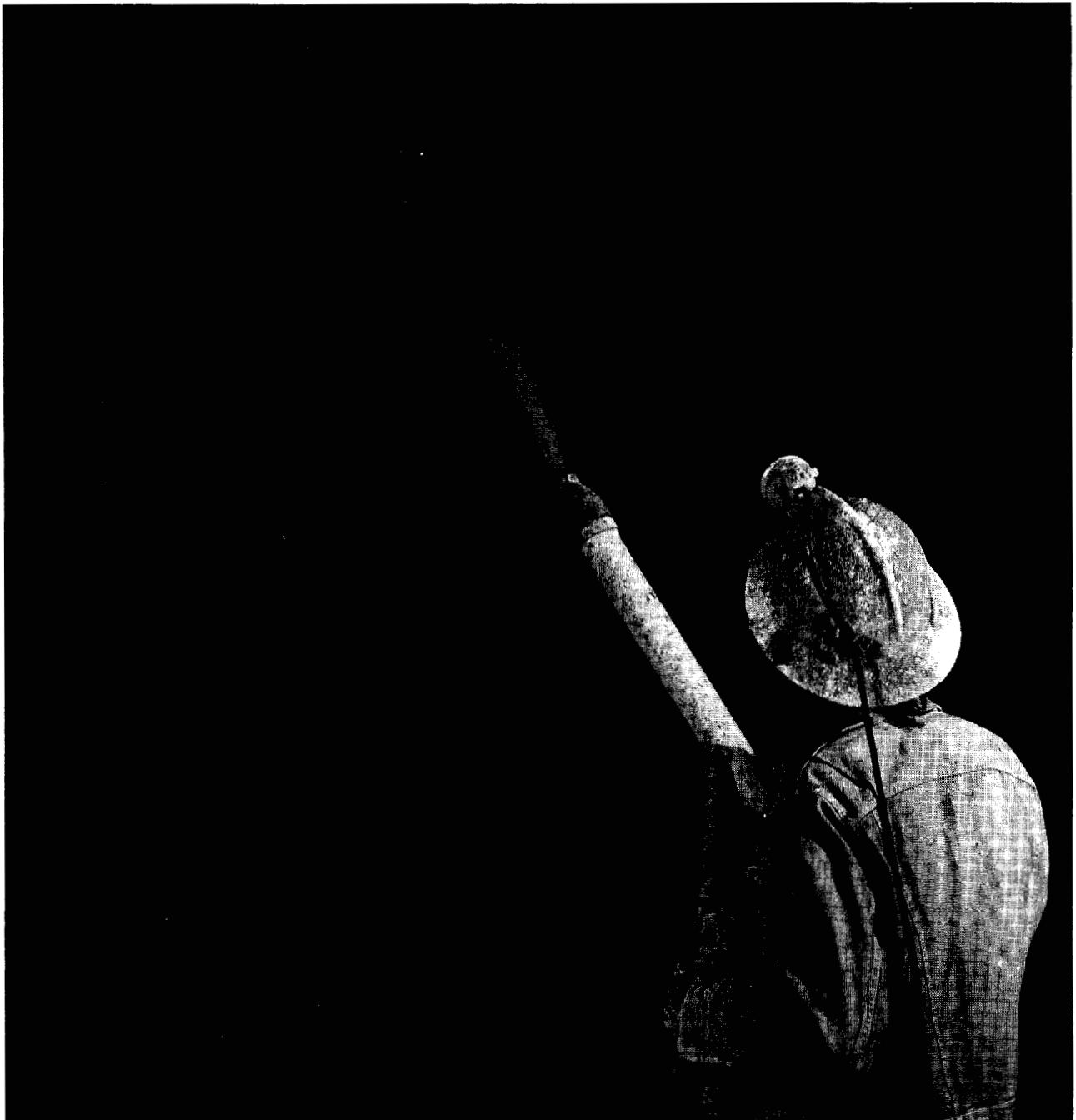


SHOTCRETE



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Preface

ACI Compilations combine material previously published in Institute periodicals to provide compact and ready reference on specific topics. The material in a compilation does not necessarily represent the opinion of an ACI technical committee — only the opinions of the individual authors. However, the information presented here is considered to be a valuable resource for readers interested in the subject.

Steven H. Gebler
Chairman, ACI Committee 506
Shotcreting



American Concrete Institute, Box 19150, Redford Station, Detroit, MI 48219



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Point of View

Is $0.85 f'_c$ Valid for Shotcrete?

by Steven Gebler and Ray Schuttz

For at least 13 years, ACI 506.2-77, "Specification for Materials, Proportioning, and Application of Shotcrete,"¹ has permitted an average compressive strength reduction to $0.85 f'_c$ for cores obtained from daily test panels or from the structure. On the surface, this strength reduction appears consistent with ACI 318-89, "Building Code Requirements for Reinforced Concrete."² ACI 318 has permitted the 85 percent rule for many years. Currently, ACI 318-89, Chapter 5, under Paragraph 5.6.4.4, states:

Concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores is equal to at least 85 percent of f'_c . . .

We do not take exception to this rule and, as correctly pointed out in the Commentary of ACI 318, the following is noted:

It should be noted that core tests having an average of 85 percent of the specified strength are entirely realistic. To expect core tests to be equal to f'_c is not realistic, since differences in size of specimens, conditions of obtaining samples, and procedures for curing, do not permit equal values to be obtained.

We take no exception with the reasons set forth in the commentary and wholly support these reasons since they are supported by considerable work conducted by early researchers. However, we do intend to examine the validity of applying the 85 percent rule for shotcrete. As you can see from the tone of the previous sentence, the authors are not in favor of allowing the 85 percent rule for shotcrete and recommend that no compressive strength reduction be permitted for shotcrete.

To present the case against the 85 percent rule for shotcrete, we shall first examine a few basic concepts and discuss some points contained in ACI 318 and ACI 506.2-77.

ACI 318-89

Specified compressive strength of concrete is denoted by f'_c . Paragraph 5.1.2 requires that f'_c shall be based

on tests of cylinders made and tested as prescribed in Paragraph 5.6.2. Further, Paragraph 5.1.3 requires that f'_c be based on 28-day tests unless otherwise noted on drawings and specifications. Typically, most agencies, authorities, and laboratories use 6 in. (152 mm) diameter by 12 in. (305 mm) long molded cylindrical specimens to determine the compressive strength of concrete.

Paragraphs 5.6.2.1 and 5.6.2.2 further state that compressive strength specimens shall be obtained in accordance to ASTM C 172, "Method of Sampling Freshly Mixed Concrete," molded and tested in accordance with ASTM C 31, "Practice for Making and Curing Concrete Test Specimens in the Field," and ASTM C 39, "Test Method for Compressive Strength of Cylindrical Concrete Specimens," respectively. We have previously stated the requirements for when low cylinder compressive strengths are obtained (see Paragraph 5.6.4).

To reiterate, drilled cores are generally the primary method for acceptance. The basic reasons for allowing the 85 percent compressive strength reduction is due to coring stresses and differences in curing and size of specimen. In addition, one must remember that these differences are relative to 6 x 12 in. (152 x 305 mm) cylinders that are molded and cured in the standard manner. As previously stated, this 85 percent compressive strength reduction is reasonable and well supported in the literature.

POINT OF VIEW

This article was selected for reader interest by the editors; however, the opinions expressed by the author are not necessarily those of the American Concrete Institute. The editors invite comments from our readers about the personal views given in this article.

ACI 506.2-77

First, we need to establish how f'_c is determined for shotcrete. The following appears under Paragraph 2.5, Proportioning:

Select shotcrete proportions to produce the specified compressive strength of the shotcrete, f'_c , for each portion of the work as designated in the contract documents. Proportions shall be selected on the basis of compressive strength tests of specimens continuously moist cured until testing at 28 days or different test age if so specified. These specimens shall be cut from the shotcrete test panels not earlier than 5 days after shotcreting. For mix acceptance purposes, average core strengths shall be at least equal to f'_c for cores with L/D of 2.0.

As presented in Paragraph 2.5, f'_c is based on cores obtained from test panels and cores must attain the specified strength for acceptance prior to shotcreting.

Under Paragraph 1.6, Quality assurance, specimens for examination and testing prior to construction are required (see Paragraph 1.6.4, Preconstruction testing). Paragraph 1.6.4.2 states:

Make a test panel at least 30 x 30 in. (762 x 762 mm) for each mix being considered, and for each shooting position to be encountered in the job (i.e., slab, vertical and overhead sections). Provide the same reinforcement as in the structure in at least half of the panel to test for proper embedment of reinforcing steel. Fabricate test panels to the same thickness as the structure, but not less than 3 in. (76 mm). Take at least five cubes or cores from panels for testing as per paragraph 1.6.3.

Paragraph 1.6.3, Construction testing, essentially requires that cores be obtained from the structure or daily test panels, Paragraph 1.6.3.1 and 1.6.3.2. Now comes the issue at hand. Paragraph 1.6.3.3 states:

The average compressive strength of three cores taken from the structure or test panel, representing a shift or 50 cu yd (38 m³) of shotcrete, must equal or exceed 0.85 f'_c with no individual core less than 0.75 f'_c .

This paragraph clearly permits, without question, the 85 percent compressive strength reduction rule, which is consistent with ACI 318-89.

As we have previously noted, the reasons for allowing the 85 percent rule are differences in conditions of obtaining samples, i.e., coring, size of specimen, and curing. In conventional concrete construction, these differences are relative to 6 x 12 in. (152 x 305 mm) molded cylinders used for daily testing, but in shotcrete, cores, not 6 x 12 in. (152 x 305 mm) molded cylinders, are the reference. Paragraphs 2.5 and 1.6.4.2 use test panels from which cores are obtained to establish f'_c and do not permit the 85 percent compressive strength reduction factor.

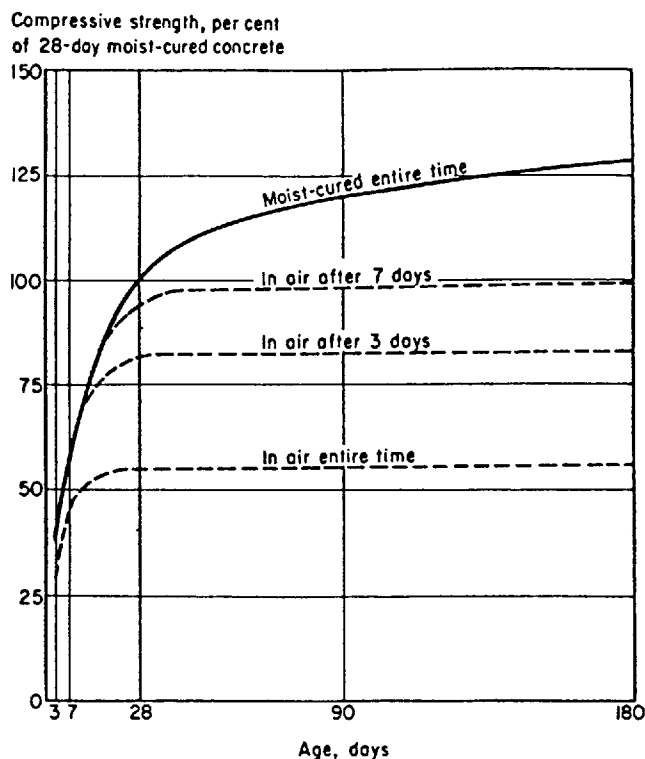


Fig. 1 — Compressive strength of concrete dried in laboratory air after preliminary moist curing.³

What is puzzling is why the 85 percent rule is allowed for construction testing, when the size of the cores and the method of obtaining and testing the cores are the same as used for initial proportioning and acceptance testing of the shotcrete. Therefore, the only difference in the reference cores to the structure cores is curing; and this is a minor difference. Paragraph 2.5 requires 28 days of moist curing and in the structure the cores obtained may not get the same curing treatment. One can not expect the 85 percent compressive strength reduction factor to be accounted for only in curing.

Inspection of Fig. 1 (reproduced from ACI 306R-88,³ Fig. 6.5) shows at 28 days only a 5 percent difference between "moist-cured entire time" versus "in air after 7 days." Cores obtained from a structure after 28 days do not cease curing or development of strength. Specimens "in air after 7 days" are considerably more adversely affected with regard to strength development than those obtained after 28 days from the cured structure, which still continues curing. Therefore, the 5 percent difference should realistically be only 2 or 3 percent.

Then why does ACI 506.2-77 allow a 15 percent (85 percent rule) strength reduction for cores obtained from the structure. At best, a 2 to 3 percent reduction would seem reasonable (but this is certainly within testing error) and possibly justified, but there are no sound engineering reasons to allow the 15 percent difference.

Furthermore, there is no published literature dealing with shotcrete to justify this strength reduction. Some may argue that this 85 percent permit rule has worked for over 20 years, so why rock the boat. It seems that without any satisfactory technical support or published

literature to support it, the 85 percent compressive strength reduction factor for shotcrete is inappropriate. Further, on behalf of the owners of structures allowing the 85 percent rule, it is not conservative.

Recommendations

In conventional concrete, a drilled core is compared to a molded standard cylinder and the conditions and limitations presented here for allowing the 85 percent compressive strength reduction are valid. In shotcrete, a drilled core is compared to a similar drilled core and the facts presented here definitely show that the 85 percent rule is unjustified.

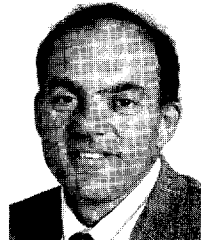
Therefore, since there is no engineering reason or published literature to support the 85 percent rule for shotcrete, we recommend that construction specifications should not permit the 85 percent compressive strength reduction factor for shotcrete.

References

1. ACI Committee 506, "Specification for Materials, Proportioning, and Application of Shotcrete (ACI 506.2-77) (Revised 1983)," American Concrete Institute Detroit, Michigan, 1983, 8 pp.
2. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-89)," American Concrete Institute, Detroit, Michigan 1989, 353 pp.

3. ACI Committee 306, "Cold Weather Concreting," (ACI 306-88), American Concrete Institute, Detroit, Michigan, 1988, 23 pp.

ACI fellow **Steven Gebler** is principal evaluation engineer at the Construction Technology Laboratories, Inc., Skokie, Ill., where he has been involved in various phases of concrete materials research, concrete construction related issues, durability and performance of concrete structures, and pipeline-related problems. He is an ASME/ACI 359 Level III Concrete Inspector and a member of many ACI committees. He is currently chairman of ACI Committee 506, Shotcreting.



ACI fellow **Raymond J. Schutz** is a materials consultant in Waupun, Wis., and has numerous publications to his credit, including three on shotcrete. He has shotcrete experience as a contractor and as a researcher in both Europe and North America. He is currently chairman of ACI Committee 503, Adhesives, a member of ACI Committees 506, Shotcrete, and 212, Chemical Admixtures. He is a past member of ACI Board of Direction and of several ACI committees.



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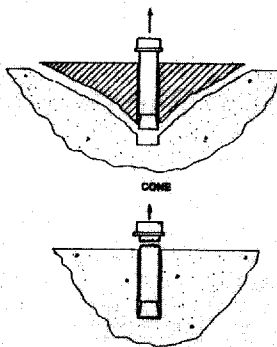
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Shotcrete and $0.85f'_c$

Mr. Gebler and Mr. Schutz in *Concrete International*, September 1990 issue, pp. 67-69, bring up an issue which has been debated extensively within ACI Committee 506. From the prospective of the shotcrete contractor, the $0.85f'_c$ factor is extremely important.

Due in a large extent to the work of Committee 506, shotcrete construction is inspected and tested far more frequently and extensively than cast-in-place concrete. In many cases, shotcrete is used as an alternate method of application to cast-in-place concrete. Generally speaking, cast-in-place concrete material is tested but the application or placement is not tested. The testing methods used for shotcrete test both the material and the placement. We use the same measuring stick, f'_c , for both cast-in-place and shotcrete, yet the cast-in-place tests only material while the shotcrete both material and placement. In my opinion, the 0.85 factor effectively deals with the differences in testing, curing, coring, and others. To eliminate this factor would be very unfair. The owner should feel as confident in the 0.85 factor for shotcrete as he/she is in the results of cylinder tests for cast-in-place.

In the particular case of wet mix shotcrete, Committee 506 should explore the use of the standard cast-in-place testing methods in lieu of sample panels or in-place testing. The process is basically the same as cast-in-place and the act of placing the shotcrete does not change the material properties significantly.

It is my opinion that $0.85 f'_c$ as applied to cores taken from test panels or in-place work is fair to the contractor and conservative for the owner. An owner should feel as confident in his/her structure based on the 0.85 factor for shotcrete as they would be based on results of cylinder tests for cast-in-place concrete.

Larry Totten
(member of Committee 506)
Johnson Western Gunit Co.
San Leandro, Calif.

Owners, specification writers, and consumers are interested in the product that they buy as well as its cost. They want confidence that the product meets the structural and other requirements. Concrete strength is represented by an arbitrary definition: 28 day moist cured, 6 by 12 in. cylinders. When these cylinders are broken in a compressive strength testing machine, they give numbers that are higher than actual site drilled cores for several reasons: 1) their larger size, 2) better curing, and 3) lack

of microcracks from the coring operation. When shotcrete is tested, the above factors do not apply, except for the better curing, which is offset by the greater age of the site drilled cores. The 0.85 factor is based on valid engineering data for concrete, but not for shotcrete test cores which are of equivalent size and equally affected by the coring operation.

...shotcrete tests represent both the material and the placement. This is quite valid as concrete placement does not substantially affect the in-place material properties, whereas with shotcrete the nozzleman's expertise is critical to obtaining the desired strength and physical properties. The owner and consumer must be guaranteed that the end product meets the necessary design requirements.

...the use of test cylinders for wet mix shotcrete is of interest and bears further research.

...Committee 506 is well balanced to represent owners, contractors, manufacturers, and researchers. Due to the work of this committee, the use of shotcrete has and will continue to increase.

Paul Carter
Bridge engineering branch
Alberta Transportation and Utilities
Edmonton, Alberta, Canada

(Editor's note: In regard to this same article, a lengthy letter was also received from a Seattle, Wash., reader. Excerpts from this letter are published below.)

...

...I've seen a lot of structural shotcrete used in Seattle, particularly in the past 10 years, and it is clear to me that shotcrete and traditionally cast-in-place and mechanically consolidated concrete are not the same product. It's not a fair assessment of shotcrete's abilities to measure it with the same stick we use to measure cast-in-place concrete.

...If I could influence Committee 506 to address issues, I would...(ask them)...to give us a core area in square inches and relate that to a square inch area of reinforcing steel cut by the core drill. Then we could relate our cores to...sample cores regardless of differences in sizes of cores and bars. Also, don't ask us to accept a porous area extending for more than a few inches along any bar.

...the 0.85 factor reduction for cores from cast-in-place concrete is not valid because we do not cast 6 by 12 in. cylinders from shotcrete to compare with

the cores. I'm sure someone will suggest we simplify the whole process by just taking 6 by 12 in. cylinders from the back of the truck instead of taking cores for shotcrete...Cores are a reasonable and a necessary method of sampling shotcrete for strength tests...the 0.85 factor reduction is not logical or reasonable.

...I very much believe in the integrity of structural shotcrete when applied by a competent nozzleman and when supported by a quality control team that includes the design professionals, concrete supplier, inspection agency, and building official. I sincerely hope that owners and developers of the future have the option of choosing to use shotcrete on their projects. Maintaining a good reputation for shotcrete will guarantee it.

Michal Rosencrans
Department of Construction and
Land Use
City of Seattle
Seattle, Wash.

Authors' reply

The authors wish to thank Messrs. Totten, Carter, and Rosencrans for their comments. We will address only the comments concerning the paper...published in the September 1990 issue...

Messrs. Carter and Rosencrans basically agree with the conclusions of our paper, and the authors thank them for submitting their comments. Mr. Totten disagrees with the authors, stating in his letter: "In my opinion, the 0.85 factor effectively deals with the differences in testing, curing, coring, and others."

This statement is incorrect. As stated in the paper, one can mold a cylinder and obtain a core from the same batch of conventional concrete. Many researchers have done this and established the 0.85 factor for cores. With shotcrete, one cannot adequately mold a cylinder; therefore, one can not determine a factor for the ratio of core to molded cylinder strength. The control for shotcrete is a drilled core which received the same "abuse" as the drilled core test specimen.

Mr. Rosencrans agrees with the authors in his statement: "Strength of shotcrete — the $0.85f'_c$ reduction for cores from cast-in-place concrete is not valid because we do not cast 6 by 12 in. cylinders from shotcrete to compare with the cores."

Mr. Carter also states: "The 0.85 factor is based on valid engineering data for concrete, but not for shotcrete test



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cores which are equivalent size and equally affected by the coring operation."

The authors also disagree with Mr. Totten's remarks in regard to wet process shotcrete. Mr. Totten states: "The process is basically the same as cast-in-place, and the act of placing the shotcrete does not change the material properties significantly." Wet process shotcrete involves pumping a complete concrete of mortar mixture; all the ingredients, including water, are mixed before introduction into the hose. Compressed air is introduced to the material flow at the nozzle, ACI 506R-90. The *ACI Manual of Concrete Inspection*, Chapter 19, states: "When concrete is placed by methods such as

pumping which may significantly affect the concrete characteristics..." ACI 304.2R relating to pumping concrete, states: "The quality of the concrete in the structure can only be measured at the placement end of the line."

Pumping does affect the properties of concrete or mortar. But with the wet process shotcrete, the mixture is not only pumped but completely broken up with injected air at the nozzle and "projected at high velocity onto a surface," (ACI 506R-90), further changing the properties. Obtaining a sample of the mixture before pumping and injection of air at the nozzle can be very misleading. Such a procedure will only indicate what the concrete supplier delivered, not what the owner received in

his structure!

Shotcrete, both wet and dry process, has a long history of use. Shotcrete can be strong, durable, and can stand on its own reputation. To continually compare shotcrete to conventional concrete is an "apple/orange" situation and does not help the shotcrete industry.

Steven H. Gebler
Construction Technology Laboratories,
Inc.
Skokie, Ill.
and
Raymond J. Schutz
Waupun, Wis.

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SHOTCRETE

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Steel Fiber Reinforced Shotcrete for Support of Underground Openings in Canada

by Dudley R. Morgan

The concept of support of underground openings with shotcrete is not new. As early as the 1930s Rabcewicz in Iran and Europe began using shotcrete for tunnel support, leading eventually to the development of the New Austrian Tunnelling Method (NATM). Rabcewicz and his colleagues used shotcrete in conjunction with rock bolts to produce a "rock arch" concept for tunnel support. The prime conceived purpose for the shotcrete was to prevent rock from ravelling between

rock bolts.¹ This simple rock support concept has since undergone considerable refinement. Sophisticated rock-mechanics approaches are now being applied to design and installation of shotcrete support systems in underground openings.

History

Prior to the 1970s shotcrete used in underground openings was either applied plain, or it was reinforced with reinforcing steel, wire mesh, or chain link mesh. In the early 1970s the Battelle Memorial Institute's

Columbus laboratories made the first application of steel fiber reinforced shotcrete (SFRS) in North America. The first use of SFRS in a tunnel in North America was in 1972 when the U.S. Army Corps of Engineers placed SFRS in an adit at the Ririe Dam. The first experimental use of SFRS in Canada was carried out in 1977.² Further experimental evaluation was conducted by Morgan et al in 1979³ to compare the performance of mesh and steel fiber reinforced shotcrete. This led to the first practical application of SFRS technology in Canada, for stabilization of a sloughing 100 m (109 yd) long railway embankment in Burnaby, B.C. in 1979. This was closely followed by the use of SFRS to rehabilitate deteriorating rock tunnels on the Canadian Pacific Railway Fraser Canyon line.⁴

SFRS has since enjoyed widespread usage in Canada. Hundreds of thousands of tons of the material have been used in dozens of different construction, infrastructure rehabilitation, tunnelling, mining, railway, and highway projects. Some 20 different projects in Canada that have used SFRS for underground support are listed in Reference 5. Rose¹ provides a review of the state-of-the-art of the use of SFRS for tunnel linings in North America. A more general overview of the state-of-the-art for SFRS world-wide, up to 1985, is provided in the US/Sweden joint seminar paper by Ramakrishnan.⁶ Additional information is provided in ACI

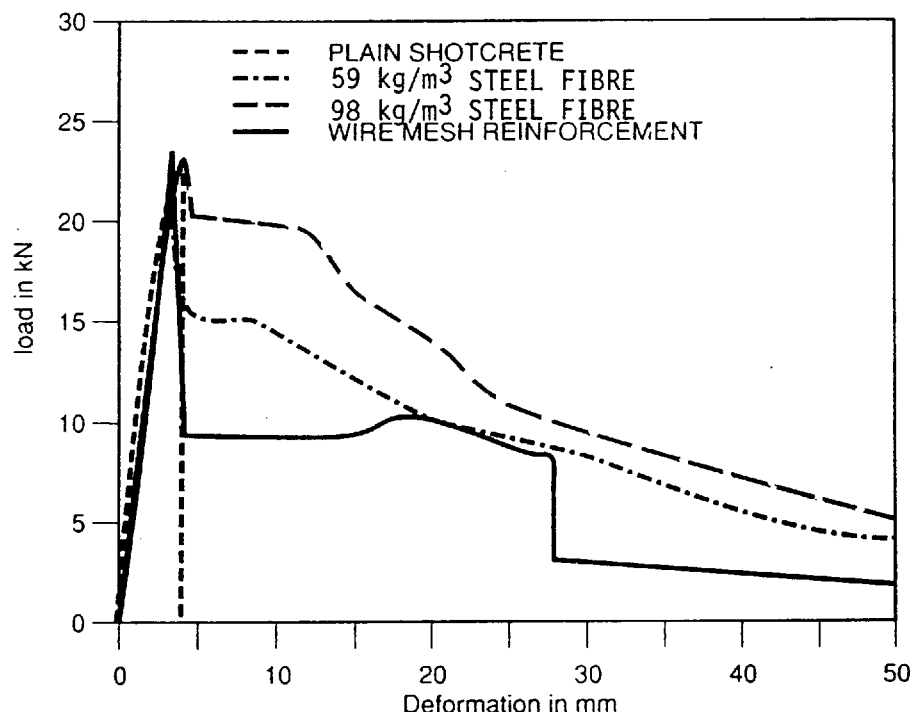


Fig. 1 — Comparison of load carrying capacity of plain, wire mesh reinforced, and steel fiber reinforced shotcretes.

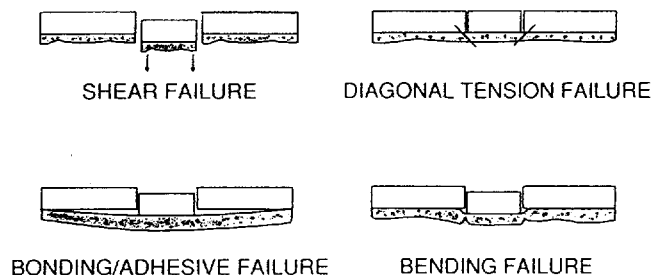


Fig. 2 — Shotcrete failure modes in simulated falling block test.

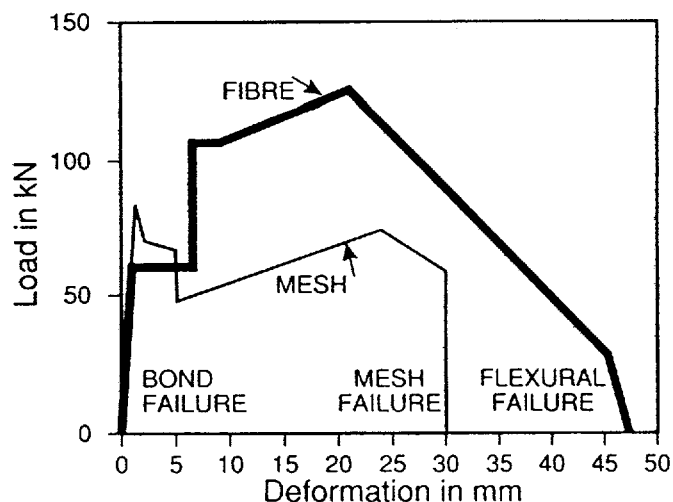


Fig. 3 — Load versus deformation behavior of wire mesh and steel fiber reinforced shotcrete in a falling block test.

506.1R-84, "State-of-the-Art Report on Fiber Reinforced Shotcrete."⁷

Why use SFRS?

Plain, unreinforced shotcrete, like unreinforced concrete, is a relatively brittle material with little capacity to resist pronounced tensile stresses or strains without cracking and disruption. Steel fibers are incorporated in the shotcrete to improve its crack resistance, ductility, energy absorption, and impact resistance. Properly designed SFRS can reduce or even eliminate the cracking that is a common cause for concern in plain shotcrete.

Mesh versus steel fibers

The question is often asked: "How does SFRS perform compared to mesh reinforced shotcrete in conditions of loading that might be experienced in applications such as support of rock slopes or underground openings?" Some limited studies at the University of Illinois and some early Scandinavian research indicated favourable performance by SFRS. In 1979 Morgan and Mowat³ undertook a detailed comparative evaluation of plain, mesh and steel fiber reinforced shotcrete. The results of part of this study are illustrated in Fig. 1. They demonstrated in load/deformation tests on large panels, that SFRS can provide superior residual load carrying capacity to wire mesh reinforced shotcrete at small deformations after first crack and equivalent perform-

ance at large deformations. These conclusions were subsequently supported by the results of similar work carried out by Little⁸ for the British Columbia Hydro and Power Authority.

Since these early studies, extensive research has been conducted in the Scandinavian countries¹⁰ comparing the performance of SFRS and mesh reinforced shotcrete under simulated "falling block" tests. This test simulates the condition where a shotcrete lining is subjected to loading from loosening blocks of rock in the crown of a tunnel. Shotcrete failure occurs through one or more of the failure modes illustrated in Fig. 2, the particular mode depending on a variety of factors, including shotcrete strength and thickness, quality of bond to the substrate, and size of the displaced block. SFRS has generally shown superior performance to mesh reinforced shotcrete in such tests. Load versus deformation response in a typical falling block test is shown in Fig. 3 from Reference 9.

Advantages of SFRS

One of the factors that makes SFRS particularly appealing to contractors is the ability to do away with the need to install wire mesh, which can be a time consuming and sometimes hazardous process. Another advantage is that SFRS can follow the exact contours of the rock, whereas mesh reinforcement often requires 50 mm (2 in.) of cover as well as filling of all the voids behind the mesh with shotcrete (Fig.

4). It is not uncommon with blocky or fractured rock surfaces to use up to 40 percent more shotcrete with mesh reinforcement than if SFRS were used.

SFRS is also free of the difficulties sometimes encountered in thoroughly encapsulating reinforcing mesh with shotcrete. Improper shooting technique can result in "shadowing" and voids behind reinforcing mesh. Such mesh reinforced shotcrete is vulnerable to the deteriorating influences of corrosion from aggressive atmospheric or groundwater exposure. "Ice-jacking" in cold weather exposure, such as is frequently encountered in tunnel and mine portal areas in Canada, is another cause of concern with improperly encapsulated mesh reinforced shotcrete. Properly applied SFRS should be free of these concerns.

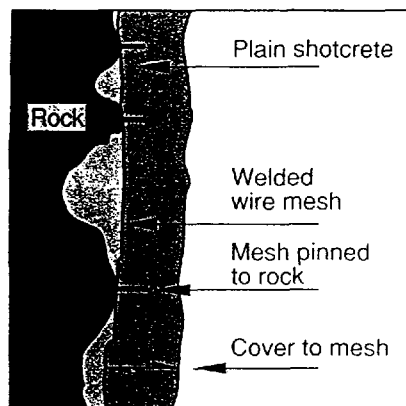
Fiber types

There are a variety of proprietary types of steel fiber available in the North American market. A variety of processes are used for manufacturing steel fibers, including:

- cutting cold drawn wire
- slitting steel sheet
- the melt-extraction process
- milling steel blocks

The most useful parameter for describing fibers is the aspect ratio, which is defined as the length-equivalent diameter ratio. The most important aspects controlling the performance of steel fiber in shotcrete (and concrete) are the aspect

MESH REINFORCED SHOTCRETE



STEEL FIBRE REINFORCED SHOTCRETE

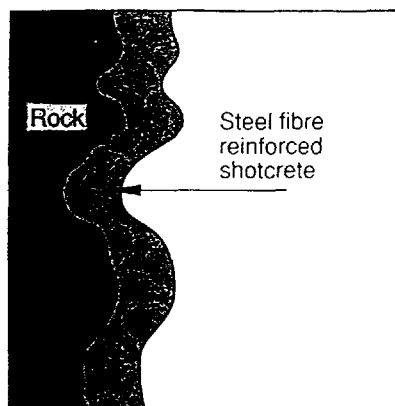


Fig. 4 — Difference in shotcrete consumption between wire mesh and steel fiber reinforced shotcrete applied to blasted rock.

ratio and volume concentration. Theoretically, the higher the aspect ratio and volume concentration of the fiber, the better the performance of the SFRS with respect to impact resistance, toughness, ductility, crack resistance, etc. Unfortunately, the higher the aspect ratio and volume concentration of the fiber, the more difficult the shotcrete becomes to mix, convey, and shoot. Thus there are practical limits to the amount of fiber that can be used in SFRS, with the amount varying with different proprietary fiber types.

In the 1970s, a wide variety of different fiber types were promoted, with fiber sizes varying from 12 x 0.25 mm ($\frac{1}{2}$ x 0.010 in.) and an aspect ratio of 50, to 64 x 0.76 mm ($2\frac{1}{2}$ x 0.030 in.) and an aspect ratio of 83. Most of these fibers were straight, and post-first-crack performance (as measured by the toughness test) was less than impressive. Manufacturers then devised a variety of means of improving the "effective aspect ratio" of steel fibers by techniques such as:

- crimping the fibers
- introducing bent or enlarged ends
- making special deformations on the fibers
- increasing roughness of the fiber surface texture

In the 1980s virtually no straight steel fibers were used in SFRS in Canada. The most commonly used fibers are deformed in one way or another and have typical fiber lengths of 30 to 38 mm ($1\frac{1}{4}$ to $1\frac{1}{2}$ in.) and aspect ratios varying from 40 to 60. Typical fiber addition

rates vary between 50 and 80 kg/m³ (85 and 135 lb/yd³), with 60 kg/m³ (100 lb/yd³) being commonly used in tunnelling and mining applications.¹⁰

Shotcrete mix proportioning

Shotcrete mix proportioning is governed by the same principles that govern concrete mix proportioning (i.e., Abrams' law applies and the prime factors controlling strength and quality are the water-cement ratio, air content, and degree of consolidation achieved). There are, however, a number of considerations in mix proportioning in which shotcrete differs from conventional structural concrete, the major differences being in the aggregate gradation and cementitious content.

ACI 506R-90¹¹ provides guidance for selecting aggregate gradations for both wet and dry-mix shotcrete (Table 1). Gradation No. 1 is essentially a mortar mix, whereas shotcrete with aggregate conforming to Gradation No. 2 typically contains about 25 to 30 percent 10 mm ($\frac{3}{8}$ in.) coarse aggregate. Gradation No. 3 contains 20 mm ($\frac{3}{4}$ in.) maximum size aggregate and produces shotcrete that is more like conventional concrete. ACI Gradation No. 1 shotcrete (mortar mix) tends to be preferred in certain parts of North America, particularly in the Southern U.S.A. The use of mortar mixes tends to be historical, relating to the original use of mortar in the Guniting process. In Western Canada, and increasingly elsewhere in North America, for both dry and wet-mix shotcrete, the great major-

ity of engineered shotcrete construction is being performed with shotcrete conforming to ACI Gradation No. 2. ACI Gradation No. 3 shotcrete is rarely used except for mass shotcrete applications such as construction of underground bulkheads.

Fortunately, no special changes need to be made to conventional shotcrete mix proportions to utilize steel fiber. The same characteristics that are inherent in shotcrete mix proportioning (low coarse aggregate content and high cementitious materials content) are also conducive to good mixing and dispersion of fibers and indeed application and performance of the hardened SFRS. The only areas in which the shotcrete mix proportioner can really get into difficulty are: where attempts are made to cut back excessively on the cementitious content of the mix; this can lead to high total rebound, as well as excessive fiber rebound, particularly in the dry-mix process; and where fibers are used that are vulnerable to the formation of "birds nests" or balling in shotcrete mixing, transporting, and application procedures (e.g., fibers with too high an aspect ratio; too high a volume concentration of fibers; first generation straight fibers without a proper means of dispensing the fiber).

A summary of mix proportioning concepts is presented in Table 2.⁵ Typical examples of both wet and dry-mix SFRS mix proportions, such as commonly used in tunnelling and mining projects in Canada in the 1980s, are shown in Table 3.

Water reducing admixtures and superplasticizers are not normally used in dry-mix shotcrete because they cannot be effectively activated in the short wetting time from mixing at the nozzle to impact on the wall. In fact, the addition of dry powdered superplasticizer can have disastrous consequences for dry mix shotcrete — it can create a delayed

Table 1 — Gradation limits for combined aggregates.¹¹

Sieve Size U.S. standard square mesh	Percent by weight passing individual sieves		
	Gradation No. 1	Gradation No. 2	Gradation No. 3
¾ in. (19 mm)	—	—	100
½ in. (12 mm)	—	100	80 - 95
¾ in. (10 mm)	100	90 - 100	70 - 90
No. 4 (4.75 mm)	95 - 100	70 - 85	50 - 70
No. 8 (2.4 mm)	80 - 100	50 - 70	35 - 55
No. 16 (1.2 mm)	50 - 85	35 - 55	20 - 40
No. 30 (600 µm)	25 - 60	20 - 35	10 - 30
No. 50 (300 µm)	10 - 30	8 - 20	5 - 17
No. 100 (150 µm)	2 - 10	2 - 10	2 - 10

fluidity, causing the plastic in-place shotcrete to sag and slough. However, water reducers and superplasticizers are commonly used in high quality wet-mix SFRS. Air-entraining agents should be used in wet-mix shotcrete that will be subjected to freeze-thaw exposure, and there is some evidence (based on recent work at Laval University in Quebec) that the addition of an air-entraining agent to the mix water added at the nozzle is beneficial for the freeze-thaw durability of dry-mix shotcrete (particularly where de-icing chemicals are used).

SFRS batching, mixing, and supply

Dry-mix SFRS can be batched, mixed, and supplied by any of the following processes:

- Central mixing in a rotary drum or pan mixer prior to discharge into a transit mixer, Moran car, conveyor belt, or other means of feeding the shotcrete gun.
- Transit mixing, with the fibers added directly into the ready mix truck together with the materials feed, or separately with special fiber feeders.
- Volumetric site batching with steel fibers added at the mixing auger with special fiber dispensers.
- Dry bagged premix with the steel fibers and any other special materials (dust suppressants, silica fume, dry powdered accelerators, etc.) in the bag.

Care has to be taken in dispensing the fibers to ensure that clusters or balls of fiber are not added to the mix, as these can be difficult to disperse and give rise to blockages in the gun and the formation of birds nests in the in-place shotcrete.

In Western Canada there has been some limited dry-mix transit mix SFRS batching, mixing, and supply, but most dry-mix SFRS has been supplied as dry bag premix. SFRS has typically been supplied in

Table 2 — Summary of mix proportioning concepts.

Material/Property	Comments
Cement content	18 to 21% by mass of dry component.
Silica fume	8 to 13% by mass of cement.
Aggregate gradation	ACI 506R-90, Table 2.1, Gradation No. 1, or (more commonly) No. 2.
Steel fiber type	High strength, deformed, drawn, or slit sheet steel fibre.
Aspect ratio	Length: Equivalent diameter ratio of 50-70.
Steel fiber addition rate	50-80 kg/m ³ (85-135 lb/yd ³) depending on required toughness.
Admixtures	1. Water reducers used in wet-mix shotcretes at about 0.5 l/100 kg cement (8 fl.oz/100 lb cement). 2. Superplasticizers required in wet-mix silica fume shotcrete at 1 to 1.5 l/100 kg cement (16 to 24 fl.oz/100 lb cement). 3. Air entraining admixtures used in wet-mix shotcrete where freeze-thaw durability important (10 to 12% air content at pump, 4 to 6% air content as-shot).
Accelerator	Dosage depends on accelerator type and required setting time (2 to 5% by mass of cement typical).
Water-cement ratio	0.3 to 0.4 for dry-mix shotcrete. 0.4 to 0.5 for wet-mix shotcrete.
Slump	40 to 100 mm (1½ to 4 in.) for wet-mix shotcrete.

30 kg (66 lb) paper bags on pallets, or in 1600 kg (3520 lb) bulk bin bags.

Wet-mix SFRS can be batched, mixed, and supplied by essentially the same processes suitable for supply of conventional concrete (i.e. it can be central-mixed or transit-mixed, or volume-batched on site using mobile mixer units or other suitable equipment). The bulk of wet-mix SFRS used in Canada has been either central or transit-mixed, with the steel fibers being added either at the batch plant during charging of the other ingredients or separately to the transit mixer at the job site.

Unlike some of the earlier generation straight fiber types (particu-

larly those with higher aspect ratios) that could be quite difficult to disperse, most current generation deformed fibers are designed so that they can be added directly to the back of a transit mixer at the job site and thoroughly dispersed without balling.

Particular care has to be taken when adding steel fibers to avoid the temptation to excessively retemper the shotcrete with water. SFRS will appear much stiffer than conventional plain shotcrete and will show much lower slump after fiber addition when tested using the standard slump test. But visual appearance and the slump test are not good indicators of the true workability of SFRS — mixes that appear stiff and have low slump can be

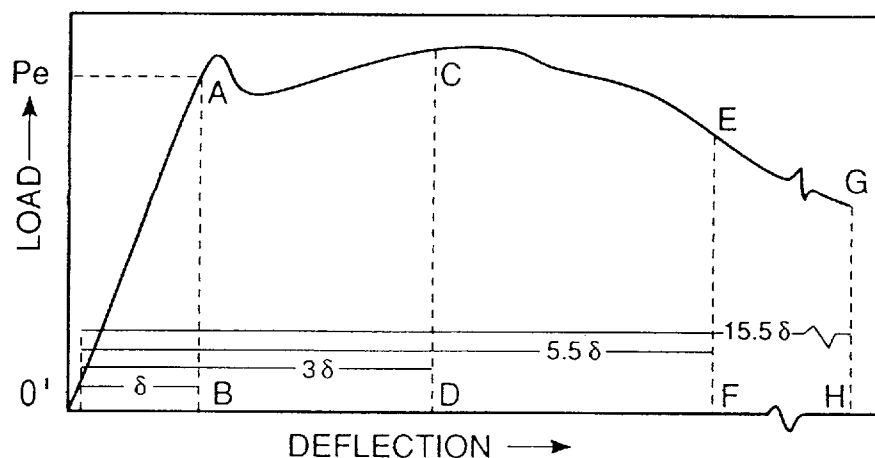


Fig. 5 — ASTM C 1018 load versus deflection curve from which toughness index values are calculated.

can still pump and shoot well. Excessive retempering with water should be avoided as it can result in segregation and fiber balling and a reduction in quality of the hardened SFRS.

Shotcrete application

Dry-mix SFRS has been applied using most of the shotcrete guns commonly available in North America, with very little need for any special equipment modifications. Some contractors have reported greater rates of wear in certain types of shotcrete equipment with rubber wearing pads when using mixes containing steel fiber. This problem can, however, be mitigated by the use of tougher wearing pads and, more importantly, careful control over tolerance of setting of the wearing pads in the gun. Some contractors have also reported greater rates of wear in hoses and nozzles when using SFRS mixes, but this is generally not considered a major concern. Sharp bends in hoses should, of course, be avoided.

When using dry-bagged premix SFRS it is recommended that the contractor use a premoisturizer to dampen the shotcrete to a "dry-earth" consistency (3 to 6 percent moisture content) prior to discharge into the shotcrete gun. Premoisturizing provides the following advantages over using bone-dry material:

- It facilitates more efficient and uniform wetting of the mix at the nozzle.
- It helps to reduce overall and fiber rebound and produce a more

consistent quality product.

- It significantly reduces the amount of dust generated in the shooting process.

Dry-bagged premix SFRS has been applied in some projects without a premoisturizer, but this is generally not recommended, particularly when working in underground openings or confined spaces where air quality is of concern.

Wet-mix SFRS can be readily applied by most of the common shotcrete pumps routinely used in North America with little, if any, equipment modification being required. Even the small ball seat type pumps normally used for pumping small maximum size aggregate 10 mm ($\frac{3}{8}$ in.) topping and infill masonry block grouting mixes have been used. In fact, the addition of fibers to the mix has been found to be beneficial in certain pumping circumstances where difficulties may be experienced in pumping plain shotcrete or concrete (e.g., in pumping downhill, the presence of fiber has been found to reduce the potential for "plug flow" and associated pumping difficulties).

Wet-mix SFRS generally shoots and adheres best when applied at slumps in the 40 to 80 mm ($1\frac{1}{2}$ to 3 in.) slump range. Lower slump material can be applied, but normally only by using the more powerful larger diameter 150 mm (6 in.) piston type pumps. Slumps in excess of 100 mm (4 in.) are generally not recommended, as the shotcrete will have a tendency to slough. As a general rule of thumb, lower slump mixes should be used when:

- shooting vertical and overhead surfaces
- shooting thicker sections
- bench gunning (shooting at a 45 degree angle to build a thick shotcrete wall or column).

Rebound

Rebound is defined as the material that ricochets off the receiving surface and falls to the ground during shotcrete application. Rebound is characteristically low in wet-mix SFRS — values in the range of 5 to 10 percent are commonly recorded, both in research and development studies¹⁰ and in field applications. Rebound is much higher with dry-mix SFRS — values of 20 to 35 percent have been reported in vertical applications and 30 to 50 percent in overhead applications.¹⁰

With wet-mix shotcrete, nearly all the steel fiber in the as-batched shotcrete ends up in the in-place shotcrete, since the total rebound is so low. But this is not true of the dry-mix shotcrete process. When the dry-mix shotcrete stream first impinges on the rock surface, nearly all the coarse aggregate and a significant amount of steel fiber rebound, and this continues until a sufficient thickness of mortar has built up to enable bedding in of the impinging coarse aggregate and steel fibers.

As the shotcrete layer thickens, less coarse aggregate and fiber rebounds. Thus it has been found that in-place fiber retention is least in thin (50 mm [2 in.] or less) shotcrete layers. In 100 mm (4 in.) thick shotcrete layers, for as-batched fiber contents of 60 kg/m³ (100 lb/yd³), in-place fiber contents have been found to range from 35 to 45 kg/m³ (60 to 75 lb/yd³)¹⁰, with the lower values typically being recorded in SFRS applied to overhead surfaces. Even lower values of in-place fiber retention have been reported in some field analyses of rebound.⁸

Table 3 — Typical SFRS mix proportions.

Material	Dry-mix shotcrete		Wet-mix shotcrete	
	kg/m ³	lb/yd ³	kg/m ³	lb/yd ³
Cement	400	674	420	708
Silica fume	50	84	40	67
10 mm coarse aggregate	500	843	480	809
Concrete sand	1170	1972	1120	1888
Steel fibres	60	101	60	101
Water reducer	—	—	2 L	52 fl.oz.
Superplasticizer	—	—	6 L	156 fl.oz.
Air entraining agent	—	—	if required	if required
Water	*170	*287	180	303
Total wet mass	2350	3961	2300	3876
Total water from premoisturizer and added at nozzle (based on saturated surface dry aggregate concept).				

There are a large number of factors that influence the final in place fiber content, including:

- the thickness of the shotcrete layer (fiber rebound is higher in thin shotcrete layers)
- overall rebound (the higher the overall rebound the lower the in place steel fiber content)
- the nature of the substrate to which shotcrete is being applied (fiber rebound tends to be higher in shotcrete applied to blocky, fractured rock than in bored tunnels)
- aggregate gradation (coarser aggregate gradations can increase fiber and overall rebound)
- consistency (degree of wetness) of the applied shotcrete (fiber rebound and overall rebound is higher in mixes shot too dry)
- shooting technique, including air pressure and shooting distance and nozzle orientation to the receiving surface.

Optimization of all these factors is important in minimizing fiber and overall rebound.

Properties of hardened SFRS

Toughness index

As previously mentioned, the main reason for incorporating steel fibers in shotcrete is to impart some ductility to an otherwise relatively brittle material. Steel fiber reinforcement improves the energy absorption, impact resistance, and crack resistance of shotcrete. Addition of steel fibers enables the shotcrete to continue to carry load after cracking. A variety of tests have been developed to measure and quantify the improvements achievable in steel fiber reinforced concrete and shotcrete.¹⁶

Perhaps the most useful of these tests is the ASTM C 1018, "Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Load-

Table 4 — Performance levels defined in ASTM C 1116-89.

Performance level	Toughness index I_5		Toughness index I_{10}	
	Specified value	Test result	Specified value	Test result
I	2.7	3.0	5.4	6.0
II	3.6	4.0	7.2	8.0
III	4.5	5.0	9.0	10.0
IV	5.4	6.0	10.8	12.0

ing)." This test has been used in Canada in both research and development studies and in specifications and contract documents on a number of large civil engineering construction projects as a means of differentiating between the merits of different steel fiber types and fiber addition rates, and as a quality control procedure for checking the quality of shotcrete construction, particularly with respect to the uniformity of steel fiber distribution.

In this test a beam, typically 75 x 75 x 355 mm (3 x 3 x 14 in.) (although other sizes may be used) is cut from a shotcrete test panel. (For shotcrete it is recommended that the width and depth of the cut beam be the same as the applied shotcrete thickness). This beam is then subjected to third point loading in flexure and a load versus deformation curve is plotted. The important characteristics of the load versus deformation curve are shown in Fig. 5 from the ASTM C 1018 Standard. The toughness indexes are defined as follows:

Toughness Index I_5

$$= \text{Area } 0'ACD \div \text{Area } 0'AB$$

Toughness Index I_{10}

$$= \text{Area } 0'AEF \div \text{Area } 0'AB$$

Toughness Index I_{30}

$$= \text{Area } 0'AGH \div \text{Area } 0'AB$$

For a hypothetical SFRS mix with fully plastic deformation response

after first crack (i.e. ability to continue to deform, without either losing or increasing in load) the I_5 , I_{10} , and I_{30} toughness index values would be 5, 10, and 30, respectively. A plain shotcrete would fall apart after reaching first crack and thus by definition have a toughness index $I_5 = 1.0$. This test procedure provides the engineer with a means of simply visualizing a graphical plot.

The ASTM C 1116-89 "Standard Specification for Fiber Reinforced Concrete and Shotcrete" provides a guide to various levels of performance that can be specified for various types of fiber mixes. Specifically it defines four performance levels, as shown in Table 4.

Various toughness index values have been specified for steel fiber reinforced shotcretes for tunnelling contracts. Some projects have specified $I_5 = 3.5$ and $I_{10} = 5.0$. Others have specified $I_5 = 4.0$ and $I_{10} = 6.0$ (i.e., values generally intermediate between the ASTM Performance Levels I and III). Designers should examine their specific project requirements before selecting a Performance Level. It should be cautioned that the Performance Level III or above is not normally achievable with the fiber types and addition rates currently being used in practical shotcrete.

Table 5 — Typical SFRS performance specifications.

Property	Test method	Minimum requirements	
Accelerated setting time Initial set Final set	ASTM C-403	10 minutes 30 minutes	
Compressive strength	ASTM C-42	MPa	psi
8 hour (accelerated)		5	725
1 day		10	1450
7 days		30	4350
28 days		40	5800
Flexural strength	ASTM C78	MPa	psi
7 days		4	580
28 days		6	870
Toughness index	ASTM C-1018		
I_1		3.5	
I_{10}		5.0	
I_{30}		14.0	
Boiled absorption Volume of permeable voids	ASTM C-642	8% Maximum 17% Maximum	

also be cautioned that the results obtained in ASTM C 1018 test are highly sensitive to the accuracy of the deflection measuring system. Toughness testing should only be conducted by qualified testing laboratories, familiar with all the intricacies of the ASTM C 1018 test procedure.

Finally, it should be noted that the I_1 toughness index alone does not adequately characterize fiber reinforced shotcrete. Current thinking is that for most SFRS support of underground openings applications it would be more useful to specify suitable I_{10} , I_{20} and I_{30} toughness index limits. Research is currently being conducted by a number of agencies to determine practically achievable values for I_{10} , I_{20} and I_{30} toughness indices for a variety of steel fiber types and addition rates in both wet and dry-mix shotcretes.

SFRS compressive and flexural strength

Compressive strength is little influenced by steel fiber addition at the fiber addition rates commonly used in SFRS (i.e., 60 to 80 kg/m³ [100 to 135 lb/yd³]). Compressive strength is mainly controlled by the shotcrete matrix design. If higher compressive strengths are required, then the addition of silica fume can be beneficial. This is particularly true of wet-mix shotcrete where compressive strengths in excess of 100 MPa (14,500 psi) can be produced, using appropriate combinations of water reducers, superplasticizers, and silica fume.

Flexural strength increases with increasing aspect ratio and volume concentration of steel fibers. However, the improvements in flexural strength attributable to steel fiber addition are fairly small for the fiber types and addition rates commonly used in SFRS. High flexural strengths, if required, can be much more readily and economically produced by increasing the matrix flex-

ural strength through the use of materials such as silica fume and superplasticizers.

In summary, the simple improvement of compressive and/or flexural strength alone is not a good reason for adding steel fibers to a shotcrete mix. It also follows that the specification and use of compressive and flexural strength testing in isolation (without toughness index, impact resistance or some other appropriate form of testing) is not appropriate for SFRS if the real benefits of steel fiber addition are to be measured.

Table 5 provides typical SFRS performance specifications used in civil engineering works.

Corrosion resistance of SFRS

The corrosion resistance of SFRS is governed by the same factors that influence the corrosion resistance of conventionally reinforced concrete or shotcrete. As long as the matrix retains its inherent alkalinity and remains uncracked, SFRS is not likely to deteriorate. It has been found¹³ that good quality SFRC and SFRS, even when exposed to conditions conducive to reduced alkalinity such as atmospheric pollution, deicing chemicals, or a marine environment, will only carbonate to a depth of a couple of millimetres (less than 1/8 in.) over a period of many years. Steel fibers in the immediate surface layer rapidly corrode to the depth of surface carbonation, causing some rust-coloured surface staining. In a

trafficked, or abrasive exposure environment such corroded surface fibers rapidly wear away and disappear. The interior fibers beneath the immediate carbonated surface layer, however, remain totally protected provided the SFRS remains uncracked.

In the event of cracking, the fibers exposed in the crack are subjected to corrosive influences. How long the fibers remain capable of transferring load across the crack and restricting crack widening depends on factors such as:

- crack width and depth
- type and diameter of fiber used
- severity of the corrosive environment

Several studies¹³ have shown that provided the crack width remains 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 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 non-rusting fiber types can be used.

One of the major advantages of SFRS over mesh reinforced shotcrete in severe exposure environ-

Table 6 — Examples of SFRS in tunnelling/mining projects in Canada.

Year	Project	Application	Shotcrete type	Supply
1980/83	CP Rail, Fraser Canyon, B.C.	Rehabilitation of rock tunnels on active rail line.	Wire mesh and then SFRS dry-mix shotcrete	Dry-bagged premix
1981/82	B.C. Hydro - Site C Dam, Fort St. John, B.C.	Ground support and lining of exploratory adits and test chambers	Dry-mix SFRS	Dry-bagged premix
1982	B.C. Hydro - Downie Slide, Revelstoke Dam, B.C.	Ground support and lining of drainage adits to stabilize slide	Dry-mix SFRS	Dry-bagged premix
1982/83	B.C. Rail - Tumbler Ridge, B.C. KM 80 & 86 rail tunnels	Ground support and lining of railway tunnels	Dry-mix SFRS	Dry-bagged premix
1983/85	Advanced Light Rail Transit Project, Vancouver, B.C.	Ground support in tunnel and ventilation shaft	Wet-mix SFRS, some mesh	Transit mix batched and supply
1984	Westmin Mines, H-W Mine, Vancouver Island, B.C.	Support of underground openings in new mine development, including shafts, rooms and drifts	Dry-mix silica fume shotcrete, with and without steel fibre	Dry-bagged premix
1984/87	CP Rail, Mount MacDonald Tunnel Rogers Pass, B.C.	Support of bad ground areas in 16 km long railway tunnel thru Selkirk mountains	Dry-mix SFRS with silica fume	Dry-bagged premix
1985/87	CP Rail, Shaughnessy Tunnel, Rogers Pass, B.C.	Ground support and rail tunnel lining in 1.8 km tunnel through the Selkirk mountains	Dry-mix SFRS with silica fume	Dry-bagged premix
1988/89	British Columbia Rail, Howe Sound, B.C.	Rehabilitation of existing rock tunnels on active rail line	Dry-mix SFRS with silica fume	Dry-bagged premix
1989/90	Kemano Completion Project, B.C.	Ground support in water tunnels	Dry-mix SFRS with silica fume	Site batched dry mix
1988/90	Golden Bear Operating Co., Bearskin Lake, B.C.	Support of underground drifts and large openings	Dry-mix SFRS with silica fume	Dry-bagged premix
1986/87	Coquitlam Lake Intake Tunnel, Coquitlam, B.C.	Ground support and lining in access decline and tunnel	Dry-mix SFRS with silica fume	Site batched and dry-bagged premix
1986/87	Oldman River Dam, Pincher Creek, Alberta	Ground support in two diversion tunnels	Wet-mix SFRS with silica fume	Transit mix
1988/89	Oldman River Dam, Pincher Creek, Alberta	Ground support in drainage tunnels	Wet-mix SFRS and polypropylene fibre reinforced shotcrete	Transit mix
1985	Hudson's Bay Mining and Smelting Co. Snow Lake, Manitoba	Ground support in mine	Dry-mix SFRS with silica fume	Dry-bagged premix
1987	Denison Mines Elliot Lake, Ontario	Construction of bulkheads and relining ore bin	Dry-mix SFRS with silica fume	Dry-bagged premix
1987	Giant Yellowknife Mines, Holtbyre, Ontario	Ground support	Dry-mix SFRS with silica fume	Dry-bagged premix
1989/90	Leck Corona Operations, Hemlo, Ontario	Ground support	Dry-mix SFRS with silica fume	Dry-bagged premix
1989	Falconbridge Limited, Lockerby Mine, Ontario	Reline coarse ore bin	Dry-mix SFRS with silica fume	Dry-bagged premix
1989	Inco Limited, Levack Mine, Sudbury, Ontario	Ground support	Dry-mix with silica fume	Dry-bagged premix
1988/90	Inco Limited, North Mine, South Mine, Crane Hill Mine, Stobie Mine, Creighton Mine, Sudbury, Ontario	Ground support	Dry-mix SFRS with silica fume	Dry-bagged premix
1986/88	Brunswick Mining and Smelting Bathurst, N.B.	Ground support in mine	Dry-mix SFRS with silica fume	Dry-bagged premix

ments is that SFRS will not support the classic galvanic corrosion cells that are often the cause of corrosion and deterioration in mesh reinforced shotcrete. The fibers, being

non-continuous and discrete and protected by an alkaline matrix, provide no mechanism for propagation of corrosion activity. This phenomenon is well established

from examination of numerous SFRC and SFRS structures subjected to aggressive exposure environments (e.g., 15 year exposure of SFRC piles in



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Australia, with no fiber corrosion beyond the depth of surface carbonation).¹³

If the presence of steel fibers on the shotcrete surface is viewed as undesirable from a safety perspective, or if surface rusting and staining of SFRS is aesthetically undesirable, then a thin surface coating of plain shotcrete (sometimes called a flash coat or finish coat) can be applied to the SFRS. This system was used to good advantage in construction of the artificial West Coast Rockscape around the whale pool addition at the Vancouver Public Aquarium. After five years of exposure in this aggressive marine environment there is no rust staining or deterioration associated with the use of SFRS.

Examples of SFRS for support of underground openings

Morgan and Wood⁵ provide some 50 examples of the use of shotcrete for support of underground openings in civil engineering and mining applications in Canada from 1980 to 1990. This information was compiled from a questionnaire mailed to members of the Tunnelling Association of Canada. Of these 50 projects approximately half used SFRS. Some of these SFRS projects are listed in Table 6. It is clear that the large majority of the use of SFRS for support of underground openings in Canada to date has been in civil engineering projects (mainly tunnels) in Western Canada. SFRS is, however, beginning to find increasing acceptance and use in the mining industry, particularly in Ontario. It is expected that as more owners, engineers, and contractors become exposed to and familiar with the advantages of SFRS over plain or conventional mesh reinforced shotcrete, SFRS will find ever increasing use in the support of underground openings in Canada and elsewhere around the world, as is already occurring in

countries such as Scandinavia, Japan, the U.S.A., Europe, and South Africa.

Following is a brief summary of some of areas of use of SFRS in underground openings in Canada:

- final tunnel lining in railway and water pressure tunnels
- ground support prior to installation of final reinforced concrete lining in railway tunnels and river diversion tunnels
- rehabilitation of existing railway rock tunnels that have experienced deterioration in rock quality
- ground support in civil engineering and mining shafts, adits and chambers
- ground support in mining drifts, raises and declines
- construction of underground bulkheads and ventilation seals in mines
- linings in ore bins, crusher stations, lunchrooms and safety bays in mines.

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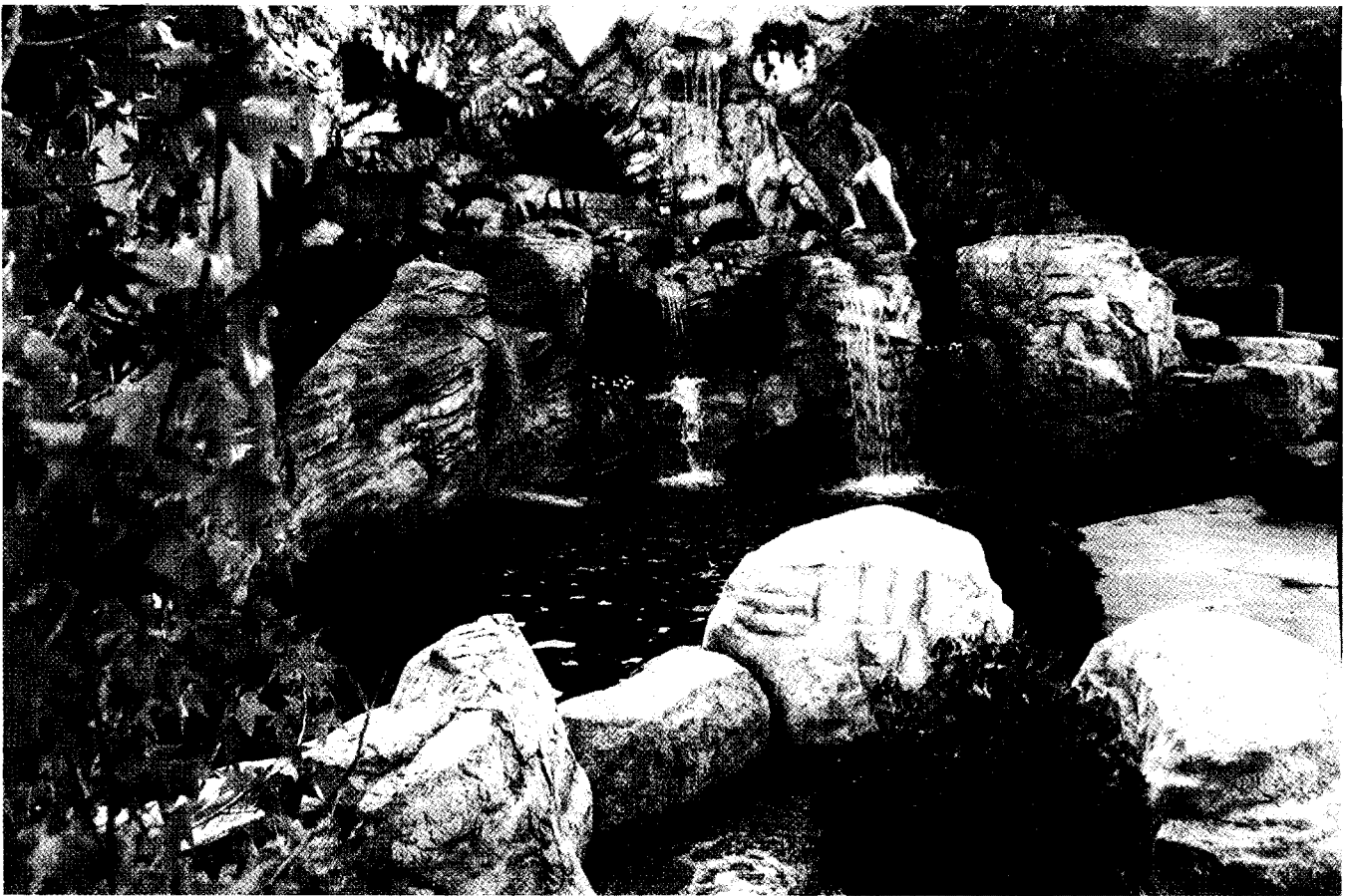
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Concrete Rocks for Aesthetic Landscapes

by Ken Macaire

New technologies using concrete are replacing the old prop-like, manufactured boulders of the fifties and sixties in leading-edge rockwork, waterscape, and landscape projects throughout the country. Citing not only aesthetics, but also regional accuracy, realistic scenery, stability, and ease of maintenance, landscape architects and contractors are turning to designs and construction by specialist firms for individualized rockwork to complete their projects.

Concrete is still the prime material, but innovative refinements in design and construction techniques are being used to provide dramatic beauty and compatibility with the

surrounding area when creating a new dimension for the environment or masking and enhancing retaining walls. Retaining walls can be highlighted by using them as part of the overall landscape design. Man-made rock outcroppings can be constructed to appear to be a continuation of the indigenous rock in the area of the site, so the wall will appear to be retaining only those portions of the hillside that are between the outcroppings.

For commercial as well as residential projects, there are two basic ways to make permanent rock formations:

- using standard molds
- individually designing each project

Rock molds can be used over and over again to produce relatively light-weight fiberglass reinforced concrete castings, but they are often impractical and limited in design application. Using standard molds restricts creativity because the design is already set: the design tends to follow the castings, whether or not they are appropriate to the individual space.

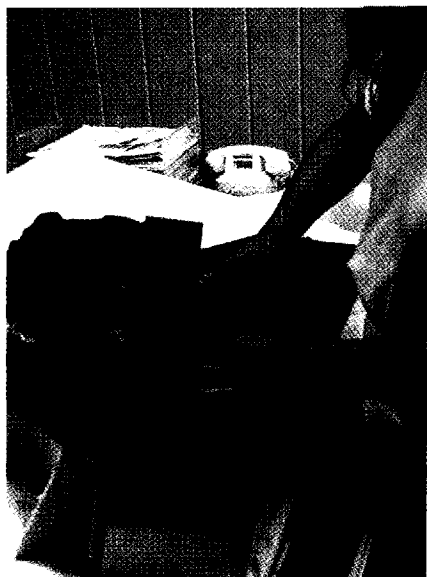
Individually designing each project has many advantages over the use of standard molds. Greater structural durability can be provided, and the overall design can be more creative. The unlimited variety of rock types and colors and the ability to blend plants directly into the rockwork can provide a geolog-



Using the techniques described in this article and shown in the photos below, the site shown at left was transformed into the rockscape with waterfall and jacuzzi shown at the top of the opposite page.

The photos below (clockwise from top right) show a design being modelled in clay, the steel frame of a rockscape being constructed from reinforcing steel, and the trowelling and shotcreting of concrete onto boulder shapes.

The photos at the bottom of the opposite page show the hand carving of rock formations into the wet finish coat of concrete using tools such as knives and small trowels, and spraying color onto the rock.



ical and regional accuracy and a natural blending with the environment that is rarely possible with standard molds.

A six-step process is used to create rock formations having the appearance of a permanent natural setting:

1. The design idea is sketched. Usually several perspectives of the design are drawn.
2. A clay model of the design concept is made. The model and renderings are often used for client presentations.
3. Rock formations are started on the job site by creating a steel frame of the rock using rebar. "Steeling out" entails attaching steel to a retaining wall and then bending it to the shape desired. This steel framework provides a solid base for the concrete. The rebar shape is either filled with rubble or covered with lath.
4. Concrete is shotcreted or trowelled onto the boulder shapes. A rough texture should be left to receive the finishing coat.
5. A finishing coat of concrete is applied. Hand tools such as knives and small trowels are then



used to carve rock formations into the wet concrete.

6. The rock is colored. Several applications are sprayed on the rockwork until the final color is obtained. Any color can be selected, from speckled grey granite to beige or yellow sandstone.

Rock and water features ranging from simple rockwork to breathtaking waterfalls with jacuzzis can enhance the beauty and value of any commercial or residential property. Man-made rocks custom-built for a specific project can be competitively-priced with rocks manu-

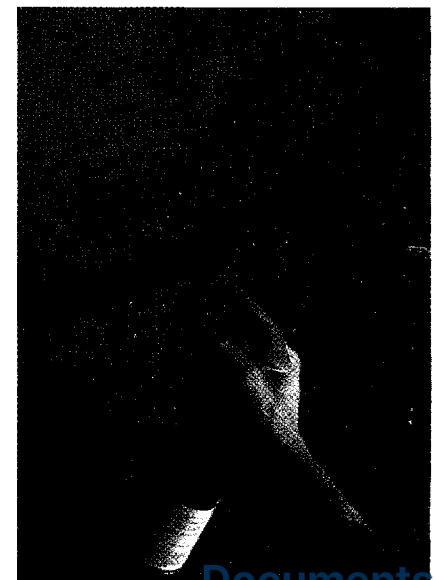
factured from standard molds. They also provide total freedom to create or change the color or shape of any project to naturally blend in geologically and geographically with the environment in creating dramatic, innovative designs that are true to nature.

Selected for reader interest by the editors.

Ken Macaire of Macaire, Inc., Sherman Oaks, California, has over 20 years experience in the design and construction of rockwork and waterscapes.



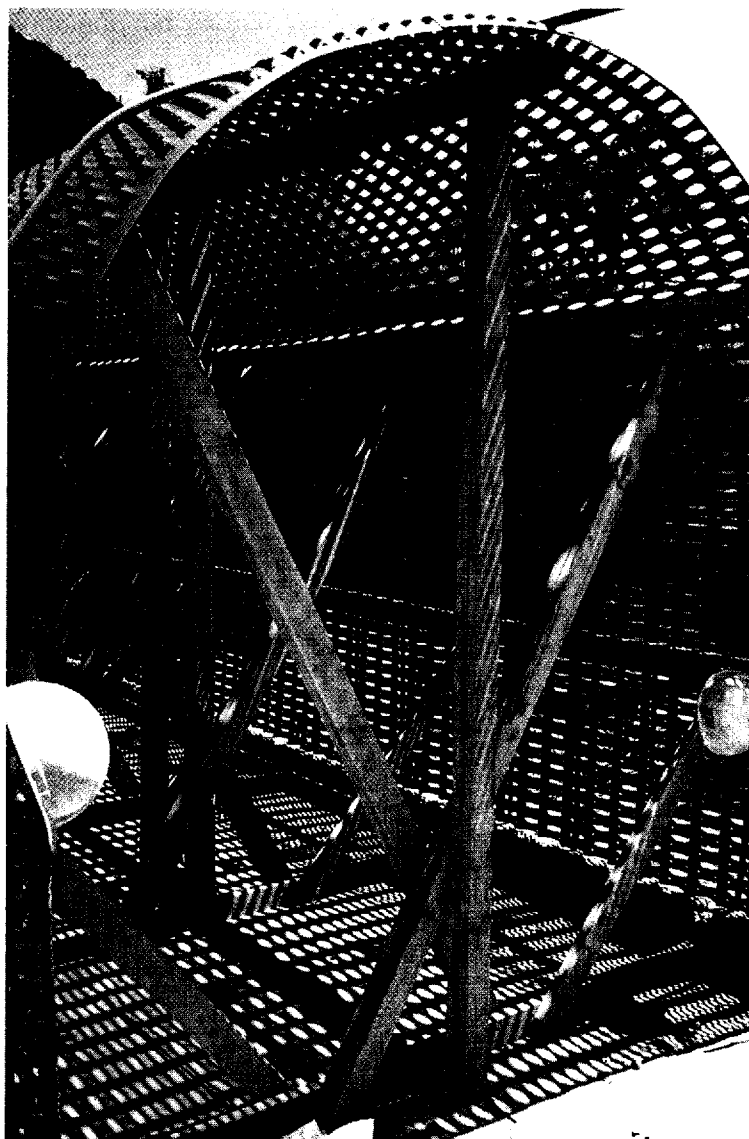
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Shotcrete Wine Storage Caves

by Jon Y. Kaneshiro



Portal structure with bracing system for shotcrete application.

Underground wine storage provides the perfect environment for the aging of wine without the high cost of energy for cooling. The Saratoga-Skyline Vineyard (Cinnabar Wine label) storage caverns are located near the town of Saratoga, California, less than ½ mile (0.8 km) from the San Andreas fault zone. The winery is located on a ridge of decomposed igneous rock, which is not economically viable for tunneling, thus the storage facilities were constructed by cut-and-cover methods.

The storage caverns are reinforced concrete structures that incorporate the Bernold forming and

reinforcing system, which was designed for Alpine tunneling by Bernold, a Swiss engineer. The Bernold system consists of interlocking steel plates about 3.5 ft (1.1 m) wide and 4 ft (1.2 m) long, and weighing about 45 lb (20 kg).

The Bernold plates are corrugated stamped steel (ASTM A569), 14-gauge, with $f_y = 40$ ksi (276 MPa). The stamping provides a "V" rib between a high-low basket-weave profile section, about 1.5 in. (3.8 cm) high. The plates are curved or bent to the appropriate radii at the factory. They are equivalent to #6 reinforcing bar ($f_y = 40$ ksi [276 MPa]) at 12 in. (30.5 cm), and are supplemented with reinforcing bar as required by design.

The plates are assembled into a framework in the desired shape of

the caves, and then covered with shotcrete to form the shell structure without using conventional plywood formwork. However, bracing to hold up the assembled framework is required until the shotcrete has hardened. The completed structure is subsequently covered with earth, resulting in a cut-and-cover cave. Bernold plates have been used in various cut-and-cover applications, including underground churches, hog shelters, libraries, printing presses, homes, highway culverts and undercrossings, mines, prison and security walls, and portal structures for other wine caves.

Layout and design

The Saratoga-Skyline Vineyard wine caves are unique in that the entire wine cave storage facility was

Keywords: reinforced concrete; shotcrete; subsurface structures; storage; tunnels.



Completed plate shell structure.



Shotcreting being performed from atop the portal structure.

built using cut-and-cover methods with the Bernold plate and shotcrete system. The general layout and configuration was based on the aesthetic and operational desires of the owner.

There are three wine caverns totaling approximately 4000 ft² (372 m²) of storage area. The caves are "fanned-out," and connected to each other by 10 ft (3 m) long cross passages. The caves also are connected to the winery building by a cross passage, and can be reached from the outside by a 25 ft (7.6 m) long portal structure.

The arch-shaped wine caves have inside dimensions of 25 ft (7.6 m) wide by 16 ft (4.9 m) high, while the cross passages are 8 ft (2.4 m) by 8 ft (2.4 m). The large wine cave arches were designed to support 9 ft

(2.7 m) of backfill plus additional design surcharges and light traffic, while the cross passages were designed for 25 ft (7.6 m) of backfill. Compaction of backfill along the sides of the structure was specified at 90 percent relative compaction (ASTM D1557) to maintain adequate pressure and to assure the integrity of the arch structure.

A computer program using a spreadsheet format was developed to compute the moment, shears, and axial loads at any location along the arch. Subsequently, the arch was designed using strength methods and the ACI-318 code. Seismic design incorporated pseudo-static methods, but from a seismic risk standpoint did not preclude damage to the caves during a maximum credible earthquake.

Construction

The construction sequence began with an open cut excavation of approximately 7,500 yd³ (5,700 m³). The concrete foundation, including footings and slab, involving about 230 yd³ (175 m³), were placed next. Footings for the 25 ft (7.6 m) wide wine cave arches were 15 in. (38 cm) thick by 5 ft (1.5 m) wide, while the end wall footings were 2 ft (0.6 m) thick by 8 ft (2.4 m) wide. The slab-on-grade was placed separately and was specified at a 5 in. (12.7 cm) minimum thickness.

The key to easy assembly was the modular Bernold plates. The structure was assembled in 8 ft (2.4 m) sections to produce two rings of plates. The plates at the bottom formed a 4 ft (1.2 m) high straight wall portion and were tied to reinforcing bars protruding from the concrete footings. The remaining plates used to form the arch interlock and fasten together with a simple wedge assembly.

The Bernold plates and bracing were erected over approximately four days. Rented extendable jacks and scaffolding were used for initial bracing, followed by erection of additional reinforcing bar and additional timber struts, bracing, and falsework to support the shotcrete loads during curing.

Approximately 410 yd³ (315 m³) of wet-mix method shotcrete (4,000 psi [28 MPa]) were placed for the reinforced shotcrete shell structure. The total thickness of the walls varied from 14 to 9 in. (36 to 23 cm), from the invert to the crown, respectively. After placement of the exterior shotcrete, a minimum cover of 1.5 in. (3.8 cm) was applied using an accelerator on the interior of the caves.

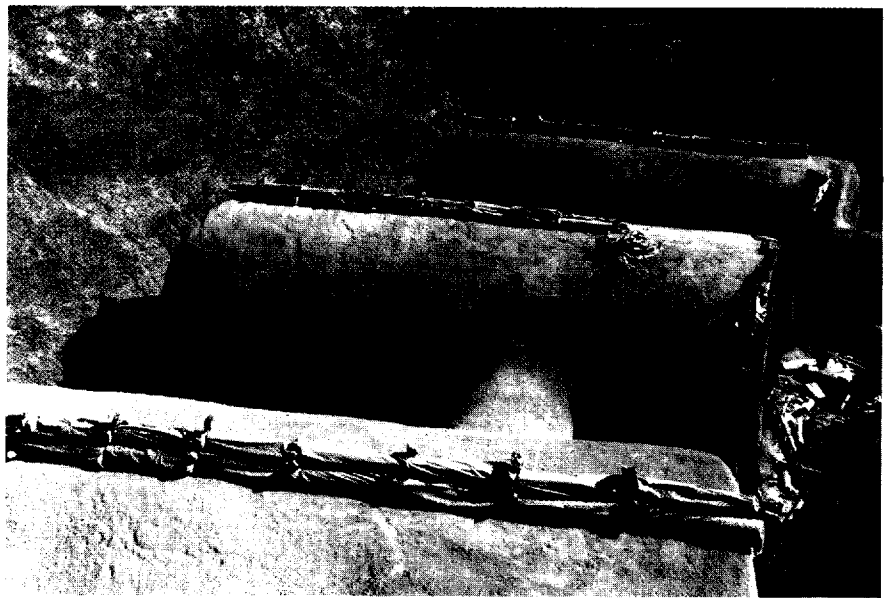
Thickness of the shotcrete on the exterior was gauged by extending a taut wire to the desired level of the

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final shotcrete, and by spot measurements. Thickness of shotcrete on the interior of the caves was gauged using the tie wires at about 5 ft (1.5 m) centers, left in from the falsework. Nine core samples from the exterior as well as shotcreted samples in wire baskets and placed cylinders were taken for testing and quality assurance.

A waterproofing membrane consisting of bentonite-backed polypropylene was placed on top of the shotcrete. A filter fabric and PVC drain board were placed on top of this membrane, along with corrugated polypropylene drains along the footings. Finally, the wine cave structures were backfilled after the shotcrete had reached its 28-day strength. The wine caves had a minimum of 6 ft (1.8 m) of fill in order to provide a constant temperature environment for aging of the wine.

The project was constructed over 3½ months during the summer of 1987, and had to be completed before the fall grape harvest for the immediate storage of wine. The costs to build the cut-and-cover wine storage structures amounted to about \$70 to \$80 per ft² (0.09 m²) of



Completed shotcrete caves, with rolls of waterproofing on top prior to placement.

cave area, and included permits, design, excavation, backfill, lighting, drains, ventilation, and water lines.

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Selected for reader interest by the editors.

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Shotcrete subcontractors:	Universal Concrete Restorations Castle Rock, Colorado Rocky Mountain Grouting Wheatridge, Colorado
HPS shotcrete accelerator supplier:	Shotcrete Technologies Idaho Springs, Colorado
Bernold plate supplier:	G.S. Metals Corporation Pickneyville, Illinois

High Early Strength Blended-Cement Wet-Mix Shotcrete

by Dudley R. Morgan

High early strength development has long been a desirable attribute in many shotcrete applications. In tunnelling and mining applications and in deep excavations in unstable ground, specifications often require rapid setting and hardening of the freshly applied shotcrete and high early strength gain. Eight-hour compressive strengths of 700 to 1000 psi (5 to 7 MPa) are specified frequently. When using normal portland cements (ASTM Type I or CSA Type 10), these high early strength levels can normally only be achieved by using shotcrete accelerators.

While shotcrete accelerators typically increase the early age (8- to 24-hour) strength, their use nearly always results in reduced strength at later ages, relative to an equivalent plain shotcrete without accelerator.^{1,2} The extent of strength reduction depends on a variety of factors, including the type and addition rate of accelerator used.

Later age strength reductions tend to be most pronounced with accelerator types and addition rates that promote "flash setting."² It has also been shown that the durability of accelerated shotcrete in aggressive-exposure environments can be affected adversely when high addition rates of accelerator are used.¹ Accelerator addition requires the use of special dispensing equipment as well.

There is a need in the shotcrete industry for a product that not only develops high early strength, but also displays good later-age strength development and provides good du-

rability in aggressive-exposure conditions. The performance of a wet-mix shotcrete made with a high early strength blended cement has been evaluated and results of that study are presented here. Parameters evaluated include the batching, mixing, supply, and application characteristics of the shotcrete made using conventional ready-mix concrete transit mixers and standard wet-mix shotcrete equipment. Properties of both the plastic and hardened shotcrete were evaluated.

Test program

Tests were conducted to evaluate the following plastic properties of the shotcrete mixture:

- slump at point of discharge into shotcrete pump
- air content as-shot into an ASTM C 231 air pressure meter base
- setting time using the ASTM C 403 penetration-resistance test
- thickness-to-sloughing on vertical surfaces

Tests on the hardened shotcrete included:

- compressive strength at 4 and 8 hours and 7 and 28 days to ASTM C 39
- flexural strength at 8 hours and 7 and 28 days to ASTM C 78
- boiled absorption and volume of permeable voids to ASTM C 642
- air content and parameters of the air-void system to ASTM C 457
- scaling resistance on exposure to deicing chemicals to ASTM C 672
- resistance to rapid freezing and thawing in water to ASTM C 666, Procedure A
- length change in a 50-percent rel-

ative humidity drying environment to ASTM C 341

Shotcrete mix proportioning

The shotcrete was dry-weight batched and prebagged in bulk-bin bags by a local premix batching company. The actual dry-batch masses are given in Table 1. The calculated batch proportions for the plastic shotcrete in lb/yd³ (kg/m³) are given in Table 2.

Batching, mixing, supply, and application

Two 3713-lb (1685-kg) bulk-bin bags were used in batching the mixture. The batch masses were sufficient to produce approximately 2-yd³ (1.5-m³) sized batches of plastic shotcrete. The dry-bagged materials were discharged into a clean ready-mix concrete transit mixer, then the water to produce the required workability for the shotcrete was weighed and added. In calculating the plastic shotcrete batch proportions given in Table 2, allowance was made for absorption in the dry aggregates. No admixtures were added to the blended-cement mixture.

The materials were mixed at full mixing speed for 5 minutes; the mixer drum was then turned slowly at agitating speed for 5 minutes to allow for absorption of the dry-batched aggregates and activation of the blended-cement mixture, followed by a further 5 minutes mixing at full speed prior to discharge of shotcrete. Water adjustments to produce the required workability were made at the end of the slow agitation period.

