Advances in Shotcrete Technology for Infrastructure Rehabilitation

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The shotcrete process was first developed in 1907 by Carl Akeley for the purpose of repairing the façade of the Field Columbian Museum in Chicago. Repairs were done using what was then referred to as the gunite process. Today this method is referred to in North America as the dry-mix shotcrete process. For the past nine decades, this dry-mix process has been used for innumerable repairs in North America and elsewhere in the world. In the mid-1950s, the wet-mix shotcrete method was developed. With advances in wet-mix shotcrete equipment and mixture designs, the wet-mix system became increasingly popular to the extent that is now widely used for shotcrete applications in North America, including shotcrete repairs. This paper uses case history examples to illustrate recent advances that have taken place in dry- and wet-mix shotcrete technology for shotcrete repairs in North America. Case history examples presented include repairs/retrofit of marine structures, dams and hydraulic structures, bridges, and some miscellaneous structures.

Introduction

While some view shotcrete simply as another means of placing concrete and mortar, it is much more than that. Modern shotcrete technology, as used in infrastructure rehabilitation, is a sophisticated process that can provide high-quality, durable solutions for repair/retrofit challenges that likely couldn't be met as effectively, either technically and/or economically, with conventionally cast concrete procedures. Shotcrete is now a mature technology for a wide range of new construction and repair/retrofit applications, as reflected in the 1998 formation of the American Shotcrete Association (ASA), with its motto: "Shotcrete: A Proven Process for the New Millennium."[1]

It is useful to examine the evolution of shotcrete technology since its development in 1907. The timeline (at right) is a summary of the key developments that have taken place in the past century.

From the aforementioned timeline, it can be seen that most of the early developments in the

1907
Development of the original cement gun by Carl Akeley in Chicago, Illinois, USA.

1910
Trade name gunite established by the Cement Gun Co., in Allentown, Pennsylvania, USA

1920
Dry-mix process patented in Germany

1930
Generic name shotcrete introduced by the American Railway Engineering Association to describe the dry-mix process

1940
Initial use of coarse aggregate in dry-mix shotcrete

1950
American Concrete Institute ACI Committee 506, Shotcreting, formed

1952
Development of the rotary style dry-mix gun in Michigan and Illinois, USA

1955
Introduction of the wet-mix shotcrete process

1970
First practical use of steel fiber-reinforced shotcrete by U.S. Army Corps of Engineers

1975
First use of silica fume in shotcrete in Norway

1980
First use of silica fume in shotcrete in North America in Vancouver, BC, Canada

1985
First use of air entrainment in dry-mix shotcrete process in Quebec, Canada

1988
First practical use of high-volume synthetic macrofibers in wet-mix shotcrete in Alberta, Canada

1998
Formation of the American Shotcrete Association (ASA)

2000
ACI Shotcrete Nozzleman Certification Program established

dry-mix shotcrete process took place in the U.S., whereas several of the more recent advances in both wet-mix and dry-mix shotcrete technology have taken place in Canada. Research initiatives in both the private sector and the universities, particularly the University of British Columbia and University Laval, Quebec, were instrumental in driving these advances.

There are now over a hundred publications in the technical literature detailing these advances in shotcrete technology in general, and providing case history examples of the use of shotcrete for infrastructure repair/retrofit in particular. The following are some useful sources of information:

American Shotcrete Association:

- *Shotcrete* (four issues per year since 1999), **www.shotcrete.org**
- Shotcrete Training Schools

American Concrete Institute (ACI)

- ACI 506R-90, Guide to Shotcrete
- ACI 506.2-95, Specification for Shotcrete
- ACI CCS-4, Shotcrete for the Craftsman
- ACI C 660, Shotcrete Nozzleman Certification

ASTM International

- Specifications for Shotcrete Materials
- Standard Test Methods
- Standard Practices for Sampling and Testing

American Association of State Highway and Transportation Officials (AASHTO-AGC-ARTBA)

- Task Force 37 Report, *Guide Specifications for Shotcrete Repair of Highway Bridges*, February, 1998.[2]
- Task Force 37 Report, *Inspector's Guide for Shotcrete Repair of Bridges*, December, 1999.

Overview

Shotcrete as used in infrastructure rehabilitation is not so much a material as a process. All the necessary ingredients need to be brought together to implement a successful repair/retrofit.

These include:

- Selection of appropriate shotcrete making materials (cement, supplementary cementing materials such as fly ash and silica fume, aggregates, chemical admixtures, and fibers [if used]);
- Optimizing shotcrete mixture designs to provide durable performance in the expected exposure conditions;
- Understanding the causes giving rise to the need for shotcrete remedial treatments and designing appropriate repair methodologies, including detailing of reinforcing and anchors;
- Proper deteriorated/damaged substrate concrete or other materials removal and preparation procedures prior to shotcrete application;
- Provision of appropriate shotcrete batching, mixing, supply, and application systems and proper curing and protection of the installed shotcrete;
- Use of a properly trained and skilled shotcrete crew, particularly shotcrete nozzleman (preferably certified); and
- Provision of detailed shotcrete specifications, with appropriate requirements for quality control (QC) and quality assurance (QA) inspection and testing and rigorous enforcement of the same.

It is not proposed to deal with each of these items systematically in this presentation, as these are well covered in References 2 to 4. Rather, the progressive advances in shotcrete technology that have occurred in North America in the past couple of decades are demonstrated in this paper by a series of case history examples, taken mainly from the author's project files. The examples selected are taken from four general infrastructure categories: marine structures, dams and hydraulic structures, bridges, and miscellaneous structures. It is hoped that these case history examples will demonstrate to the reader the many benefits of the shotcrete system for infrastructure rehabilitation.

Marine Structures

Canada Place, Vancouver, BC

Between 1983 and 1985, approximately $1.7 million (CAN $2 million) was spent in the shotcrete repair of Pier B-C in Vancouver Harbor, which presently supports the Canada Place Trade and Convention Center and Pan Pacific Hotel.[4] Dry-mix shotcrete was used to repair deteriorated cast-in-place reinforced concrete seawalls, pile caps, beams, stringers, and deck slab soffits. The work was started using a conventional plain dry-mix shotcrete. Due to the need for enhanced productivity when working in intertidal zones, however, silica fume was subsequently employed in the mixture. This resulted in improved adhesion and cohesion and resistance to sagging and sloughing, as well as excellent washout resistance of the freshly applied shotcrete. Figure 1 shows a view of the shotcrete repaired beams. This pioneering project marked the first use of silica fume in dry-mix shotcrete for remedial

Fig. 1: Dry-mix shotcrete repaired beams at Canada Place

work in Canada, and has since led to the routine use of silica fume in shotcrete for the repair of marine and other infrastructure throughout North America. When reexamined in 2003, after nearly 20 years in service, the shotcrete repairs were still showing excellent performance.

Port of Saint John, New Brunswick

In 1986, an annual repair program for berth faces at the Port of Saint John, New Brunswick, was initiated and subsequently continued for over 10 years.[5] Deterioration of the mass concrete berth faces was caused by an aggressive environment including mechanical damage from ship impact, exposure to strong currents laden with salt and abrasive sediments, alkali-aggregate reactivity, and most significantly, between 200 to 300 freezing-and-thawing cycles per year over a 28 ft (8.5 m) tidal range. Figure 2 shows a typical damaged section of original concrete berth face. Between 1986 and 1996, approximately 5250 ft (1600 lineal meters) of the 33 ft (10 m) high berth face were repaired using tied-back and anchored wet-mix, air-entrained, steel fiber-reinforced silica fume modified shotcrete. Table 1 shows the mixture design used.

Fig. 2: Typical deterioration in 60-year-old berth faces at Port of Saint John, New Brunswick, caused by frost, alkali aggregate reactivity, and tidal/wave action

Actual compressive strengths were in the 5800 to 7250 psi (40 to 50 MPa) range at 28 days and values of boiled absorption ranged between 3.5 and 8.3%. Air void spacing factors were typically less than 0.010 in (260 μm). A condition survey conducted in 1995 revealed that the shotcrete had excellent freezing-and-thawing durability after exposure to over 2000 freezing-and-thawing cycles and was generally in very good condition in such a harsh marine environment.[6] Other than for some restrained shrinkage cracking and peeling type delaminations at featheredged joints, there was little deterioration of the shotcrete. Figure 3 shows a view of berth faces after 10 years in service.

Table 1: Wet-mix steel fiber-reinforced silica fume shotcrete

Material	Material mixture proportions	
	lb/yd^3	kg/m^3
Normal portland cement (Type 10)	674	400
Silica fume	94	56
10 mm coarse aggregate (SSD)	775	460
Concrete sand (SSD)	1854	1100
Water	303	180
Water-reducing admixture	52 fl oz	2 L
High-range water-reducing admixture	182 fl oz	7 L
30 mm steel fiber	101	60
Air-entraining admixture		As required for
Air content	7 ± 1%	7 ± 1%
Total	3818	2265
Slump	3 in	80 ± 20 mm
Minimum 28-day compressive strength	5800 psi	40 MPa
Maximum boiled absorption	8%	8%

Port of Montreal, Quebec

In 1995, a prototype repair program was undertaken of berth faces at the Port of Montreal in the St. Lawrence River.[7] The combined effects of frost damage, alkali-aggregate reactivity, and deicing chemical attack had caused severe deterioration of the original concrete structure. In some places, the concrete was turning into rubble. Repairs were carried out by removing disintegrated material, as shown in Fig. 4, and applying a tied-back and anchored wet-mix, air-entrained, silica fume shotcrete. Approximately two-thirds of the berth

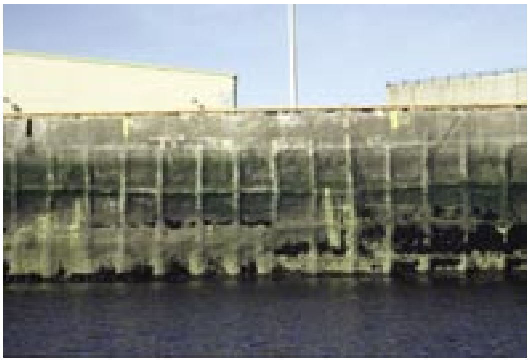

Fig. 3: View of shotcrete repaired berth faces at the Port of Saint John after 10 years in service and over 2000 freezing-and-thawing cycles

Fig. 4: Removal of deteriorated berth face concrete at Port of Montreal, Quebec

face, 400 ft (122 m) long and 23 ft (7.1 m) high, was repaired using 19.2 lb/yd^3 (11.4 kg/m^3) of polyolefin fiber-reinforced shotcrete. The remaining third of the berth face was repaired using 101 lb/yd^3 (60 kg/m^3) of steel fiber-reinforced shotcrete. Figure 5 shows a portion of the completed works. The shotcrete has performed well, and the comparative behavior of the steel and polyolefin fiber-reinforced shotcrete sections is being monitored.

Fig. 5: Portion of the completed wet-mix shotcrete repairs to berth face at the Port of Montreal

Lighthouse, Gulf of St. Lawrence, Quebec

The Haut-Fond Prince Lighthouse, located in the Gulf of St. Lawrence near Tadoussac, Quebec, was constructed in 1964.[8] The steel and concrete components forming the pier structure suffered severe abrasion and erosion over the years from the high pressure of ice grinding on the intertidal part of the structure. Some sections of the pier concrete were eroded to depths of as much as 4.9 ft (1.5 m). Repair was urgently needed to prevent undermining of the structure; and in 1996, a repair program was carried out. The repair consisted of removal of damaged steel plates and deteriorated concrete and application of an air-entrained dry-mix, steel fiber-reinforced, silica fume shotcrete. The work was particularly challenging as shotcrete had to be applied in intertidal regions from an inflatable boat, under conditions of strong tidal action and waves impacting the freshly applied shotcrete. Table 2 shows the dry-mix shotcrete composition.

Table 2: Dry-shotcrete mixture composition

Component	Percentage of dry materials by mass
Type 30 cement	20.0
Silica fume	2.5
Sand (0.1 to 0.2 in. [0 to 5 mm])	61.1
Coarse aggregates (0.1 to 0.4 in. [2.5 to 10 mm])	14.8
Set accelerator	1.0
Steel fibers	1.7

The steel fiber was added to increase resistance to restrained shrinkage cracking and improve impact resistance against ice flows. The silica fume and set accelerator was added to improve wash-out resistance of the shotcrete because the fresh shotcrete was typically in contact with sea water within 20 minutes of application. The prebagged shotcrete materials were stored in the hold of a large barge moored next to the lighthouse. The hold was heated to approximately 86 °F (30 °C) and hot water was used during shooting such that the temperature of the applied shotcrete was approximately 77 °F (25 °C). This, in conjunction with the use of a Type 30 high-early-strength cement and accelerator, enabled the shotcrete to rapidly set, harden, and develop strength so it wasn't damaged by tidal action and waves. Specified and typical performance characteristics of the shotcrete are summarized in Table 3.

Table 3: Shotcrete test results

Parameter	Specified		Actual	
Compressive strength minimum at 7 days	2900 psi	20 MPa	5670 psi	39.1 MPa
Salt scaling loss to ASTM C 672	—	—	2.58 lb/yd^3	1.53 kg/m^3
Max air void spacing factor to ASTM C 457	0.012 in.	300 μm	0.008 in.	200 μm
Specific surface	—	—	1.4 in.$^{-1}$	35.8 mm^{-1}

The shotcrete applied readily met the specified performance requirements and the parameters of the air void system indicated that the shotcrete should be resistant to damage from freezing and thawing in this chloride-laden environment. Figure 6 shows a view of the shotcrete repaired lighthouse. Examination of the lighthouse after 4 years in service demonstrated that the repairs were displaying excellent resistance to damage from freezing-and-thawing cycles, erosion, and impact from ice.

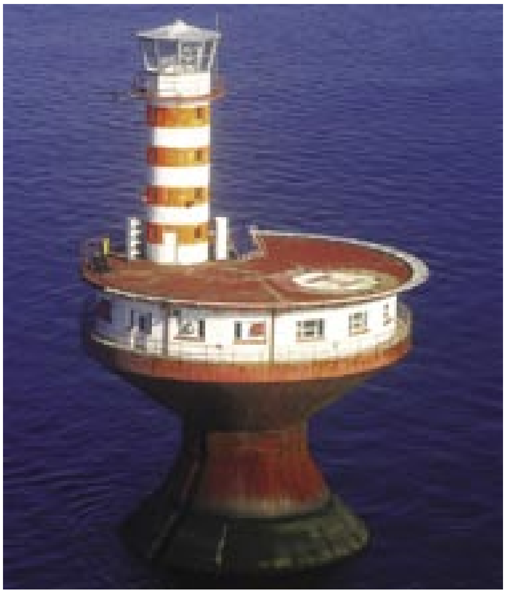

Fig. 6: Haute-Fond Prince Lighthouse in Gulf of St. Lawrence, Quebec, after completion of shotcrete repairs

Stanley Park Seawall, Vancouver, British Columbia

The Stanley Park Seawall is a 6.25 mile (10 km) long combined walkway and cycle path along the oceanfront in English Bay, Burrard Inlet and Coal Harbor, Vancouver, British Columbia.[10] It is the most widely used public recreational facility in Vancouver, with over 1 million users per annum. The seawall is primarily constructed of granite masonry and mortar, with an asphalt pavement surface. It was started in the early 1920s as an erosion control measure and took 53 years to build. For 32 years, construction of the seawall was under the direction of James Cunningham, an immigrant Scottish master stonemason, who devoted most of his life to the project.

The seawall is subjected to daily tidal action and waves. In addition, during winter storms it can be subjected to severe impact from floating logs, which are common in English Bay. The majority of the seawall has demonstrated remarkable durability, considering its age and the exposure conditions. By 2000, however, there were numerous locations, comprising approximately 1640 ft (500 m) in total length, where waves and tidal action had caused scour and erosion, undermining the seawall. Figure 8 shows one such location near Siwash Rock where scour and erosion from wave and tidal action had created a cave in the sandstone under the seawall.

The seawall was repaired in these environmentally sensitive intertidal regions using a specially designed air-entrained, wet-mix, silica fume shotcrete reinforced with macrosynthetic fibers. The shotcrete mixture design and specified and actual shotcrete performance characteristics are shown in Tables 4 and 5, respectively.

The shotcrete was supplied in 1763 lb (800 kg) bulk bin bags that were discharged into a 2.6 yd^3 (2 m^3) tilting drum mixer mounted on a flatbed truck. All shotcrete equipment and materials were mounted on a shotcrete train that moved along the seawall performing the underpinning repairs where required. Figure 7 shows a view of the shotcrete train. On relatively calm days, when there was no major wave action, the contractor was able to continue shotcreting until about half an hour before the incoming tide reached the work, with no washout or detrimental effects on the shotcrete.

Table 4: Shotcrete mixture design

Material	Mass	
	lb/yd^3	kg/m^3
Cement Type 10	674	400
Silica fume	76	45
Fly ash	50	30
Coarse aggregate* 10 to 25 mm (SSD)	758	45
Fine aggregate* (SSD)	2040	1210
Synthetic fiber	8.4	5
Water (estimate)†	303	180
Water-reducing admixture		Standard dose
High-range water-reducing admixture	Sufficient for slump of 2.5 in. ± 1 in.	Sufficient for slump of 60 ± 20 mm
AEA for air content at pump of	7 to 10%	7 to 10%
Air content as shot	4%	4%
Total	3910	2320

*Combined coarse and fine aggregate gradation to conform to ACI 506R-90 Table 2.1 Gradation No. 2 requirements

†Added on site, based on aggregates in saturated surface dry (SSD) condition

Table 5: Specified and actual shotcrete performance

Property	Test	Age	psi	MPa	Specified
Compressive strength (MPa)	CSA A23.2-14C	7 days	4350	47.3	30 MPa
		28 days	5800	53.9	40 MPa
Boiled absorption	ASTM C 642	7 days	8%	5.0%	8%
Volume of permeable voids	ASTM C 642	7 days	17%	11.0%	17%

Fig. 7: Shotcrete "train" on the Stanley Park Seawall, Vancouver, BC

Fig. 8: Underpinning of a cave under the seawall near Siwash Rock, Stanley Park Seawall, Vancouver, BC, using macrosynthetic fiber-reinforced wet-mix shotcrete

On windy days, shotcreting work was terminated about an hour before the incoming tide reached the work. The most challenging area to shoot was the cave at Siwash Rock. It had to be filled in three passes to a total thickness of about 8.2 ft (2.5 m). Figure 8 shows this work in progress. Figure 9 shows shotcrete repairs to damaged concrete-faced rip-rap in the Devonion Park part of the seawall in Coal Harbor. This project was completed on time and on budget to the satisfaction of all in a challenging working environment of tidal and weather constraints and public and environmental scrutiny.

Fig. 9: Shotcrete repairs to damaged concrete-faced rip-rap in the Devonian Park part of Stanley Park Seawall

Dams And Hydraulic Structures

Littlerock Dam, California

In 1994, a major seismic retrofit program was carried out on the Littlerock Dam in southern California.[10] This multiple-arch dam provides vital water supply for both the Palmdale Water District and the Littlerock Creek Irrigation District. Its location just 1.5 miles (2.4 km) south of the San Andreas fault raised concerns about the adequacy of the dam and its stability in the event of an earthquake. To provide seismic strengthening, air-entrained, silica fume modified, steel fiber-reinforced, wet-mix shotcrete was applied at a nominal thickness of 4 in. (100 mm) over 48,420 ft^2 (4500 m^2) surface area, together with over 3400 anchors. Figure 10 shows shotcrete retrofit on the dam face in progress. Quality control testing indicated excellent shotcrete performance (compressive strength, bond pull-off strength, consolidation, toughness, boiled absorption and volume of permeable voids). Upon completion of the project, the shotcrete was observed to be essentially crack free, in spite of the work being completed in a desert climate, where the ambient temperatures rose as high as 104 °F (40 °C) during the daytime and by project end fell below zero at night. The work was successfully completed on time and within budget to the satisfaction of the owner.

Fig. 10: Seismic retrofit of the upstream face of the Littlerock Dam

Jordan River Dam, Vancouver Island, British Columbia

The Jordan River Dam is a 131 ft (40 m) high Ambersen buttress-type dam built from 1912 to 1913 in Southern Vancouver Island, British Columbia.[11,12] It comprises inclined reinforced concrete slabs resting on downstream buttresses. Figure 11 shows the seismically retrofitted dam in 1990. The slabs are 4.6 ft (1.4 m) thick at the base of the dam, tapering to 1.3 ft (0.4 m) thick at the top. Over the years, the slabs and buttress elements progressively deteriorated as a result of water leaking through joints in the slabs above the buttresses, leaching, and frost action. In addition, there was some abrasion and wear on the upstream face of the dam from logs and ice abrasion as the water level in the dam rose and fell. Also, the low-outlet structures were eroded from high-velocity water flows.

Fig. 11: Shotcrete repairs to upper buttresses, Jordan River Dam

Over the years, a series of shotcrete repairs was carried out to maintain the dam in a serviceable condition, culminating in a major seismic retrofit of the dam in 1990. Many of the repairs were conducted using the shotcrete technology of the day. Brief examination of these repairs reflects the progress in shotcrete technology in Canada. During the period from 1969 to 1971, the upstream face of the dam was repaired using a mortar-type dry-mix shotcrete reinforced with a 3 x 3 in. (75 x 75 mm) grid of 0.16 in. (4 mm) diameter welded wire mesh applied in a 3 to 4 in. (75 to 100 mm) thick layer. A 3/4 in. (20 mm) thick layer of unreinforced dry-mix shotcrete of similar composition was applied to the buttress elements on the downstream face. Compressive strength of the original concrete was highly variable (the original concrete was placed at a quite fluid consistency, using puddling sticks and displayed pronounced segregation within lifts). Strengths in cores from the slab concrete ranged from 2755 to 4785 psi (19 to 33 MPa) and averaged about 3770 psi (26 MPa) in 1994. Strengths in cores from the buttress concrete ranged from 870 to 5655 psi (6 to 39 MPa) and averaged 2610 psi (18 MPa) in 1994.

Deterioration of the dam continued, and in 1989 major repairs to leaks at joints in the slabs in the upstream face of the dam were conducted. These repairs were carried out using dry-mix, steel fiber-reinforced, silica fume shotcrete. In 1990, the old dry-mix shotcrete repairs to the downstream buttresses, which had largely debonded (as a result of the poor quality of concrete to which they were applied), were removed. The lower parts of the buttresses were massively strengthened with new reinforcing and cross beams using cast-in-place concrete. The upper tiers of the buttresses were encapsulated in an air-entrained, wet-mix, silica fume shotcrete, a minimum 2.5 in. (65 mm) thick, reinforced with anchored hook dowels, reinforcing bar, and mesh. Testing of the shotcrete applied to the buttresses in 1990 by Heere in 1994[11] demonstrated that the shotcrete was of excellent quality, as shown in Table 6.

Both the dry-mix shotcrete repairs to the upstream face applied in 1989 and the wet-mix shotcrete repairs applied as part of the seismic retrofit of the downstream buttresses in 1990 continue to show good performance.

Wachussett Aqueduct, Massachusetts

From 2001 to 2002, the historic 6.9 mile (11 km) long Wachussett Aqueduct in eastern Massachusetts was rehabilitated with wet-mix shotcrete. The original aqueduct was constructed between 1897 and 1903 and was the primary source of drinking water for the city of Boston. The original aqueduct was horseshoe shaped and 11 ft (3.35 m) high. The sidewalls up to the spring line and invert were constructed of dressed brick ashlar masonry. The crown of the original aqueduct (from 9 o'clock to 3 o'clock) was constructed of unreinforced concrete. In the 1960s, new water supply systems were developed for Boston and the aqueduct ceased to be used. By 1999, however, water demand in the area required the Wachussett Aqueduct to be put back into service.[13] The restoration project primarily consisted of application of 3 in. (75 mm) of wet-mix shotcrete through wire mesh reinforcement to line the aqueduct. Over 15,030 yd^3 (11,500 m^3) of wet-mix shotcrete were applied. The shotcrete lining was designed to strengthen the structure, control water inflow into the aqueduct, and provide a smooth tunnel surface to maximize the volume of water flowing through the tunnel. The lining was finished to an exacting cast-concrete equivalent finish. The shotcrete lining was completed within 18 months and provided better water flow capacity than the original brick ashlar and cast concrete aqueduct, in spite of the reduction in cross-section area, due to the improved lining smoothness achieved with the shotcrete.

Table 6: Laboratory test results, Jordan Dam, buttresses, 1990 shotcrete

Test	Shotcrete	
Air content—ASTM C 457	4.0%	4.0%
Specific surface—ASTM C 457	1.4 in.$^{-1}$	35.7 mm^{-1}
Spacing—ASTM C 457	0.0067 in.	0.17 mm
Permeable voids—ASTM C 642	13.4%	13.4%
Absorption—ASTM C 642	5.6%	5.6%
Carbonation depth	0 to 0.04 in.	0 to 1 mm
Tensile bond strength	72.5 to 160 psi	0.5 to 1.1 MPa
Compressive strength—ASTM C 39	7395 psi	51 MPa

Bridges

General

One of the most widespread uses of shotcrete in North America has been for bridge repair. Initially, most of this work, which was conducted mainly on substructure elements (girders, beams, columns deck soffits, and abutments), was carried out using the dry-mix shotcrete process. However, increasingly small-line shotcrete pumps and a prebagged shotcrete supply are allowing wet-mix shotcrete to be used for this type of shotcrete repair.

In 1992, the author was retained by the Canadian Strategic Highway Research Program (C-SHRP) to conduct a condition survey and evaluation of the durability of shotcrete rehabilitation treatments of bridges.[14] In this study, some 60 bridges from the Pacific to the Atlantic coasts of Canada were assessed. An end-product of this study was the document "Recommended Practice for Shotcrete Repair of Highway Bridges."[2] This document was subsequently adopted and modified by a joint task force of the American Association of State Highway and Transportation Officials (AASHTO); the Associated General Contractors of America (AGC); and the American Road and Transportation Builders Association (ARTBA), which issued a Task Force 37 Report, "Guide Specifications for Shotcrete Repair of Highway Bridges."[3] This document provides good guidelines for repair of bridges and other infrastructure.

In the C-SHRP study,[14] it was found that in bridges with shotcrete repairs ranging in age from 10 to 30 years:

- 62% of the repairs were rated as being in good to excellent condition;
- 25% were rated as being in fair condition;
- 10% were rated as being in poor condition; and

- only 3% were found to have failed.

The poor and failed conditions were attributed to factors such as the following:

- improper substrate preparation;
- placement during unfavorable weather conditions;
- poor detailing, such as lack of use adequate reinforcing and anchors, or featheredging of construction joints; and
- poor workmanship, including a failure to properly encase reinforcing steel and inadequate curing.

The Task Force 37 Report, "Guide to Specification for Shotcrete Repair of Highway Bridges,"[3] emphasizes procedures to eliminate these causes of poor or failed behavior in shotcrete repairs.

Depoe Bay Bridge, Oregon

This historic reinforced concrete arch bridge was constructed over an entrance to a bay for the fishing village of Depoe Bay on the Oregon Coast in 1927. Over the years, the bridge suffered substantial reinforcing steel corrosion-induced damage from the marine salt spray. A decision was made to rehabilitate the bridge in 1995 using dry-mix shotcrete repair of spalled and delaminated concrete, followed by an application of a thermal-sprayed zinc anode cathodic protection system. Figure 12 shows a photo of the bridge after completion of the shotcrete repairs and application of the zinc coating. For reasons of uniformity of current flow between the reinforcing steel and zinc anode, the corrosion protection design team required calcium chloride to be added to the shotcrete mixing water. This was done in an attempt to have consistency between the chloride content in the residual unrepaired concrete and the shotcrete repairs. Also, to enhance bond between the concrete/shotcrete and thermal-sprayed zinc anode, the concrete/shotcrete surfaces were force-dried using ignited gas flames (Tiger torches). The combination of these two factors had the unfortunate consequence of increasing the amount of shrinkage experienced by the shotcrete, resulting in some areas of delamination of the shotcrete repairs. Changes were made to eliminate chloride addition to the shotcrete mixture water in subsequent remedial work and the shotcrete was provided with a longer moist curing period before being allowed to dry out.

In spite of these challenges, the Depoe Bay Bridge provides an excellent example of the quality of artistic detail that can be reconstructed using the shotcrete process as can be seen in Fig. 12.

Ministry of Transport, Quebec

Shotcrete has been widely used by the Ministry of Transport in Quebec (MTQ), particularly in the city of Montreal since the mid-1960s for bridge repair.[15] From 1965 to 1975, repairs were conducted using the gunite process, that is, a sand/cement/water mixture applied by the dry-mix shotcrete process. At the time, structural inspections revealed poor in-place performance in some repairs as a result of factors such as:

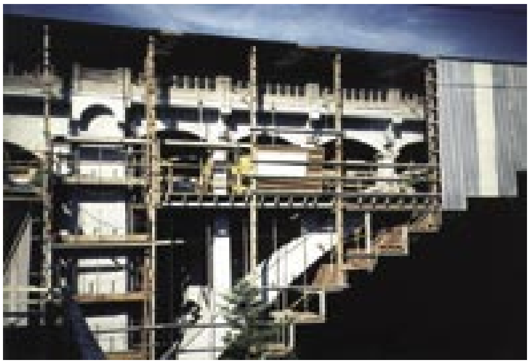

Fig. 12: Shotcrete repaired Depoe Bay Bridge with thermal-sprayed zinc anode cathodic protection coating

- cracking and debonding; and
- freezing-and-thawing and deicing salt scaling-induced damage

From the mid-1980s to the mid-1990s, a substantial research initiative was undertaken by the MTQ, in conjunction with Laval University to improve the durability of shotcrete repairs to bridges in the aggressive exposure environments that exist in Quebec. Some of this work was done cooperatively with the author and the University of British Columbia through the Network of Centers of Excellence on High Performance Concrete program.[16,17]

Much of the MTQ bridge repair work continues to be done with the dry-mix shotcrete process and key factors in developing a product which displays durable performance in this aggressive environment have been:

- Incorporation of silica fume in the mixture (typically 8% by mass of cement) to enhance bond and reduce permeability;
- Use of polypropylene microfibers (1.69 lb/yd^3) (1.0 kg/m^3) for plastic shrinkage cracking control;
- Addition of an air-entraining admixture, either to the mixture water, or as a dry powder in prebagged shotcrete to provide a suitable air void system in the applied shotcrete (Air content of 3.5 to 6.0% and spacing factor of less then 0.012 in (300 μm); and
- Incorporation of 3/8 in. (10 mm) maximum size coarse aggregate in the shotcrete, that is, to meet ACI 506.2R-90, Gradation No. 2, combined aggregates gradation requirement (reduces water demand and shrinkage).

The current standard Quebec DOT dry-mix shotcrete formula is shown in Table 7. Table 8 shows typical performance parameters for this mixture design.

In addition, care was taken to improve substrate preparation procedures to maximize bond. Best bond was achieved on surfaces that were prepared either by hydrodemolition processes or sand-blasting of mechanically removed concrete. In addition, shotcrete bond strength is maximized when the concrete substrate is presaturated, followed by allowing it to dry back to a saturated surface dry (SSD) condition immediately prior to shotcrete application.

In 1990, the mixture design shown in Table 7 was used for a CAN $80 million repair of the 6.25 mi (10 km) long elevated Metropolitan Boulevard expressway in Montreal. Shotcrete repairs were made to the underside of the deck as well as over 5000 columns. After 14 years of exposure to service, severe weather, and deicing salts, the repairs are performing very well. Figure 13 shows shotcrete repair to the deck soffit and columns in progress in 1990.

Table 7: Standard Quebec DOT dry-mix shotcrete

Cement (10SF)	758 lb/yd^3	450 kg/m^3
Fine aggregates	2545 lb/yd^3	1510 kg/m^3
Coarse aggregate 10 to 2.5 mm	396 lb/yd^3	235 kg/m^3
Polypropylene fibers	1.69 lb/yd^3	1.0 kg/m^3
Air-entraining admixture	26 to 52 fl oz/yd^3	1 to 3 L/m^3 (approximately 150 ml/L of shooting water)

Table 8: Typical properties for standard Quebec MOT dry-mix shotcrete

Compressive strength: 7 days 28 days	4350 psi 5800 psi	30 MPa 40 MPa
Water absorption (ASTM C 642)	4.5%	4.5%
Volume of permeable voids (ASTM C 642)	10.2%	10.2%
Air content (as-shot)	4.5%	4.5%
Spacing factor (μm)	0.004 to 0.006 in.	100 to 150 μm
Chloride permeability (ASTM C 1112)	—	1150 Coulombs
Scaling resistance (ASTM C 672)	—	0.4 kg/m^2

Fig. 13: Shotcrete repairs to Metropolitan Boulevard, Montreal, Quebec

Miscellaneous Shotcrete Repairs

General

In addition to the structures already described, the author has been involved in projects where shotcrete has been used for repair and/or strengthening of a wide variety of structures, including:

- Jacketing and strengthening of cracked and leaking grain silos[18] (refer to Fig. 14);
- Repair of corrosion damaged bulk shipping facilities such as potash, coal, and sulphur load-out dumper pits, loading towers, and conveyors;
- Seismic upgrading of heritage and other masonry and reinforced concrete structures;
- Repair and strengthening of large diameter corrugated metal culverts;
- Repair of water and sewer pipes;

Fig. 14: Shotcrete strengthening of grain silos at Prince Rupert, BC

Fig. 15: Shotcrete repaired floating concrete ships, Powell River, BC

Fig. 16: Shotcrete repair of heritage building, Vancouver, BC

- Repair of deteriorated aqueducts, pressure head-race tunnels, canals, and other water conveyance devices;
- Repair of deteriorated and leaking swimming pools, water reservoirs, sumps, pits, sewage treatment facilities, and other liquid containing facilities;
- Repair of 50-year-old concrete ships now used as a breakwater at Powell River, British Columbia[19,20] (refer to Fig. 15); and
- Repair of a steel framed terracotta and masonry clad heritage high rise building.[21] (refer to Fig. 16).

Space precludes a detailed discussion of these various projects, but references are provided for the projects that have been written up by the author or others and published in technical literature.

Closure

This paper provides an overview of advances in shotcrete technology for infrastructure rehabilitation in North America, with particular emphasis on the past two decades. Case history examples of infrastructure repair/retrofit with shotcrete drawn primarily from the author's project experience are presented to illustrate the continuing changes and improvements that have occurred in this field. Shotcrete is now a mature technology with continuing improvements in shotcrete nozzleman skills being developed through programs such as the American Shotcrete Association Shotcrete Nozzleman Training Schools and American Concrete Institute Shotcrete Nozzleman Certification Program. Shotcrete is indeed now living up to the claims for it by the American Shotcrete Association as a "Proven Process for the New Millennium."

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