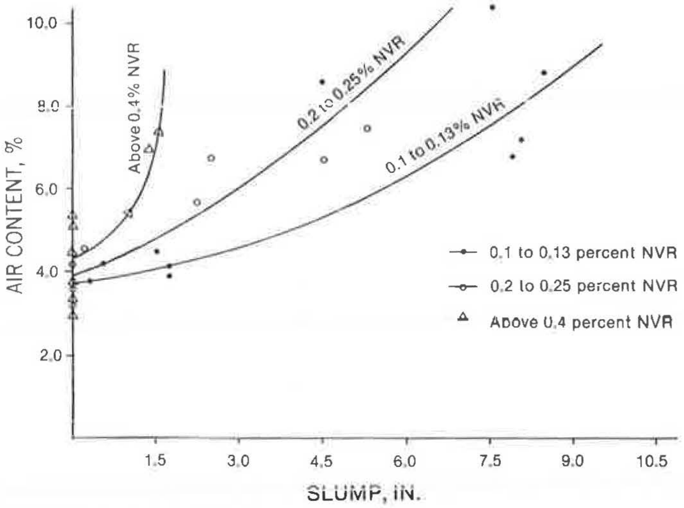

FIGURE 4 Relationship between slump, air-entraining agent, and air content.

There was a substantial loss in entrained air during retempering; however, the air content could be increased by adding an air-entraining agent at each stage of retempering.

Hardened Concrete Properties

Compressive Strength

The analysis has shown that for the same water-cement ratio and superplasticizer dosage, concretes with a higher cement content showed higher strength, and an increase in superplasticizer dosage caused an increase in compressive strength. An increase in fiber content caused no appreciable change in compressive strength.

Flexural Strength

When all other factors were the same, an increase in fiber content caused an increase in ultimate flexural strength. However, the increase in flexural strength was only about 10 percent for an increase in fiber content from 36.63 kg/m^3 to 56.36 kg/m^3. The flexural strength values varied in the same way as compressive strength values, with respect to variation in all factors, except in the case of fiber content. For a given compressive strength, the corresponding flexural strength was greater for superplasticized fiber concrete when compared to plain superplasticized concrete.

A significant difference in the performance of plain superplasticized concrete and superplasticized fiber-reinforced concrete was found in the static flexural test. The hooked fibers had proved their ability as crack arrestors. The cracks were prevented from propagating until the composite ultimate stress was reached. The mode of failure was simultaneous yielding of the fibers and the matrix. During the test, one could actually hear the popping sound of the fibers failing in tension and not because of the bond failure. It appears obvious that the deformed ends contributed significantly to the increase in bond between fiber and matrix. The significance of good bond can be observed from the typical load deflection curves (Figure 5). The curves indicate a ductile behavior. These curves also show the advantage of fiber-superplasticized concrete versus nonfiber-superplasticized concrete in obtaining higher flexural strength, higher toughness, and high energy absorption qualities.

Toughness Index

The toughness index is a measure of the amount of energy required to deflect the 102 x 102-mm beam a given amount, compared to the energy required to bring the beam to the point of the first crack. It is calculated as the area under the load-deflection curve up to 1.9 mm, divided by the area under the load-deflection curve of the fibrous beam up to the first crack strength (proportional limit, defined as first deviation from linear).

In general, the toughness index for the fiber-reinforced superplasticized concrete varied greatly depending on the position of the crack and the distribution of fibers. An increase in fiber content caused an increase in toughness index; the toughness index increased from 4.75 to 6.5 for an increase in fiber content from 32.63 kg/m^3 to 56.36 kg/m^3. All specimens made of plain superplasticized concrete failed immediately after the first crack and, consequently, the toughness index for these specimens is equal to 1.

Impact Strength

The fiber-reinforced concrete showed a tremendous ability to absorb impact loading. The measured impact resistance at various ages for the selected concretes are shown in Figure 6. Concrete containing 44.5 kg/m^3 steel fibers had 10 times greater impact resistance at 28 days than its corresponding concrete without fibers.

The relationships between compressive strength and other properties such as tensile strength, flexural strength, pulse velocity, dynamic modulus of elasticity, and static modulus of elasticity were determined based on the regression analysis (1). For compressive strengths varying from 13.8 to 55 MPa, there was an approximate linear relationship between the compressive strength and other properties. For both concretes with and without steel fibers, higher early strengths were achieved with the addition of superplasticizer.

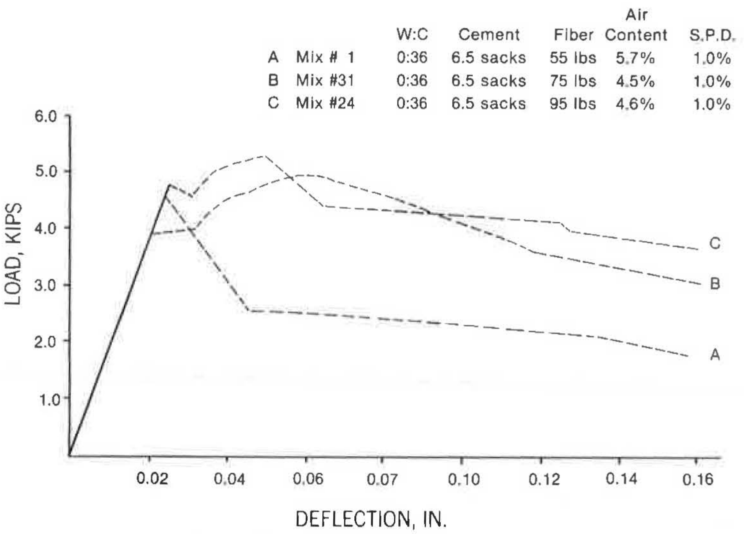

FIGURE 5 Comparison of load deflection curves for mixes with different fiber contents (7-day).

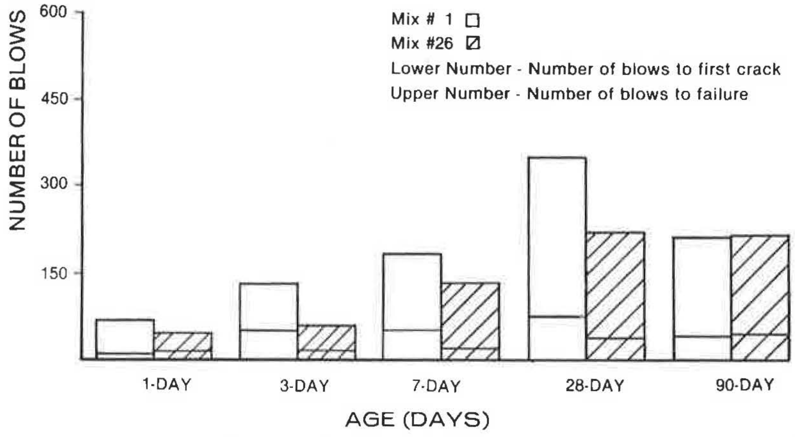

FIGURE 6 Impact resistance with age.

Shrinkage and Creep

The shrinkage and specific creep strains increased with an increase in the water-cement ratio and the concrete that exhibited higher shrinkage also had higher creep. The total shrinkage strains measured at the end of 566 days were 42.9 x 10^{-5} and 49.85 x 10^{-5}, respectively, for low (0.3) and medium (0.4) water-cement ratio concretes. The total specific creep strains measured at the end of 375 days were 45.6 x 10^{-6} and 58.6 x 10^{-6} (in./in./psi), respectively, for low and medium water-cement ratio concretes. These creep and shrinkage strains are much lower than those obtained for the normally used structural concretes.

The fiber-reinforced superplasticized concretes had less shrinkage and comparable creep than that of the corresponding superplasticized concrete without fibers.

Thermal Conductivity

The thermal conductivity of the concrete specimens was measured with a guarded hot box apparatus. The use of steel fibers appeared to have very little effect on the thermal conductivity of superplasticized concrete. For Mix 1, the plain mix had an average thermal conductivity of 0.659 Btu/hr-ft-°F (0.975 g cal m/hr m^2 °C) and the mix with fiber had an average value of 0.613 Btu/hr-ft-°F (0.907 g cal m/hr m^2 °C). This is a 7.5 percent difference. This shows that the plain concrete was a slightly better heat conductor. For Mix 26, the plain mix had an average thermal conductivity of 0.625 Btu/hr-ft-°F (0.925 g cal c/hr m^2 °C) and the mix with fiber had an average value of 0.665 Btu/hr-ft-°F (0.984 g cal mhr m^2 °C); this is a 6.4 percent difference. In this case, the concrete with fibers was a slightly better heat conductor.

The measured thermal conductivity values are lower than those obtained for conventional structural concretes made with limestone aggregates.

Chloride Permeability

The migration of sodium chloride solution (8 percent solution) into superplasticized concrete cylinders at room temperature was investigated. The superplasticized concretes offered a slightly greater resistance to chloride penetration at 50 mm depth, compared to regular concretes without superplasticizer (2).

Resistance to De-Icing Chemicals

The resistance to scaling when exposed to de-icing chemicals (4 percent calcium chloride solution) was determined as per the recommendations of ASTM C672. At every 5-cycle interval, each specimen was evaluated for damage for a total of 50 cycles. The observed rating of scaling resistances for the two concretes (Mixes 1 and 26) are given in Table 1. The high cement content concrete showed no scaling at the air contents tested. The medium cement concrete showed very slight scaling at the end of the 50 cycles. The resistance to scaling when exposed to de-icing chemicals improved with lower water-cement ratio and higher cement content. Some rusting of the exposed fibers was observed on all the beams, but this rusting was found only at the surface. The fibers inside the beams showed no signs of rusting.

TABLE 1 Scaling Resistance to 4 Percent Calcium Chloride Deicing Solution by ASTM Ratings

	Mix by Specimen Number							
	26C		1C		26D		1D	
Cycle	1	2	1	2	1	2	1	2
0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
30	0	0	0	0	0^+	0^+	0	0
35	0	0	0	0	0^+	0^+	0	0
40	0^+	0^+	0	0	0^+	0^+	0	0
45	0^+	0^+	0	0	0^+	0^+	0	0
50	0^+	0^+	0	0	½	½	0	0

The high resistance to de-icer scaling of Mix 1 resulted from a greater impermeability of this concrete. This greater impermeability resulted from higher cement content, which caused lower water absorption. As compared to concrete without steel fibers, it can be stated that the addition of fibers did not adversely affect the de-icer scaling resistance.

Freeze-Thaw Durability

The durability of both concretes (Mixes 1 and 26) subjected to rapid freezing and thawing was evaluated as per ASTM C666-77, Procedure A, "Rapid Freezing and Thawing in Water." All specimens were tested at approximately 30-cycle intervals, for a total of 300 cycles for any weight change, pulse velocity, and dynamic modulus. At the conclusion of 300 cycles, all beams were also tested for flexural strength and moisture absorption. For the moisture absorption test, the specimens were kept immersed in water for 30 min. The specimens were then taken out, surface water wiped with an absorbing paper, and the specimens were weighed accurate to 1 gram. These specimens were placed in an oven at a temperature of 105°C ± 5° for 48 hr. The moisture absorption is taken as the difference in weight of the wet and dry specimens divided by the weight of the dry specimen.

Durability

For both concretes, except for Mix 26D, the calculated durability factors were greater than 98.25 percent, whereas ASTM C494-77 sets the minimum durability factor at 80 percent. The higher cement-content concrete showed a higher durability even though the air content was less than for the medium cement-content concrete.

For the concrete with low air content (3.8 percent) and medium cement content (362.5 kg/m^3), Mix 26D, there was slight scaling after 300 cycles of freeze-thaw, and the reduction in dynamic modulus was much higher than for concretes with higher air contents but having the same cement and water contents. The calculated durability factors for these specimens were not satisfactory. It is evident that for superplasticized concretes with low air contents even when steel fibers are added, there will be deterioration due to freeze-thaw cycles. It is therefore recommended that a minimum of 6 percent air content should be used for superplasticized fiber-reinforced concretes.

Flexural Strength

The high-cement-content concrete showed an increase in flexural strength after 300 cycles of freeze-thaw as compared to the 14-day flexural strength, whereas the freeze-thaw specimens of the medium-cement-content concrete with higher air contents showed the same flexural strength after 300 cycles of freezing and thawing as compared to the 14-day flexural strength. However for medium cement concretes with lower air contents (Mixes 26D and 26F), there was a considerable reduction in their flexural strengths after 300 cycles of freeze-thaw when compared to their 14-day flexural strengths.

Weight Loss

The loss of weight at different freeze-thaw cycles was more for the concretes with medium cement content than for the concretes with high cement content.

Moisture Absorption

In all concretes, there was an increase in the water absorption after they were subjected to 300 cycles of freeze-thaw showing that there is an apparent deterioration or increase in internal microcracking due to freezing and thawing. This appears to be true for concretes with or without fibers, with high or low strengths, high or low cement contents, high or low water contents, and high or low air contents. However, higher cement and air contents reduce the damage considerably. Both reference and freeze-thaw specimens made from the high-cement-content concrete showed lower water absorption than those of the medium-cement-content concrete. The percentage difference of water absorption between freeze-thaw and reference specimens is less for the high cement-content concrete.

There appears to be a relation between the water absorption and the durability factor. Concretes with higher water absorption coefficients showed lower durability. Therefore, a simple determination of the water absorption coefficients for different concretes might give a qualitative evaluation of their durabilities.

Pulse Velocity

The change in pulse velocity followed the same pattern as the change in dynamic modulus for almost all the specimens. In this investigation, the pulse velocity determination was used as an alternate test for verifying the observations based on the transverse resonant frequency readings.

A comparison of concretes with and without steel fibers had shown that the concretes with steel fibers had higher freeze-thaw durability, higher pulse velocity, and lower moisture absorption than their corresponding concretes without fibers and having the same air content.

Air-Void Characteristics

For the selected concretes (Mixes 1 and 26), the air-void characteristics of the hardened concretes were determined using the Linear Traverse Method as described in ASTM C457-71 with modifications to suit the use of a minicomputer. Four specimens (two from each mix) were studied (1).

Two specimens showed very good air-void characteristics. All the air-void parameters, as well as the distribution of the chord intercepts, were satisfactory. One specimen showed air-void characteristics slightly outside the recommended parameters, but the results were still acceptable. The last specimen showed low specific surface due to larger air bubbles in the concrete. This specimen also had high air content. Larger air bubbles and high air content had only reduced the strength in the concrete. The distribution of the chord intercepts for the two last specimens was acceptable, but they lacked some smaller air bubbles. However, all four concretes had highly satisfactory resistance to rapid freeze-thaw cycles and their durability factors were above 94 percent.

CONCLUSIONS

Substantial improvement in workability with consequent reduction in placement costs or a considerable saving in cement content is the realistically achievable advantages through the use of superplasticizer for whatever purpose conventional concrete is being used. Superplasticized concretes with low water-cement ratios and high early strengths are particularly suitable for concrete repair and rehabilitation of bridges and other structures.

The addition of the special type of steel fibers (with deformed ends and glued together into bundles with a quick water-soluble adhesive) to superplasticized concrete greatly increases its ductility, toughness, impact resistance, ultimate flexural strength, post-crack load-carrying capacity, shear and torsional strength, fatigue strength, and shock resistance. This is achieved without a reduction of workability or the usual "balling" of steel fibers. Therefore, the fiber-reinforced superplasticized concrete is an almost ideal material for the rehabilitation of concrete structures.

ACKNOWLEDGMENTS

Grateful acknowledgment is expressed to William V. Coyle (co-principal investigator of the project) and Peter A. Kopac, project monitor, for their help and valuable suggestions. The author is thankful to all the graduate research assistants for their help rendered during the experimental work. The author gratefully acknowledges the financial support of the Office of University Research, U.S. Department of Transportation (Contract No. DOT-RC92035) and C.W. Josifek of the Bekaert Steel Wire Corporation, Chicago.

REFERENCES

1. V. Ramakrishnan, W.V. Coyle, and P.A. Kopac. Steel Fiber Reinforced Superplasticized Concretes for Rehabilitation of Bridge Decks and Highway Pavements. Final Report CDT-822. South Dakota School of Mines and Technology, Rapid City, July 1982, 375 pp.
2. V. Ramakrishnan, W.V. Coyle, and P.A. Kopac. Superplasticized Concretes for Rehabilitation of Bridge Decks and Highway Pavements. Report DOT/RSPA/DPB-50/81/3, Office of University Research, U.S. Department of Transportation, Jan. 1981.
3. V. Ramakrishnan, W.V. Coyle, and P.A. Kopac. Supplement to Phase One Interim Report--Superplasticized Concretes for Rehabilitation of Bridge Decks and Highway Pavements. Report CDT-821. South Dakota South of Mines and Technology, Rapid City, July 1982.
4. V. Ramakrishnan, T. Brandshaugh, W.V. Coyle, and E.K. Schrader. A Comparative Evaluation of Concrete Reinforced with Straight Steel Fibers and Fibers with Deformed Ends Glued Together into Bundles. American Concrete Institute Journal, Vol. 77, No. 3, 1980, pp. 135-143.
5. V. Ramakrishnan. Performance Characteristics of Steel Fiber Reinforced Superplasticized Concrete. Proc., Symposium L, Materials Research Society, University Park, Pa., 1980, pp. 145-148.
6. V. Ramakrishnan, W.V. Coyle, L.F. Dahl, and E.K. Schrader. A Comparative Evaluation of Fiber Shotcretes. Concrete International, Design and Construction, Vol. 3, No. 1, 1981, pp. 59-69.
7. V. Ramakrishnan, W.V. Coyle, P.A. Kopac, and T.J. Pasko. Performance Characteristics of Steel Fiber Reinforced Superplasticized Concrete. SP68-29. American Concrete Institute, 1981, pp. 315-334.