Steel Fiber Shotcrete for Rehabilitation of Concrete Structures

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ABSTRACT

Steel fiber-reinforced shotcrete (SFRS) was first introduced into North America in the early 1970s. Since that time, it has been used in numerous applications, mainly in new construction or lining rock slopes and underground openings in mines and tunnels. There has been relatively little use of this innovative material for rehabilitation of concrete structures. Some of the mix design, batching, mixing, and placing procedures that have been successfully used in numerous SFRS projects in British Columbia are reviewed. Physical properties of SFRS that make it particularly attractive as a rehabilitation material include its good bond characteristics, flexural strength, toughness, impact strength, fatigue resistance, and durability. These characteristics of SFRS are reviewed. Existing SFRS rehabilitation projects are briefly reviewed and suggestions are made for applications where SFRS could provide a viable alternative to conventional rehabilitation procedures.

Steel fiber-reinforced shotcrete (SFRS) was first used for structural applications in North America in the early 1970s. The early experimental work with this material was carried out by Battelle Laboratories in 1971. The first major practical application was SFRS lining of a tunnel adit at the Ririe Dam, Idaho, in 1973. Since that time, there has been considerable use of this new construction material in most of the world's industrialized nations. Henager (1) and Johnston (2) have summarized many of the applications of SFRS.

The largest volume of SFRS application has been found in support of underground openings. It has been extensively used in mining operations and for forming linings in various road, railway, and water tunnels. In British Columbia, SFRS has been used to: line several kilometers of new tunnels constructed through the Rocky Mountains by the British Columbia Railway in 1981-1983; rehabilitate deteriorating old tunnels on the Canadian Pacific Railway main trans-Canada line (used to control water flow and ice formation and stabilize rock scaling) (3); line exploratory adits in a slaking cretaceous shale; and line drainage tunnels in a rock slide area in two British Columbia hydroelectric projects (4). Large-volume applications of SFRS have been found in numerous rock slope stabilization projects (1,2).

It is apparent from reviewing the use of SFRS that its most successful applications are where it has been used in lieu of mesh-reinforced shotcrete. Morgan (5) has conducted a comparative evaluation of plain, mesh, and steel fiber-reinforced shotcrete and has demonstrated that SFRS can provide equivalent and, indeed, even superior performance to mesh-reinforced shotcrete.

There has been relatively little reported use of SFRS for rehabilitation of concrete structures. Some reported repair applications are detailed in the Applications section of this paper. SFRC mix design and materials are discussed and the main physical attributes that make SFRS an attractive material for rehabilitation of certain concrete structures are reviewed. Also presented is a discussion of those structures and structural elements to which SFRS may provide an economical and technically viable alternative to conventional rehabilitation procedures. Information in this paper is drawn from the experience of the author in successfully completed SFRS projects in British Columbia, Canada.

STEEL FIBER

SFRS is defined as a mortar or concrete containing discontinuous discrete steel fibers that are pneumatically projected at high velocity onto a surface (6). Steel fibers are available in a number of shapes, sizes, and metal types. A conventional numerical parameter describing a fiber is the aspect ratio of the fiber, defined as the fiber length divided by the equivalent fiber diameter. Typical aspect ratios range from about 30 to 150 for length dimensions of 5 to 75 mm (0.25 to 3 in.). Most successful shotcrete applications have, however, used fibers with lengths of 13 to 30 mm (0.5 to 1.2 in.). Many different types of fibers are commercially available. Fibers with round, rectangular, and crescent-shaped cross sections have been produced. Straight, crimped, deformed, hooked end, and a variety of other fibers have been used in shotcrete projects (1,2).

Ramakrishnan et al. (7) carried out a comparative evaluation of various types of fibers and found that hooked end fibers provided better physical properties than straight fibers for a given volume concentration of fiber. This is because of the better end anchorage provided by the hooked end fibers; that is, these fibers provide a higher effective aspect ratio than equivalent length straight fibers. Alternatively, lower volume concentrations of hooked end fibers are required for a given level of physical performance compared to shotcrete with straight fibers. Virtually all the major SFRS projects carried out in British Columbia have used a 30 mm-long x 0.4- or 0.5-mm-diameter and hooked-end fiber.

Concentrations of steel fiber used on construction projects have typically ranged from 0.6 to 2.0 percent by volume: 47 to 157 kg/m^3 (80 to 265 lb/yd^3) (1). Fiber concentrations in excess of 1.0 percent by volume 78 kg/m^3 (132 lb/yd^3) have generally been used with straight fibers; most of the tunneling and rock slope stabilization projects in British Columbia have used hooked end fibers at concentrations of 0.75 percent by volume: 59 kg/m^3 (99 lb/yd^3). Note that all these quantities refer to fibers added to the shotcrete mix; the volume concentration of fiber in the in situ shotcrete may be greater or smaller, depending on the degree of rebound of steel fiber relative to the other shotcrete materials. Henager (1) has reviewed the issue of rebound of SFRS at some length.

MIX DESIGN AND MATERIALS

Normal Type I portland cement has been used in most SFRS applications, although Type III high early strength cements have been used in tunnels and marine structures where high early strength development was important to resist the effects of blasting or wave action at an early age; Type V sulfate-resisting cements have been used in sulfate bearing soil or groundwater conditions.

Cement contents as batched have ranged from 390 kg/m^3 (658 lb/yd^3: the US 7 bag mix) to as much as 558 kg/m^3 (940 yd^3: the US 10 bag mix) in certain mortar mixes. Typical shotcrete mixes incorporating a 10-mm (0.375-in.) maximum size aggregate used in SFRS projects in British Columbia have contained 445 kg/m^3 (750 lb/yd^3: the US 8 bag mix) cement. It should be recognized that the cement content of the in situ shotcrete will always be higher than the as-batched cement content because of the higher degree of rebound of coarse aggregate and sand particles than cement. This is particularly true of shotcrete placed by the dry-mix process, shotcrete placed in thin layers [25 mm (1 in.) or less] and shotcrete sprayed overhead.

The American Concrete Institute (ACI) Standard Specification for Materials, Proportioning and Application of Shotcrete (8) lists three desirable combined aggregate gradation limits for shotcrete aggregates (see Table 2.2.1). Gradation No. 3 refers to a 20-mm (0.75-in.) maximum size aggregate gradation; this is seldom used in steel fiber shotcrete. Gradation No. 2 refers to a 10-mm (0.375-in.) maximum size aggregate gradation as shown in Figure 1. This is the gradation envelope most commonly used in SFRS projects in British Columbia. Generally, mixes are proportioned to the finer side of the gradation envelope for overhead applications (e.g., soffits of beams and slabs, arches and crowns of tunnels); to the middle of the gradation envelope for vertical applications (e.g., walls and columns); and to the coarser side of the gradation envelope for downward applications (e.g., canal linings, rock slopes, tunnel inverts).

The American Concrete Institute (ACI) Gradation No. 1 refers to a mortar mix containing no coarse aggregate. Mortar mixes have been successfully used in steel fiber shotcrete projects, but tend to require higher cement contents for equivalent strength performance because of the higher water demand of the mix (particularly in wet-mix shotcrete applications). These mixes tend to have higher porosity than mixes containing coarse aggregate as measured by boiled absorption and air voids (9). This is because of the higher water/cement ratio of the mix, as well as the reduced energy of consolidation compared to that imparted by coarse aggregate particles. Also, mortar mixes have a greater creep and shrinkage potential.

Most SFRS used in British Columbia has contained concrete sand and between 20 and 35 percent by mass of the total combined aggregates of 10- to 5-mm (0.357-in. to No. 4) coarse aggregate. Such aggregate would generally conform to the ACI Gradation No. 2 requirements. One commonly used premixed dry process SFRS mix is comprised of the following proportions by mass for a nominal cubic meter of shotcrete:

Mix	Kilograms	Pounds
Portland Cement, Type I	445	979
10-mm (0.375-in.) coarse aggregate	526	1,157.2
5-mm (No. 4) fine aggregate	1230	2,706
30 x 0.5-mm hooked-end steel fiber	59	129.8

Shotcrete accelerators are generally not required in SFRS and should only be used with extreme caution. Accelerators may be used in special circumstances (e.g., where shotcrete is subjected to blast vibrations, wave action, or traffic at an early age) but they should be free of corrosion-inducing chemicals such as chlorides, fluorides, sulfites, sulfides, and nitrates that could promote corrosion of the steel fibers.

BATCHING, MIXING, AND PLACING

There are two basic methods of applying SFRS: the dry process and the wet process. In the dry process, batching and mixing can be done in a variety of different ways. The cement, damp sand, and coarse aggregate can be mixed in a ready-mix concrete truck with the discrete steel fibers then being added to the truck. Alternatively, the shotcrete materials can be mixed in a central mix plant or mobile site

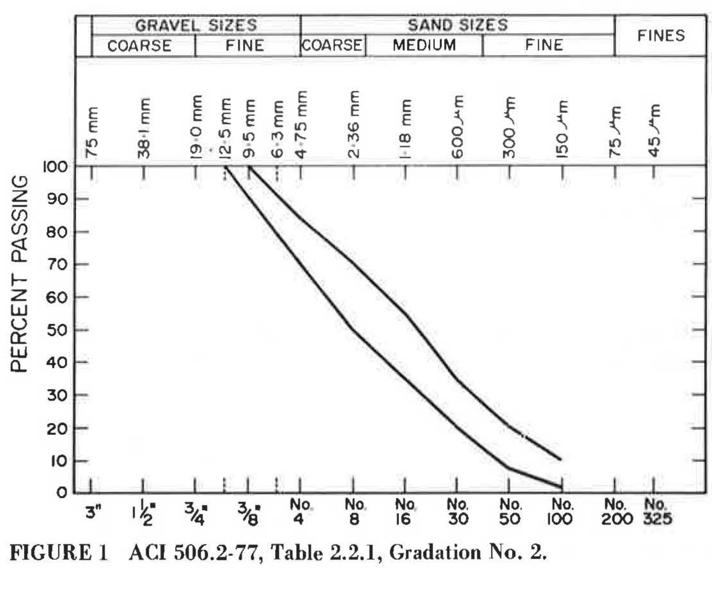

FIGURE 1 ACI 506.2-77, Table 2.2.1, Gradation No. 2.

batch plant (1,6). A variety of different techniques has been developed for adding the fibers. These include dispensing the fibers through a shaker or vibrating screen such that clusters of fiber are not dispensed into the shotcrete materials. Fibers have been discharged onto conveyor belts and fed in with the aggregates or added through special fiber dispensers (1,6).

The most widely used system in British Columbia, however, has been prebagged SFRS. The cement, completely dry aggregates, and steel fiber are weighed, batched, and mixed in a dry bag plant and then discharged into paper bags or bulk synthetic cloth bags. Paper bags have generally been supplied in 23-kg (50-lb) or 40-kg (88-lb) sizes. Bulk bin bags have been supplied with masses varying from 1134 kg (2,500 lb) to 1814 kg (4,000 lb). The dry materials are then discharged into a premoisturizer in which water is added to bring the moisture content of the SFRS into a 3 to 6 percent-by-mass range before discharge into the shotcrete pot.

Bulk bin bags have the advantage of requiring very little manpower; once supported above the premoisturizer hopper, they are essentially self-discharging. Bags with bottom opening spouts are also returnable. In mining and remote tunneling operations, however, it has generally been found more economical to use single-use bulk bin bags; the rate of attrition on supposedly returnable bags is high.

In volume placements of 10 m^3/hr (13 yd^3/hr) or more, it is generally more economical to use ready-mix or site-batched shotcrete. In the small volume and intermittent placement often encountered in rehabilitation of concrete structures, it is often more economical to use prebagged SFRS supply. Prebagged material is also technically preferable from a set-time-control perspective because the time of contact between cement and moisture before discharge into the shotcrete pot is kept to a minimum. Schutz (10) has shown that the set-time of shotcrete mixtures is markedly affected by the time of prehydration of the cement before shooting. For example, in plain shotcrete, he found that a 15-min prehydration period delayed final set of shotcrete by 2.5 hr. The effect was even more pronounced in shotcrete containing accelerators as shown in Figure 2.

Conventional dry process shotcrete equipment has been successfully used to place SFRS. Henager (1) lists various types that have been used for this purpose. Much of the SFRS placement in British Columbia has been carried out using the Meynadier Meyco GM-57 or 60 or Reed Guncrete shotcrete pots. Some contractors have reported a greater rate of wear with the rubber hoses used to convey the shotcrete to the discharge nozzle in the steel fiber shotcrete mixes, compared with plain shotcrete; other than some minor adjustments to wearing plate tolerances, no special procedures are needed to shoot SFRS.

In wet process shotcrete, procedures for batching and mixing SFRS are essentially the same as those used for steel fiber-reinforced concrete (SFRC). Good guidance for batching and mixing SFRC is given in the ACI State-of-the-Art Report on Fiber Reinforced Concrete (11). Henager also gives details of procedures for batching and mixing wet process SFRS as well as information concerning equipment used for placing the material (1). Use of the wet process for applying SFRC in British Columbia has been limited to the rehabilitation of deteriorated concrete bridge abutments.

PHYSICAL PROPERTIES

Plain unreinforced shotcrete, like unreinforced concrete, is a brittle material with little capacity to resist pronounced tensile stresses or strains without cracking and disruption. Steel fibers are incorporated in shotcrete to improve the ductility, energy absorption, fatigue, and impact resistance characteristics of the plain material. Steel fibers perform this role in shotcrete by controlling cracking and holding the material together, even after extensive cracking has occurred. The ability of steel fibers to improve these characteristics of shotcrete is well-demonstrated in studies by Morgan (5,9) and Ramakrishnan (7).

Compressive Strength

As a generalization, the compressive strength of SFRS is governed by the compressive strength of the shotcrete matrix. Increases in compressive strength attributable to the incorporation of fibers are generally small (6,7,9). The useful characteristics of fibers in compression are really only evident in a complete stress-strain curve. The descending portion of the post-peak stress-strain curve is much flatter, characterizing a more ductile material, which is useful in preventing sudden and explosive failure under static loading and in absorbing energy under dynamic loading.

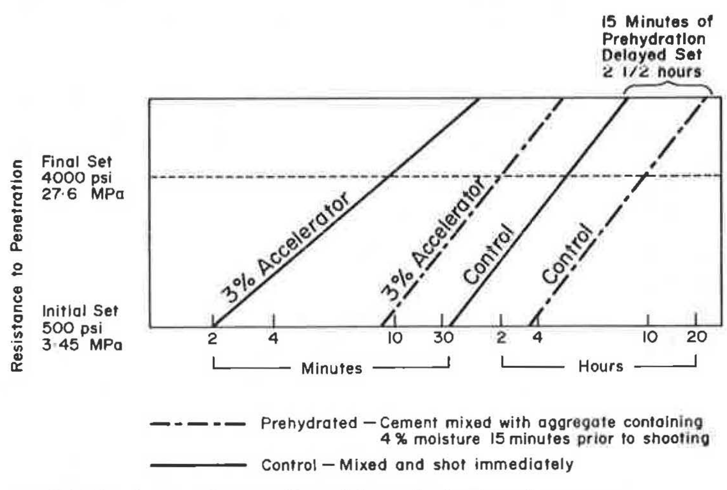

FIGURE 2 Setting time as affected by prehydration; dry process shotcrete (ASTM C403), (*12*).

The compressive strength of well-designed and applied SFRS mixes will usually be in excess of 35 MPa (5,000 psi) at 28 days. The results of tests on 75-mm (3-in.) diameter x 100-mm (4-in.) long cores extracted from SFRS test panels on a British Columbia tunneling project over a 3-month period are given in Table 1. The 28-day compressive strength averaged 43.1 MPa (6,250 psi). The mix contained 445 kg/m³ (750 lb/yd³) cement and 0.75 percent-by-volume of a 30-mm (1.2-in.) long x 0.50-mm (0.02-in.) diameter hooked-end steel fiber.

TABLE 1 Compressive Strength Results for 75 mm Diameter Cores from SFRS Test Panels

Date Yr-Mo-Day	Compressive Strength, MPa 7 Days a	b	Avg.	28 Days a	b	Avg.
82-12-07	26.2	26.2	26.2	37.3	36.5	36.9
82-12-07	43.3	43.1	43.2	52.1	50.2	51.2
82-12-07	44.2	41.6	42.9	46.2	44.0	45.1
83-02-03	30.9	32.8	31.9	45.5	42.8	44.1
83-02-14	44.9	31.4	38.2	42.2	35.0	38.6
83-02-15	34.3	38.1	36.2	44.7	43.8	44.3
83-02-17	31.1	34.2	32.6	43.2	42.2	42.7
83-02-22	31.4	37.1	34.3	45.7	36.4	41.1
83-02-23	42.2	47.2	44.7	45.0	45.0	45.0
83-02-26	36.7	38.7	37.7	47.6	46.6	47.1
83-02-26	41.2	40.0	40.6	43.8	41.9	42.9
83-03-01	39.9	37.7	38.8	45.4	44.9	45.2
83-03-04	29.5	31.5	30.5	39.3	37.4	38.4
83-03-07	31.4	35.2	33.3	44.7	42.8	43.7
83-03-07	29.6	30.5	30.1	47.6	35.9	41.8
83-03-11	39.0	42.8	40.9	42.8	40.5	41.6
Average			36.4			43.1

Flexural Strength

Placement of shotcrete tends to orient the fibers in a plane parallel to the surface being shot. This orientation is beneficial to the properties of the shotcrete layer, particularly when thin sections are being applied. The flexural strength increases with increasing volume concentration and aspect ratio of fibers. This aspect is well demonstrated in studies by Ramakrishnan (7). Two values of flexural strength are generally reported: the first crack flexural strength (the point at which the load versus deformation curve departs from linearity) and the ultimate flexural strength (point of maximum load). For low aspect ratio or low-volume concentrations of fiber, these two strength values may be the same; that is, there may be no increase in strength after the first crack, as shown in Figure 3.

Values of flexural strength for well-designed and applied steel fiber shotcrete mixes are generally in the range of 4.5 to 7.5 MPa (650 to 1,090 psi) at 28 days with values of 6 MPa (870 psi) being commonly achieved (7,9).

Toughness

The addition of steel fibers simply to increase flexural strength is not a good reason for using steel fibers in shotcrete; simple increases in flexural strength alone can be more economically achieved by increasing the strength of the shotcrete matrix (e.g., by the use of higher cement contents). The main reason for adding steel fibers is to increase the toughness of the shotcrete. Toughness may be defined as the work required to cause a specified deformation in a shotcrete beam tested under static flexural loading. The ACI 544 Committee (13) has developed a definition for toughness for flexural testing of 100 x 100 x 355-mm (4 x 4 x 14-in.) beams defined as follows:

Toughness Index = [Area under load-deflection curve to 1.9 mm (0.975 in.) center point deflection]/[Area under load-deflection curve to first crack].

For plain shotcrete, which sustains no post-first-crack load, this value is 1.0. The toughness index of SFRS increases with increasing volume concentration and aspect ratio of fiber. The toughness index is also affected by the aggregate size, tending to decrease as the maximum aggregate size is increased. This is a good reason to avoid using aggregate larger than 10 mm (0.375 in.) in SFRS.

Typical toughness index values for SFRS reported in the literature (5,9) range from about 4 to 10, depending on the volume concentration of fiber and maximum aggregate size, as given in Table 2. Note that the much higher values for toughness index (range of 4 to 23.5) reported by Ramakrishnan (7)

TABLE 2 Toughness Index for SFRS at 28 days (*11*)

Mix No.	Description	Toughness Index
A	Plain control	1.0
B	0.5 percent fiber	3.7
C	1.0 percent fiber	5.9
D	1.5 percent fiber	6.7
E	Sanded, 1.0 percent fiber	10.8

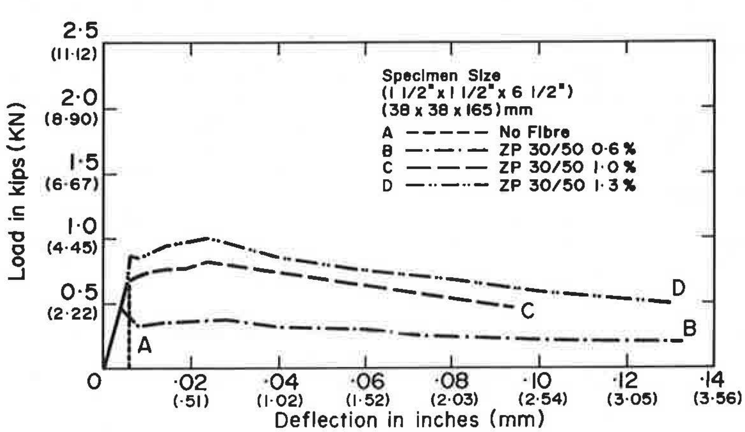

FIGURE 3 Load-deflection curves for static loading at 28 days (*2*).

were based on a different definition than that developed by the ACI 544 Committee (3).

The real benefits of incorporating steel fiber in shotcrete are well-illustrated by this parameter. The substantial load-carrying capacity of SFRS, even after the development of substantial cracking and deformation, gives a good indication of the energy absorbing and ductile characteristics of this material.

Impact Resistance

Some of the earliest SFRS experiments involved the construction of inflated domes for protection of military personnel from exploding missiles and projectiles. In these studies, the excellent impact resistance of SFRS was recognized. The ACI 544 Committee (13) has developed a test procedure for measuring impact resistance. It involves dropping a 4.54-kg (10-lb) hammer 457 mm (18 in.) onto a 64-mm (2.5-in.) diameter ball that rests on a 152-mm (6-in.) diameter by 64-mm (2.5-in.) high shotcrete core. The number of blows to first crack, as well as the number of blows to cause disruption of the specimen are measured. Although the test is basically empirical and the test results do have a high coefficient of variation, it does give a useful indication of the benefits the incorporation of steel fiber has on the impact resistance of shotcrete. Typical test results recorded by Morgan (9) are given in Table 3.

TABLE 3 Impact Resistance of SFRC (*11*)

		Impact Resistance			
		7 Days		28 Days	
Mix No.	Description	Blows to First Crack	Blows to Failure	Blows to First Crack	Blows to Failure
A	Plain control	20	22	39	41
B	0.5 percent fiber	30	68	119	140
C	1.0 percent fiber	66	112	111	211
D	1.5 percent fiber	141	237	218	280
E	Sanded, 1.0 percent fiber	110	223	117	291

Fatigue Strength

There are no reported studies in the literature of the performance of SFRS under fatigue loading conditions. It is reasonable, however, to assume that performance would be similar to that attained in SFRC with similar volume concentrations of fiber. The ACI State-of-the-Art Report on Fiber-Reinforced Concrete (11) has reviewed the results of fatigue testing on SFRC beams. They report that the addition of fibers increases fatigue life and decreases the crack width under fatigue loading. It has also been shown (11) that the fatigue strength of conventionally reinforced beams made with fibrous concrete increases and the resulting deflection caused by fatigue decreases. These are attractive considerations for the use of SFRC for rehabilitation of structures subjected to repetitive flexural loading, such as bridge decks and girders and beams supporting traveling cranes.

Johnston (2) has shown that the greater fatigue endurance of SFRC has resulted in greatly increased pavement life or has alternatively permitted the use of substantially reduced pavement thickness in design of road and airfield pavements and bridge deck overlays. Thickness reductions on the order of 30 to 50 percent or more have been achieved in numerous projects. Morgan (12) has reviewed the performance of SFRC overlays placed on some 20 different bridges in the United States between 1972 and 1983. The major- ity of these overlays were placed to rehabilitate existing deteriorated bridge decks. Nearly all of them have displayed excellent fatigue endurance, with much reduced cracking relative to conventional plain concrete overlays.

Bond Strength

There is little quantitative data in the literature concerning the bond strength of SFRS. Published data (6) indicate that bond strengths in the range of 0.9 to 3.7 MPa (135 to 540 psi) are achievable with SFRS, with the actual bond strength obtained being highly dependent on the condition of the substrate to which the shotcrete is applied. Bond strengths in excess of 1 MPa (145 psi) could reasonably be expected on properly prepared concrete surfaces. Field experience indicates that bond strength is likely to be significantly greater for shotcrete (either plain or SFRS) than for conventional concrete cast up against a surface. Excellent bond has been found in shotcrete applied to surfaces as varied as clay brick masonry, formed concrete, and a wide variety of rock types in tunneling projects.

Durability

The durability of SFRC is governed by the same factors that influence the durability of conventionally reinforced shotcrete or concrete. As long as the matrix retains its inherent alkalinity and remains uncracked, there is no durability problem. It has been shown (2,11) that even when the exposure conditions cause reduced alkalinity, for example, air pollution, de-icing salts, or a marine atmosphere, only the outer 1 to 2 mm (0.04 to 0.08 in.) or so of a good quality, impermeable SFRC are affected over a period of many years. Fibers in the immediate surface layer could rapidly corrode and disappear, but the interior fibers remain totally protected, provided the concrete or shotcrete remains uncracked.

In the event of cracking, the fibers would be exposed to corrosive influences. How long the fibers remain capable of effectively restricting the widening of a crack depends on the crack width, the severity of the corrosive environment, and the type and diameter of fiber used. Some studies have shown (2) that if the crack widths remain in the range of 0.03 to 0.08 mm (0.001 to 0.003 in.) carbon steel fibers will not oxidize even after several years of exposure. Other studies have shown (2) that although corrosion takes place in a moist marine environment when crack widths are in the range of 0.10 to 0.30 mm (0.004 to 0.012 in.), much of the composite strength may be retained because the fibers can tolerate a considerable reduction in diameter by corrosion before failing and permitting unrestricted crack opening. In severe exposure conditions, stainless steel or other nonrusting types of fiber can be used.

In shotcrete applications where surface rusting and staining is aesthetically undesirable, a thin coating of plain shotcrete applied monolithically on top of the SFRS can solve the problem. This procedure has been used with good success in British Columbia in stabilization of rock slopes and embankments adjacent to highways. In pavements and hydraulic structures, any corroded surface fibers are rapidly worn off by traffic or water flow.

SFRC is considered particularly useful for waterfront marine structures, which must have resistance

to deterioration at the air-water interface and resist impact loadings. SFRC or SFRS is particularly attractive for construction and rehabilitation of nominally reinforced marine structures such as dolosse, surge breakers, and sewer outfall pipe coatings. These elements have apparently displayed superior performance to conventionally reinforced structures in that there appears to be no mechanism with discreet fibers in a concrete matrix to support the macrocell galvanic corrosion processes that develop in conventional reinforced concrete or shotcrete.

APPLICATION

SFRS has been used in recent years in various innovative types of new construction. It has been used to construct dome and barrel-vault structures, using a process in which an inflated membrane is sprayed with a polyurethane foam that creates the form for application of SFRS. These self-supporting structures have been used for farm storage sheds, commercial offices, industrial warehouses, residential complexes, and military hardened shelters (11).

SFRC has been used to rehabilitate many concrete structures such as bridge decks (12), airfield and road pavements (2), industrial floors, and marine and hydraulic structures (1,2,11). There has been relatively little reported use of SFRS for rehabilitation of concrete structures, however.

Henager (1) reported that SFRS was used to strengthen brick arches under three bridges for British Rail in England. In Sweden, a lighthouse damaged by freeze-thaw conditions was repaired by SFRS, as was the interior of a 50-m (150-ft) tall concrete chimney (1). Reported uses in Australia include repair of an eroded roof in a concrete bunker used for absorbing energy from impacting projectiles, relining a steel bin used for aggregate storage, and lining curved sections of a stormwater drain.

Clearly, there are many concrete structures where SFRS provides a viable alternative to conventional rehabilitation procedures. It is suggested that SFRS may provide an economical and technically viable alternative to conventional rehabilitation procedures in the following situations:

1. Where the use of mesh-reinforced shotcrete was the proposed remedial procedure.
2. Where repair of corrosion induced spalling is required; for example, in bridge deck soffits, girders, and abutments.
3. Repair of impact damage and corrosion-induced spalls in marine structures such as surge breakers, jetties, sea walls, dolosse, and piles.
4. Rehabilitation of deteriorated tank linings, drains, trenches, and electrolytic cell tops in the aggressive chemical environments encountered in the chemical and pulp and paper industries. In such situations, special corrosion-resistant fibers and chemically resistant cements may be required (e.g., stainless steel fiber and Type V sulfate-resisting cement).
5. Refractory shotcrete repair; special SFRS mixes have been used in construction and repair of refractories. Information is contained in a paper by Glassgold (14).

In summary, although there has been relatively little use of SFRS to date for rehabilitation of concrete structures, it is clear that the material has many attributes that make it attractive as an alternative to conventional rehabilitation procedures. SFRS mix design, batching, mixing, and placing has now become routine, and there is sufficient long-term case history performance in a wide variety of applications so that user confidence can be assured. Its potential for use in the rehabilitation of concrete structures is limited only by economic considerations and the imagination of the rehabilitation engineer or contractor.

CONCLUSIONS

Since its first applications in North America in the early 1970s, SFRS has passed from the realm of a new, relatively untried material to one that has achieved considerable success in a variety of applications simply because, despite certain recognized limitations, it can offer both technical and economic advantages over conventional alternatives.

Most SFRS applications have, however, been in either new construction or lining rock slopes and underground openings in mines and tunnels. There has been, to date, relatively little use of this innovative material for rehabilitation of existing concrete structures.

Also reviewed are the physical attributes of SFRS (such as improved flexural strength, toughness, impact and crack resistance, fatigue strength, and durability), which make it attractive as a rehabilitation material.

Current uses of SFRS are summarized and potential applications for rehabilitation of existing concrete structures are presented. These include repair of corrosion and impact-damaged structures such as bridge deck soffits, girders, and abutments and marine structures such as surge breakers, jetties, sea walls, dolosse, and piles. The potential for use of special chemically resistant cements and fibers for rehabilitation of deteriorated structures in the chemical and pulp and paper industries is also discussed. It is suggested that SFRS has many attributes that make it attractive as an alternative to conventional rehabilitation procedures.

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Properties of Latex-Modified Shotcrete Beneficial to Concrete Repairs

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ABSTRACT

The inclusion of a latex into a shotcrete mix imparts a new set of mechanical properties to shotcrete and enhances the benefits of shotcrete when used for the repair of concrete. The effects of the polymer binder on the shotcrete matrix are discussed and then related to the mechanical properties of latex-modified shotcrete. The mechanical properties of latex-modified shotcrete are presented along with a discussion of how they benefit the repair of concrete structures that have experienced corrosion or freeze-thaw damage, particularly in environments subject to chloride exposure. The application of latex-modified shotcrete is discussed and guidelines are provided for preparing the mix proportions and specifications.

Latex-modified shotcrete refers to the inclusion of a latex into a conventional shotcrete mixture of portland cement and aggregate that is conveyed through a hose and pneumatically projected, at high velocity, onto a surface (1). A latex is a form of polymer system, and it generally consists of a water emulsion of a synthetic plastic or natural rubber (2). The most commonly used latex for shotcrete applications utilizes a styrene-butadiene polymer that is the same polymer system used for latex-modified concrete bridge deck overlays. The inclusion of a latex into a shotcrete mixture results in the development of a polymer binder throughout the shotcrete matrix, which imparts a new set of mechanical properties to the shotcrete.

The mechanical properties of the latex-modified shotcrete system are the result of the individual and combined effects of the cement and polymer binders. The proper interaction of these two binders is essential in obtaining the benefits of the latex-modified shotcrete (LMS); this interaction is dependent on the mix proportions and the development of bonds between the binders as the material cures.

The cement in LMS will hydrate and cure in the same manner as in conventional shotcrete and the polymer particles bond to each other as the latex emulsion dries. Bond development between the polymer and cement, however, is dependent on the chemical reactions that take place during the hydration of the cement.

The bond between the polymer and cement appears to occur in the early stages of the cement hydration process with the polymer bonding through the calcium ions present in the cement (3). Once this bond is developed, it is strong and irreversible. As the cement hydration process continues, the polymers will coalesce and bond to form a continuous polymer film. This film formation is the result of loss of water from the latex emulsion, either to evaporation or to the cement hydration, after which the polymer particles are forced together, either by the growth of the cement hydrate or by capillary action created by the water loss. In order to obtain the benefits of LMS, it is important that sufficient polymer particles be present in the mix to develop a continuous polymer film throughout the shotcrete matrix.

As the LMS begins to dry, the cement paste will shrink and microscopic cracks will develop throughout the shotcrete matrix. The polymer binder is capable of undergoing strain and can bridge these cracks and restrain their propagation. The high bond strength of the polymers to the cement paste allows the polymer to sustain the tensile stresses resulting from the restraint of the microscopic cracking and results in an increased tensile capability for