AASHTO-AGC-ARTBA Joint Committee

Task Force 37 Report

Guide Specifications for Shotcrete Repair of Highway Bridges

February 1998

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS • 1914 •

THE ASSOCIATED GENERAL CONTRACTORS • OF AMERICA •

AMERICAN ROAD & TRANSPORTATION BUILDERS ASSN. • 1902 •

AASHTO-AGC-ARTBA Joint Committee
Subcommittee on Materials
Task Force 37 Report

Guide Specifications for Shotcrete Repair of Highway Bridges

February 1998

Introduction

This document is disseminated upon the sponsorship of the Joint Committee of the American Association of State Highway and Transportation Officials, the Associated General Contractors of America and the American Road and Transportation Builders Association (the Joint AASHTO-AGC-ARTBA Committee) in the interest of information exchange, based on the combined technical expertise of the authors. As such, the opinions and conclusions implied or expressed herein do not necessarily reflect the official views or policies of the Joint Committee or its member organizations.

This report was approved for publication by the three member organizations comprising the Joint Committee and was published on behalf of the Joint Committee by AASHTO.

American Association of State Highway
and Transportation Officials
444 North Capitol St., N.W., Suite 249
Washington, D.C. 20001

Fax (202) 624-5806

February 1998

Preface

This Guide Specification is adapted from the Recommended Practice for Shotcrete Repair of Highway Bridges which was prepared by Dr. D. R. Morgan, Professional Engineer of HBT AGRA Limited, Vancouver, B.C., Canada, under the auspices of the Canadian Strategic Highway Research Program (C-SHRP) study titled *Durability of Shotcrete Rehabilitation Treatments of Bridges*. C-SHRP is a program of the Transportation Association of Canada (TAC). The guidance, review and critical comment of the following C-SHRP Project Committee on Shotcrete Repair of Bridges' members in preparation of the original document is gratefully acknowledged:

Dr. David Manning, Professional Engineer, Ministry of Transportation, Ontario

Mr. Paul Carter, Professional Engineer, Alberta Transportation and Utilities

Mr. Daniel Vizina, Ing., Transports Québec

Mr. Greg Williams, Professional Engineer, C-SHRP National Coordinator

The contributions of Mr. W. S. Langley, Professional Engineer, of W. S. Langley and Associates Limited and Dr. Doug Hooton, Professional Engineer, of John Emery Geotechnical Engineering Limited to the initial C-SHRP study are also gratefully acknowledged.

Permission to adapt the document was provided under Cooperative Agreement DTFH61-95-X-00005 between the Federal Highway Administration and the Transportation Association of Canada. The original document was revised and adapted for use in the U.S. by Joint Task Force 37, Shotcrete Repair of Highway Bridges.

Joint Task Force 37
Shotcrete Repair of Highway Bridges

Chairman:	Gerald White, North Carolina DOT, Raleigh, NC
Secretary:	Bruce Johnson, Federal Highway Administration, Salem, OR
Members:	Jim Asher, Fibermesh Company, San Antonio, TX
	Ken Boedecker, W. R. Grace and Company, Charleston, SC
	Jim Dikeou, ACI, Detroit, MI
	Mahmoud Elnahal, Virginia DOT, Richmond, VA
	Steven H. Gebler, Construction Technology Laboratories, Inc., Skokie, IL
	George Yoggy, Master Builders Technologies, Cleveland, OH
	Leon Glassgold, Masonry Resurfacing and Construction Company, Baltimore, MD
	Frank Nelson, Oregon DOT, Salem, OR
	Christy Philipp, California DOT, Sacramento, CA
	Dan Thomas, California DOT, Sacramento, CA
	John Simmons, Pneumatic Concrete Inc., Birmingham, AL
	Peter C. Tatnall, Bekaert Corporation, Marietta, GA
	Larry Totten, Johnson Western Gunite Company, San Leandro, CA
	Curt White, Coastal Gunite Construction Company, Cambridge, MD

Guide Specifications for Shotcrete Repair of Highway Bridges

Table of Contents

Introduction to the Joint AASHTO-AGC-ARTBA Guide Specifications for

Shotcrete Repair of Highway Bridges

1.0 BACKGROUND This Guide Specification is adapted from the Recommended Practice for Shotcrete Repair of Highway Bridges which was prepared by Dr. D. R. Morgan, Professional Engineer of HBT AGRA Limited, Vancouver, B.C., Canada, under the auspices of the Canadian Strategic Highway Research Program (C-SHRP) study titled *Durability of Shotcrete Rehabilitation Treatments of Bridges*. C-SHRP is a program of the Transportation Association of Canada (TAC). The guidance, review and critical comment of the following C-SHRP Project Committee on Shotcrete Repair of Bridges' members in preparation of the original document is gratefully acknowledged:

Dr. David Manning, Professional Engineer, Ministry of Transportation, Ontario

Mr. Paul Carter, Professional Engineer, Alberta Transportation and Utilities

Mr. Daniel Vizina, Ing., Transports Québec

Mr. Greg Williams, Professional Engineer, C-SHRP National Coordinator

The contributions of Mr. W. S. Langley, Professional Engineer, of W. S. Langley and Associates Limited and Dr. Doug Hooton, Professional Engineer, of John Emery Geotechnical Engineering Limited to the initial C-SHRP study are also gratefully acknowledged.

This document represents the best current practice for the durable shotcrete repair of bridges and is based on the professional experience of the prime author and persons acknowledged above in the implementation of many shotcrete repair projects.

Permission to adapt the document was provided under Cooperative Agreement DTFH61-95-X-00005 between the Federal Highway Administration and the Transportation Association of Canada. The original document was revised and adapted for use in the U.S. by Joint Task Force 37, Shotcrete Repair of Highway Bridges, comprised of the following members:

Jim Asher, Fibermesh Company, San Antonio, TX

Ken Boedecker, W. R. Grace and Company, Charleston, SC

Jim Dikeou, ACI, Detroit, MI

Mahmoud Elnahal, Virginia DOT, Richmond, VA

Steven H. Gebler, Construction Technology Laboratories, Inc., Skokie, IL

George Yoggy, Master Builders Technologies, Cleveland, OH

Leon Glassgold, Masonry Resurfacing and Construction Company, Baltimore, MD

Frank Nelson, Oregon DOT, Salem, OR

Christy Philipp, California DOT, Sacramento, CA

Dan Thomas, California DOT, Sacramento, CA

John Simmons, Pneumatic Concrete Inc., Birmingham, AL

Peter C. Tatnall, Bekaert Corporation, Marietta, GA

Larry Totten, Johnson Western Gunite Company, San Leandro, CA

Curt White, Coastal Gunite Construction Company, Cambridge, MD

Gerald White, Chairman, North Carolina DOT, Raleigh, NC

Bruce Johnson, Secretary, Federal Highway Administration, Salem, OR

It is believed that if remedial works are conducted rigorously in accordance with the procedures outlined in this Guide Specification, the Owner will be provided with durable shotcrete repairs and greater service life than the surrounding non-repaired concrete.

2.0 SPECIFIER'S GUIDE

This document has been prepared in a three-part format:

(a) Guide Specifications for Dry-Mix Shotcrete Repair of Highway Bridges,

(b) Guide Specifications for Wet-Mix Shotcrete Repair of Highway Bridges, and

(c) Commentary on Guide Specifications for Shotcrete Repair of Highway Bridges.

There is a considerable amount of repetition of content between the Dry-Mix and Wet-Mix Specifications, but it was considered that there were sufficient differences between the dry-mix and wet-mix shotcrete processes that they warranted separate treatment. The Guide Specifications are followed by a Commentary, which applies to both the dry- and wet-mix shotcrete processes. This Commentary draws distinctions between the two processes, and provides the Specifier with guidance to assist in selection of the appropriate shotcrete process for a given project. The Commentary also provides additional guidance to the Specifier and Contractor regarding the practical repair of bridges with shotcrete.

The Joint Task Force recognized that a National Specification cannot be written which would be directly applicable to each State or even each region of the country. Nevertheless, the Specifier should be able to readily adopt material from the document in preparation of project-specific specifications, including combining the two Guide Specifications to allow the contractor to select the most efficient process for a given project.

The Specifier will be required to make certain design selections and choices in preparing a specification. **The Commentary**

section of the document must be used in conjunction with the Guide Specifications section to aid the Specifier in preparation of contract documents. The same numbering system has been used in the Guide Specifications and Commentary section of the document to aid the Specifier in this process. As a further aid to the specifier, a CHECKLIST is provided in Section 5 of this Introduction. This CHECKLIST summarizes items requiring action by the Engineer.

The Payment section was based on a consensus of the Joint Task Force. Nevertheless, it is recognized that agencies may change to other methods of measurement and payment depending on local preferences. These documents concentrate on technical requirements for the remedial work.

Pertinent American Concrete Institute (ACI) and American Society for Testing and Materials (ASTM) documents are invaluable for providing background and details of common practice when making decisions about a specific project. However, they are not normally referenced in Specification documents since they are not written in specification format. Of these documents, the most useful is the ACI 506R-90, *Guide to Shotcrete*. While this document does not specifically address the use of shotcrete for repair of bridges, it contains much useful information which will be of assistance to the Specifier in preparing contract documents. The Guide Specifications cite specific chapters in ACI 506R with the intent that the specifier, using the Commentary, will choose the requirements which apply to the project and insert those requirements in the project specifications using appropriate imperative language.

3.0 DEFINITIONS

The following definitions refer to words and terms used in this specification. For definitions not covered in this document, refer to ACI 506R and ACI 506.2.

3.1 **Acceptable, approved or permitted**: Acceptable to, approved or permitted by the Engineer.

3.2 **Bench gunning**: The practice of shooting thick members of full section by building from the bottom up.

3.3 **Blowpipe**: Air jet operated by nozzleman's helper in shotcrete gunning to assist in keeping rebound and overspray out of the work.

3.4 **Contractor**: The person, firm or corporation with whom the Owner enters into agreement for construction of the work.

3.5 **Dry-Mix Shotcrete**: Shotcrete in which most of the mix water is added at the nozzle.

3.6 **Engineer**: The accepting authority responsible for issuing the project specifications and administering work under the contract documents.

3.7 **Ground Wire** (also called **screed wire** or **shooting wire**): Small gauge, high strength wire used to establish line and grade to guide shotcrete work.

3.8 **Gunning** (also called **shooting**): The act of applying shotcrete.

3.9 **Nozzleman**: Worker on the shotcrete crew who manipulates the nozzle, controls air or water addition at the nozzle and controls final deposition of the material.

3.10 **Overspray**: Shotcrete material deposited away from the intended receiving surface.

3.11 **Predampener** (also known as **premoisturizer**): An apparatus used to predampen dry-mix shotcrete materials prior to discharge into the shotcrete gun.

3.12 **Rebound**: Shotcrete material leaner than the original mixture which ricochets off the receiving surface and falls to accumulate on the ground or other surfaces.

3.13 **Rod**: Sharp-edged cutting screed used to trim shotcrete to forms or ground wires.

3.14 **Shotcrete**: Mortar or concrete pneumatically projected at high velocity onto a receiving surface.

3.15 **Sloughing** (also called **sagging**): Subsistence of shotcrete, due generally to excessive water in the mix or placing too great a thickness of shotcrete in a single pass.

3.16 **Specifier**: The authority issuing the project specifications, normally the Engineer.

3.17 **Wet-Mix Shotcrete**: Shotcrete in which all the shotcrete ingredients, including mix water, are mixed prior to introduction into the shotcrete delivery system, and compressed air is introduced to the material flow at the nozzle.

4.0 DESIGN CONSIDERATIONS

4.1 Review of the performance of some 60 shotcrete repaired bridges in Canada (Reference 1, Commentary) has revealed that there are certain basic considerations which should be applied in the design of shotcrete repairs for bridges in order to provide durable, long service-life repairs.

4.2 Most deterioration in bridge structures, which has given rise to the need for shotcrete repair, has resulted from the combined actions of deicing chemicals and frost action on saturated concrete. In the remedial design, every attempt should be made, wherever possible, to protect the existing concrete and new shotcrete repairs from continuing exposure to deicing chemicals and saturation. Such measures may include sealing, repair or replacement of bridge decks and/or expansion joints; redesign of deck and abutment drainage systems; re-profiling substructure elements such as pier caps and abutments to prevent ponding and facilitate drainage. If this is not done, the original concrete can continue to deteriorate around the shotcrete repair, ultimately compromising the repair.

4.3 In many bridges it may be necessary to maintain either full or partial traffic on the bridge deck during the period of shotcrete remedial work. It should be noted that it may be difficult to effect quality repairs on elements which are subjected to continuous vibration or deflections from traffic during shotcreting operations. Careful consideration should be given at the design stage as to whether traffic control measures or restrictions need to be placed on the bridge during the repair program. Questions which need to be considered include the following:

- Will live loads be allowed on the bridge during repairs?
- Will temporary shoring or strengthening of the structure be required?
- How long must the repairs be allowed to cure before the bridge is returned to full service?

4.4 Some shotcrete repair of bridges has been required because of general deterioration of the concrete matrix, attributable to alkali-aggregate reactivity, or the use of inherently non-freeze/thaw durable, non-air-entrained concrete in the original construction. In shotcrete repair of such structures, reliance should not be placed solely on the quality of bond of the shotcrete to the original concrete for long-term performance of the repair. Concrete could continue to deteriorate behind the shotcrete repair and thus it becomes important to tie back the repair shotcrete into the existing concrete, using appropriately designed anchors or the existing reinforcement. If this is not done, there is a danger of long-term "slabbing" failure of the repair, the failure being initiated in the original concrete with the shotcrete still adhered to it.

4.5 Corrosion of embedded reinforcing steel and subsequent spalling in the original concrete has been the cause of the need for shotcrete repair of many bridges. In many instances, corrosion has resulted from a lack of adequate cover to reinforcing steel (sometimes caused by cage movement during original construction). In such repair, it is important that all spalled, deteriorated and delaminated concrete be removed. Also, concrete should be removed and replaced in areas displaying high reinforcing steel corrosion activity as indicated by half-cell potential measurements or other suitable procedures. In such repairs, concrete should be removed from around corroded reinforcing steel to provide a minimum of 20 mm clearance behind the steel, to facilitate full encapsulation with shotcrete. Tests have shown (Reference 2, Commentary) that only partial removal of concrete to the front face of the reinforcing steel will compromise the longevity of the repair, particularly in elements subjected to repetitive dynamic loading. Reinforcing bars should be bent back or surface contours adjusted to provide adequate cover.

4.6 In many severely corroded bridge elements, it may be necessary to remove and replace, or supplement existing reinforcing steel with additional reinforcement. Some older bridges may be inadequately reinforced by current design standards. Additional reinforcement can be included as part of the designed repair. Fiber reinforcement can be effectively used in some structures, in lieu of reinforcing mesh, but not in lieu of primary reinforcing steel. Fiber reinforcement can be very effective in minimizing thermal and shrinkage-induced cracking in the shotcrete repair. It also provides increased toughness and impact resistance to the shotcrete repair.

4.7 In repair of deteriorated load-bearing elements, it may be necessary to carry out the repair work in a sequential manner, with partial concrete removal, preparation and shotcreting being completed in repair of a bridge component, prior to removal of more material. This is particularly important in repair of pier caps and abutments in areas adjacent to bearings. Careful consideration should be given by the Engineer and Contractor to the needs for shoring and sequential repair so that the safety of the structure is not compromised.

4.8 The design should prohibit "featheredging" of shotcrete repairs or the application of "skim-coats" of shotcrete to unprepared original concrete surface. Such types of repairs have a high occurrence of failure in the field. The perimeter of all prepared areas for shotcrete repairs should be chipped on a 45-degree angle (to facilitate escape of rebound) except that the outer edges of prepared repair areas should be saw cut to a square edge, to a minimum depth of 15 mm, to neatly define the extremity of the repair and eliminate shotcrete "featheredging".

4.9 Where considerable thicknesses of shotcrete are required to be applied (particularly in overhead applications), consideration should be given to the use of dry-mix silica fume shotcrete. Wherever possible, shotcrete should be applied in a single lift, rather than in multiple-layer construction; dry-mix silica fume shotcrete is better suited to single lift construction than any of the other shotcrete types.

4.10 In repair of structural elements such as piers, abutments and parapets, the designer should attempt to completely cap the element with repair shotcrete. If the shotcrete repair does not cap the element, there is a potential for the shotcrete to act as a "dam" and promote the saturation of the original concrete with water and salt solution. This can accelerate deterioration of the original concrete. Caps should be designed with a minimum 3 percent grade to facilitate drainage.

4.11 Superstructure elements, such as deck soffits, girders, beams and arches, should be designed with grooves or drip strips, to prevent wetting and staining of the soffits of such elements with water and salts.

4.12 Finally, the designer should consider the aesthetic requirements for the shotcrete repairs. The particular type of shotcrete used, and type of finish selected, will affect aesthetics. The most economical finish is the as-shot, gun finish. This may suffice for many structures with low visibility or on secondary highways, but may not be satisfactory for bridges in city areas, or on primary highways, where visual aesthetics and public perception are important. In such structures, the requirements for finishing of shotcrete repairs and possibly even the application of pigmented coatings should be considered at the design stage.

5.0 CHECKLIST

This CHECKLIST summarizes items requiring action by the Engineer. The reference numbers in the checklist refer to numbers in the clauses in the Guide Specifications which follow.

1.2 Qualifications

1.2.1 Specify contractor and nozzlemen qualifications.

1.3 Requirements

1.3.1 Provide details in the contract documents and in the field regarding areas of spalled, deteriorated and damaged concrete requiring removal.

1.3.1 Provide details regarding replacement of excessively corroded reinforcing steel.

1.3.1 Provide details for all new reinforcing steel, mesh and anchors.

1.3.2 Provide criteria and guidelines or details for temporary support of portions of the bridge, if needed.

2.0 Submittals

2.0 Review submittal and approve contractor qualification test reports, mix design, preconstruction trial results, quality control program, curing details and temporary support.

4.0 Materials

4.1.1 Specify required cement type.

4.2.1 Specify which supplementary cementing materials, if any, to be used.

4.4.1 Specify nominal maximum aggregate size and gradation.

4.5.1 Specify whether air-entraining admixture is required and the amount or rate of addition at the nozzle, if appropriate.

4.5.2 Specify which chemical admixtures are required or allowed.

4.6.2 Provide details for all replacement reinforcing steel.

4.6.4 Specify whether fiber is to be used, and if so, type, length, diameter, if appropriate, and addition rate (kg/m^3).

5.0 Shotcrete Proportioning

5.1.1 Review and approve shotcrete mixture proportions proposed for use by Contractor.

5.1.4 Review shotcrete mix performance test data from previous experience, if available.

5.2.1 Specify silica fume content, if appropriate.

5.3 Performance Requirements

5.3.1 Specify shotcrete performance requirements.

(Note: Make any project-specific changes to Table 1 that may be required.)

5.3.2 (Optional) Establish maximum permissible rapid chloride permeability coulomb limits for shotcrete which does not contain silica fume.

6.0 Supply and Equipment

6.1.1 Provide written approval for site batching using either the volume or mass batching method.

6.1.5 Specify frequency for mass batch checks on volumetrically proportioned shotcrete mixtures.

7.0 Preparation for Shotcreting

7.1.1 Provide direction for removal of unsound concrete and for removal depths greater than 150 mm, if appropriate.

7.1.7 Specify whether requirement for abrasive blast cleaning of prepared surfaces may be waived (e.g., in case of surface preparation with high-pressure water blasting).

7.1.8 Approve the method of disposal of debris.

7.2 Reinforcement

7.2.2 Direct Contractor as to which corroded reinforcing steel to remove and replace. Specify the percent of loss of cross section for which bars must be augmented or replaced.

7.2.4 Specify the minimum lap length for replacement reinforcement.

7.2.6 Specify whether welding of replacement reinforcement is permitted.

7.2.11 Specify whether fiber reinforcement is permitted as an alternative to mesh reinforcement; provide details for anchor and tie-back systems.

7.3 Anchors

7.3.1 Specify anchor spacing.

7.3.2 Specify anchor type.

7.3.3 Specify minimum pull-out force required for anchors; specify frequency of anchor testing to verify pull-out force.

7.4 Alignment Control and Cover

7.4.2 Review and approve Contractor's proposed means of alignment and cover control.

7.4.7 Specify required tolerances on finished work.

8.0 Quality Assurance and Quality Control Testing

8.1.1 Administer quality assurance program, as detailed in Section 8.1.1.

8.2.1 Specify the hardened shotcrete properties to be tested in the contractor's quality control program and the frequency of the tests.

8.3.1 Evaluate Contractor performance in preconstruction trial.

8.3.3 Direct the contractor to core preconstruction trial panels at reinforcement intersections and in unreinforced areas.

8.3.7 Evaluate quality of cores extracted from prequalification test panel.

10.0 Shotcrete Application and Finishing

10.1.1 Review and approve prepared areas prior to application of shotcrete.

10.1.6 Specify whether use of curing compound is permitted in multiple-layer shotcrete construction.

10.1.8 Approve areas not requiring temporary support.

10.1.9 Verify whether sufficient lighting and ventilation is being provided to enable safe application of quality shotcrete.

10.1.12 Specify the tolerance for line and grade of shotcrete repair surfaces.

10.2.1 Specify type of finish required.

11.0 Curing and Protection

11.1.1 Specify whether use of curing compound permitted.

11.1.3 Specify minimum period of moist curing.

11.2.3 Review and approve Contractor's proposed hot weather shotcreting procedures.

11.2.5 Review and approve Contractor's proposed heating procedures for cold weather shotcreting.

12.0 Shotcrete Acceptance and Repair

12.1.1 Reject shotcrete work which does not conform to the project specifications.

12.1.4 Examine the completed shotcrete work for any deficiencies.

12.1.5 Implement a program of testing for in-place shotcrete if compliance testing on shotcrete test panels, or assessment of plastic or hardened shotcrete indicates non-conformance with project specifications; provide details for locations of cores to evaluate in-place shotcrete. Specify core hole patching details.

12.2.3 Inspect and approve prepared repair areas prior to application of repair shotcrete.

Part II of the Joint AASHTO-AGC-ARTBA Guide Specifications for

Dry-Mix Shotcrete Repair of Highway Bridges

1.0 GENERAL DESCRIPTION AND REQUIREMENTS

1.1 Scope

1.1.1 This document provides a guide specification for the repair of highway bridges using the dry-mix shotcrete process. It provides guide specifications for: selection of materials; shotcrete mixture proportioning; selection of shotcrete equipment; preparation for shotcreting; quality assurance and quality control testing; safety measures; shotcrete application, finishing and curing procedures; and shotcrete acceptance. If incorporated into the Contract Documents, this document shall become a part of the Contract Documents and the Contractor shall comply with all provisions in this document unless otherwise specified by the Contract Documents or modified in writing by the Engineer.

1.2 Qualifications

1.2.1 The shotcrete contractor's crew foreman and nozzlemen shall meet the following requirements unless otherwise *specified in the Contract Documents*:

(a) Furnish proof that the shotcrete crew foreman has at least 5 years experience in shotcrete repair work on projects of similar size and character along with 5 references who were responsible for supervision of similar projects. Include name, address and telephone number of references who will testify to the successful completion of these projects by the shotcrete crew foreman.

(b) Furnish proof that the nozzlemen have successfully completed 3 projects of similar size and character along with 3 references of those responsible for supervision of these projects. The nozzlemen shall also pass a test, described in Section 8.3, demonstrating their competence.

1.3 Requirements

1.3.1 The Contractor shall furnish all labor, materials and equipment for the following:

(a) Removal of all spalled, deteriorated and damaged concrete as detailed in the Contract Documents and directed by the Engineer;

(b) Cleaning corrosion product from corroded in-place reinforcing steel and *where specified* removing and replacing excessively corroded reinforcing steel with new reinforcement;

(c) Preparing concrete surfaces to receive shotcrete by either high-pressure water blasting or abrasive grit blasting;

(d) Installing all new reinforcing steel, mesh and anchors as detailed in the Contract Documents;

(e) Supply, application, finishing, curing and protection of shotcrete; and

(f) Provision of a quality control program to ensure compliance of completed shotcrete remedial work with contract documents.

1.3.2 The Contractor shall implement a safety program which shall include but not necessarily be limited to the following:

(a) Ensuring that the structural integrity of all bridge elements is protected during the repairs by shoring or other suitable means *as specified in the Contract Documents;*

(b) Protecting all personnel and the traveling public from falling debris, blasting grits and high-pressure water jets during concrete removal processes;

(c) Protecting all personnel and the traveling public from pneumatically applied shotcrete and rebound materials during the shotcrete application process;

(d) Ensuring that all employees have training for materials being handled on site and that Material Safety Data Sheets for all materials being used are available on site for inspection and use; and

(e) Ensuring compliance with all state and Federal OSHA regulations.

2.0 SUBMITTALS The Contractor shall submit to the Engineer 10 working days before the commencement of production shotcreting work written documentation which provides:

2.1 The qualifications of the work crew, including the supervisor, shotcrete nozzlemen, gunmen and blowpipe operators, and the references for the supervisor and nozzlemen required in 1.2.1 (a) and (b).

2.2 Test records, showing source and proof of conformance to project specifications of all shotcrete materials, including:

(a) Portland cement,

(b) Supplementary cementing materials (silica fume, fly ash, ground blast furnace slag),

(c) Aggregates,

(d) Mix water,

(e) Chemical admixtures, and

(f) Reinforcement, including welded wire mesh fabric, reinforcing steel, fibers.

2.3 Details of proposed shotcrete mixture(s) including shotcrete proportions and means of shotcrete supply.

2.4 Results of the preconstruction testing program and a description of the proposed construction quality control testing program, including the frequency of specific tests.

2.5 Proposed curing procedures and protection to be provided to shotcrete.

2.6 Proposed scaffolding or other temporary support system for workers and inspectors.

2.7 Proposed falsework or temporary support system for all bridge elements which undergo loss of strength or support during concrete removal operations. Design criteria for temporary structural support systems shall be as listed in the Contract Documents.

3.0 REFERENCE DOCUMENTS

3.1 The documents referenced below form a part of this document only to the extent referenced. In case of conflicts between the referenced portions of these documents and this specification, the requirements of this specification take precedence.

3.1.1 American Concrete Institute (ACI)

ACI 305R	Hot Weather Concreting
ACI 306R	Cold Weather Concreting
ACI 506R	Guide to Shotcrete
ACI 506R.3	Guide to Certification of Shotcrete Nozzlemen
ACI 506.2	Specifications for Materials Proportioning and Application of Shotcrete

3.1.2 American Society for Testing and Materials (ASTM)

ASTM A 185	Specification for Steel Welded Wire Fabric, Plain, for Concrete Reinforcement
ASTM A 385	Practice for Providing High-Quality Zinc Coating (Hot Dip)

ASTM A 615	Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement
ASTM A 641	Specification for Zinc-Coated (Galvanized) Carbon Steel Wire
ASTM A 706	Specification for Low-Alloy Steel Deformed Bars for Concrete Reinforcement
ASTM A 767	Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement
ASTM A 775	Specification for Epoxy-Coated Reinforcing Steel Bars
ASTM A 820	Specification for Steel Fibers for Fiber Reinforced Concrete
ASTM C 33	Specification for Concrete Aggregates
ASTM C 39	Test Method for Compressive Strength of Cylindrical Concrete Specimens
ASTM C 42	Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
ASTM C 150	Specification for Portland Cement
ASTM C 260	Specification for Air-Entraining Admixtures for Concrete
ASTM C 387	Standard Specification for Packaged, Dry, Combined Materials for Mortar and Concrete
ASTM C 494	Specification for Chemical Admixtures for Concrete
ASTM C 595M	Specification for Blended Hydraulic Cements
ASTM C 618	Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete

ASTM C 642	Standard Test Method for Specific Gravity, Absorption and Voids in Hardened Concrete
ASTM C 685	Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing
ASTM C 989	Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars
ASTM C 1017	Specification for Chemical Admixtures for Use in Producing Flowing Concrete
ASTM C 1116	Standard Specification for Fiber Reinforced Concrete and Shotcrete
ASTM C 1140	Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels
ASTM C 1202	Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
ASTM C 1240	Specification for Silica Fume for Use in Hydraulic-Cement Concrete and Mortar

3.1.3 American Association of State Highway and Transportation Officials (AASHTO)

AASHTO M 6	Standard Specification for Fine Aggregate for Portland Cement Concrete
AASHTO M 80	Standard Specification for Coarse Aggregate for Portland Cement Concrete
AASHTO M 157	Ready-Mixed Concrete

4.0 MATERIALS

4.1 Cement

4.1.1 Cement shall conform to the requirements of ASTM C 150 or C 595M. Engineer shall select appropriate cement type.

4.2 Supplementary Cementing Materials

4.2.1 *Engineer shall specify* which supplementary cementing materials, if any, are permitted or required for use on project.

4.2.2 Fly ash shall conform to the requirements of ASTM C 618.

4.2.3 Granulated slag shall conform to the requirements of ASTM C 989, Grade 100 or 120, ground granulated blast furnace slag.

4.2.4 Silica fume shall conform to the requirements of ASTM C 1240.

4.3 Water

4.3.1 All water used in shotcrete production, including water added in premoisturizer and at the shotcrete nozzle, shall be of drinking water standard and free of oil and chemical or organic impurities.

4.3.2 Similarly, all water used for high-pressure water blasting, predampening of concrete surfaces prior to application of shotcrete, in blowpipes for removal of rebound and overspray, and for shotcrete curing shall be of drinking water standards and free of oil and chemical or organic impurities.

4.4 Aggregates

4.4.1 Aggregates shall be normal weight aggregates conforming to the requirements of AASHTO M 6 for fine aggregate and AASHTO M 80 for coarse aggregate. Gradation of aggregates shall be as required in the Contract Documents or as approved by the Engineer.

4.5 Admixtures

4.5.1 No admixtures shall be added to the shotcrete *without approval of the Engineer.* In particular any admixtures containing chlorides shall not be used. Shotcrete accelerators shall not be used *without written authorization by the Engineer.*

4.5.2 Air-entraining admixtures shall be added to the mix water *if specified in the Contract Documents.* Air-entraining admixtures shall conform to the requirements of ASTM C 260.

4.6 Reinforcement

4.6.1 Welded wire mesh fabric shall be welded galvanized steel of dimensions and mass specified in drawings and shall conform to ASTM A 185.

4.6.2 New or replacement reinforcing bars shall be installed as detailed in the Contract Documents. Reinforcing bars shall conform to ASTM A 615, A 706, A 767, or A 775.

4.6.3 Inserts for attachment of welded wire mesh fabric to existing concrete shall be galvanized in accordance with ASTM A 385 and A 641, and be of adequate length and strength to resist a 10-kN pull-out force.

4.6.4 Fibers shall conform to the requirements of ASTM C 1116. Fiber type, length and addition rate shall be as *specified in the Contract Documents*.

4.7 Materials Handling and Storage

4.7.1 Portland cement and supplementary cementing materials shall be stored so as to be protected from exposure to moisture and temperatures below 5 degrees C and above 30 degrees C.

4.7.2 All admixtures shall be maintained at temperatures above 5 degrees C and below 30 degrees C at all times.

4.7.3 Aggregates used in site batching of shotcrete shall be stockpiled and handled so as to prevent segregation, and shall be maintained in a 3 to 7 percent moisture content range. Shelters or tarpaulins shall be used to protect the aggregate stockpiles during periods of wet weather.

4.7.4 Fiber shall be stored in dry, sealed containers until ready for batching and shall be free from corrosion, oil, grease or other contaminants.

5.0 SHOTCRETE PROPORTIONING

5.1 Mixture Design

5.1.1 The Contractor shall be responsible for shotcrete mixture proportioning and shall submit the proposed shotcrete mixture proportions *to the Engineer for review and approval* 10 working days prior to application of production shotcrete. As a minimum, for each shotcrete mixture design the following information shall be submitted:

(a) An easily identifiable mix designation, number or code;

(b) Batch quantities of fine aggregate, coarse aggregate, cement, supplementary cementing material, expected water demand (to include all water from moisture in aggregates, and water added in premoisturizer and at nozzle) and all other shotcrete ingredients, in kg/m^3, based on saturated surface dry aggregates; and

(c) Aggregate source, gradation, relative bulk density (specific gravity) and absorption.

5.1.2 Allowance shall be made for the shooting orientation and rebound in shotcrete mixture proportioning.

5.1.3 Shotcrete shall be proportioned to meet the performance requirements detailed in the project drawings and Section 5.3.

5.1.4 The Contractor shall submit performance test data from previous experience, if available, along with the shotcrete mixture proportions *for review by the Engineer.*

5.1.5 In the absence of suitable shotcrete mixture proportioning experience, the Contractor shall use the nominal trial mixture proportions detailed in Section 5 of the Commentary section of this Guide Specification. Adoption of these nominal trial mixture proportions shall not relieve the Contractor of responsibility for meeting the performance requirements detailed in the Contract Documents.

5.2 Silica Fume Shotcrete

5.2.1 The silica fume content of silica fume shotcrete shall be between 5 and 15 percent by mass of cement content or *as specified in the Contract Documents.*

5.2.2 Silica fume shall be supplied and added to the mixture in either a slurry; loose, uncompacted; or partially compacted form. Densely compacted silica fume shall not be used.

5.3 Performance Requirements

5.3.1 Shotcrete shall conform to the performance requirements in Table 1.

TABLE 1
Dry-Mix Shotcrete Performance Requirements

Test Description	Test Method	Age (Days)	Specified Requirement
Min. Compressive Strength, MPa (f'_c)	ASTM C 39 ASTM C 42	7 28	28 35
Max. Boiled Absorption, % Max. Vol. of Permeable Voids, %	ASTM C 642	7 7	8 17
Max. Rapid Chloride Permeability, Silica-Fume Shotcrete, Coulombs	ASTM C 1202	7	1500

5.3.2 For dry-mix shotcretes other than silica-fume shotcrete, *the Contract Documents shall establish* maximum permissible rapid chloride permeability coulomb limits.

6.0 SUPPLY AND EQUIPMENT

6.1 Batching, Mixing and Supply

6.1.1 Dry-mix shotcrete shall be batched, mixed and supplied by one of the following methods:

(a) Dry-bagged premix material supplied in either small bags (30 kg typical) or large synthetic cloth bulk bin bags (1600 kg typical),

(b) Site batching, using either volume or mass batching subject to *written approval by the Engineer* of the proposed batching equipment.

6.1.2 The use of mobile volumetric batcher units shall be permitted, provided such units are properly calibrated in accordance with ASTM C 685.

6.1.3 The use of central or transit mix batched and transit mix supplied dry-mix shotcrete shall not be permitted unless the Contractor can demonstrate satisfactory conformance to all the project performance requirements.

6.1.4 All dry-mix shotcrete shall be shot within 45 minutes of the time that moisture (either from damp sand or the premoisturizer) comes into contact with the cementitious materials.

6.1.5 When using volume batching, proportions shall be verified *at the frequency specified in the Contract Documents,* using a mass batching check. The minimum checking frequency shall be at the beginning of the work and at least once a week thereafter.

6.1.6 Dry-bagged premixed shotcrete materials shall be produced in conformance with the pertinent requirements of ASTM C 387. In particular, all aggregates shall be dried to a moisture content of less than 0.1 percent by mass, based on oven drying at 105 to 110 degrees C.

6.1.7 Dry-bagged premixed shotcrete materials shall be protected from moisture during handling, transport and storage. Any bags which display lumps of pre-hydrated shotcrete shall not be used on the project.

6.1.8 Dry-bagged premixed shotcrete materials shall be maintained in a temperature range of 5 to 30 degrees C during storage and application. Frozen material shall not be used.

6.2 Shotcrete Placing Equipment

6.2.1 Shotcrete batching, mixing and supply equipment shall be capable of combining the dry-mix shotcrete materials into a uniform mixture and discharging it without segregation.

6.2.2 Dry-bagged premixed shotcrete materials shall be predampened to provide a consistent moisture content in the range of 3 to 5 percent by mass in a predampener, prior to discharge into the shotcrete gun. Discharge of completely dry materials into the shotcrete gun shall not be permitted, unless satisfactory performance is demonstrated in the test panel.

6.2.3 Similarly, for site-mixed materials, if the moisture content in the sand is too low to provide a moisture content of the mixed shotcrete materials in the range of 3 to 5 percent, then the shotcrete shall be predampened in a predampener, prior to discharge into the shotcrete gun.

6.2.4 The mixing and predampening units shall be capable of producing a shotcrete mixture with a uniform moisture content, such that the nozzleman is not required to repeatedly adjust the water content at the nozzle water ring.

6.2.5 The delivery equipment (gun) shall be capable of discharging a continuous, smooth stream of uniformly mixed material into the delivery hose.

6.2.6 The discharge nozzle shall be equipped with a manually operated water injection system (water ring) for directing an even distribution of water through the mixture. The water valve shall be capable of ready adjustment to vary the quantity of water and shall be convenient to the nozzleman.

6.2.7 The water pressure at the discharge nozzle shall be sufficiently greater than the operating air pressure so that the water is intimately mixed with the predampened shotcrete materials. If the line water pressure is inadequate, a water booster pump shall be introduced into the water line to provide a steady, non-pulsating water pressure. Water heaters shall be provided during cold weather if required to produce shotcrete at a suitable temperature.

6.2.8 The water ring shall be carefully monitored for any signs of blockage of individual water spray holes. If non-uniform wetting of discharged shotcrete becomes apparent, shooting shall be stopped, and the water ring cleaned or other appropriate corrective actions taken.

6.2.9 The delivery equipment shall be thoroughly cleaned at the end of each shift. Any build-up of coatings in the delivery hose and nozzle liner shall be removed. The water ring and nozzle shall be regularly inspected and replaced as required.

6.3 Auxiliary Shotcrete Equipment

6.3.1 The Contractor shall supply a clean, dry air supply, capable of maintaining sufficient nozzle velocity for all parts of the work and simultaneous operation of a blowpipe and, if pneumatically operated, the predampener.

6.3.2 The air supply system shall contain a moisture and oil trap to prevent contamination of the shotcrete.

6.3.3 Auxiliary shotcrete equipment such as delivery hose, water hose, water booster pumps, blowpipes, couplings, admixture dispensers and fiber feeders shall conform to the recommendations in Section 3.8 of ACI 506R.

7.0 PREPARATION FOR SHOTCRETING

7.1 Concrete Removal and Preparation

7.1.1 The Contractor, *at the direction of the Engineer*, shall locate and remove all loose, spalled, deteriorated and delaminated concrete. Sounding shall be used to locate delaminated areas. Care shall be exercised not to damage areas of sound concrete or reinforcing steel during concrete removal operations. Unless specifically *directed by the Engineer*, depth of removal shall not exceed 150 mm. Concrete removal shall be in accordance with a sequence approved by the Engineer.

7.1.2 Concrete removal shall be accomplished using one or more of the following methods:

a) Chipping with hand picks, chisels or light-duty pneumatic or electric chipping hammers (not to exceed 7 kg mass);

b) Scarifiers, scabblers or other suitable mechanical means; and/or

c) High-pressure (100 to 275 MPa) water jetting.

7.1.3 If sound concrete is encountered before existing reinforcing steel is exposed, the surface shall be prepared and repaired without further removal of the concrete. When corroded reinforcing steel is exposed, concrete removal shall continue until there is a minimum 20-mm clearance around the exposed, corroded reinforcing bar. Care shall be taken to not damage bond to adjacent non-exposed reinforcing steel during concrete removal processes.

7.1.4 The perimeter of all areas where concrete is removed shall be tapered at an approximately 45-degree angle, except that the outer edges of all chipped areas shall be sawcut to minimum depth of 15 mm to prevent featheredging unless otherwise approved by the Engineer.

7.1.5 After all deteriorated concrete has been removed, the repair surface to receive shotcrete shall be prepared by abrasive blast cleaning or high-pressure (100 to 275 MPa) water jetting. The repair surface shall have an adequate surface roughness determined as three peak-to-valley measurements of 5 mm within 150 mm.

7.1.6 Abrasive blast cleaning or high-pressure water jetting shall remove all fractured surface concrete and all traces of any unsound material or contaminants such as oil, grease, dirt, slurry, or any materials which could interfere with the bond of freshly placed shotcrete. Cleaned areas shall have shotcrete applied within 48 hours or shall be reblasted.

7.1.7 The requirement for abrasive blast cleaning or high-pressure water jetting may be waived by *the Engineer* where concrete removal has been performed with high-pressure water blasting and the prepared surface is free of any residual slurry or other material detrimental to adequate shotcrete bond.

7.1.8 Unless otherwise *specified in the Contract Documents*, all material removed shall become the property of the Contractor and shall be disposed of as approved by the Engineer.

7.2 Reinforcement

7.2.1 All corroded reinforcing steel exposed during concrete removal shall have corrosion products removed by abrasive grit blasting. The exposed reinforcing steel surface that is facing away from the sandblast nozzle shall be cleaned to remove all dust and loose particles.

7.2.2 Reinforcing steel displaying deep pitting or loss of more than 20 percent of cross-sectional area or as *specified in the Contract Documents* shall be removed and replaced or augmented with additional reinforcement, *as detailed in the Contract Documents.*

7.2.3 In cases of isolated pitting, the existing reinforcing steel need not be cut, but shall be reinforced by addition of appropriately placed reinforcing bar of suitable length *as detailed in the Contract Documents.*

7.2.4 The minimum lap splice length of all replacement and new reinforcing steel shall be *as detailed in the Contract Documents.* Such bars shall be placed in accordance with the recommendations of ACI 506R, Sections 5.4 and 5.5. In particular, bars shall not be bundled in lapped splices, but shall be placed such that the minimum spacing around each bar is three times the maximum aggregate size or 20 mm, whichever is larger, to allow for proper encapsulation with shotcrete.

7.2.5 Intersecting reinforcing bars shall be tightly secured to each other using 1.6-mm or heavier gauge tie wire, and adequately supported to minimize vibration during shotcrete placement.

7.2.6 As an alternative to lapped splices, replacement reinforcing steel shall be welded to existing reinforcing, subject to verification of weldability of both existing and new reinforcing steel and *as specified in the Contract Documents*.

7.2.7 Welded wire mesh fabric reinforcement shall conform to the requirements of ASTM A 185 and shall be galvanized.

7.2.8 Welded wire mesh fabric shall be provided as *detailed in the Contract Documents* and at each repair area larger than 0.1 square meter if the depth of the repair exceeds 70 mm from the original dimension of the repaired member. Sheets of adjoining mesh shall be lapped by at least one and one-half spaces at all intersections, in both directions, and be securely fastened. Welded wire mesh fabric shall have a minimum shotcrete cover of 50 mm.

7.2.9 Mesh shall be fastened to preset anchors or existing reinforcing using 1.6-mm or heavier gauge tie wire, on a grid not more than 300 mm square. Large knots of tie wire which could result in sand pockets and voids during shotcreting shall be avoided.

7.2.10 The minimum clearance between installed reinforcing steel or mesh and existing concrete shall be 20 mm.

7.2.11 As an alternative to welded wire mesh fabric, steel or synthetic fiber reinforced shotcrete may be used, as *specified in the Contract Documents*. Fiber reinforced shotcrete shall only be used in conjunction with appropriate anchor and tie-back systems, as *specified by the Contract Documents*.

7.3 Anchors

7.3.1 Anchors shall be positioned at the spacing *detailed in the Contract Documents*. Any given area shall have a minimum of four anchors. The reinforcing shall not vibrate or deform excessively during shotcreting. Unless otherwise specified, the maximum anchor spacing shall not exceed 600 mm on a grid pattern over the entire repair area.

7.3.2 Anchors shall be of the type *specified in the Contract Documents* and shall be either mechanically set or grouted, as specified.

7.3.3 Anchors shall develop the minimum pull-out force *specified by the Contract Documents.* Anchors shall be randomly tested at a frequency *specified by the Contract Documents* to verify pull-out force. In no case shall the pull-out force be less than 10 kN. If any anchors fail to meet the minimum acceptable pull-out value, corrective measures shall be taken.

7.4 Alignment Control and Cover

7.4.1 Alignment control shall be implemented to establish control over line and grade and ensure that the minimum specified shotcrete thickness and cover to reinforcing steel are maintained.

7.4.2 Alignment control shall be accomplished by means of shooting wires, guide strips, depth gauges or forms. The proposed means of alignment control shall be *submitted to the Engineer for review and approval.*

7.4.3 When shooting wires (also called ground wires) are used, they shall consist of a high-strength steel wire (piano wire) kept taut during shotcreting. Shooting wires shall be removed after completion of shotcreting and screeding operations.

7.4.4 Guide strips and forms shall be of such dimensions and installation configuration that they do not impede the ability of the nozzleman to produce uniform, dense, properly consolidated shotcrete. In particular, installations which are conducive to the formation of sand pockets and voids shall not be used.

7.4.5 When depth gauges are used for alignment control, they shall be installed at a spacing not exceeding 1200 mm on a grid pattern. Metal depth gauges shall be cut back to 5 mm below the finished surface to prevent corrosion staining on the surface.

7.4.6 All repaired members shall be restored as close as practicable to their original dimensions, including chamfered, if detailed. A minimum of 50-mm shotcrete cover shall be provided over reinforcing steel exposed during repair.

8.0 QUALITY ASSURANCE AND QUALITY CONTROL TESTING

8.1 Quality Assurance

8.1.1 The owner shall implement a quality assurance program for the work. Such a program will normally be administered by the Engineer and shall include:

(a) Review of Contractor Submittals;

(b) Review and approval of Contractor's proposed materials, supply, equipment and crew. In particular, all shotcrete nozzlemen proposed for use on the project shall be evaluated in the preconstruction testing program; only nozzlemen approved in writing by the Engineer shall be used on the project.

(c) Examination and approval of all areas prepared for shotcreting, including installation of anchors, reinforcement, and devices to control line and grade, prior to application of any shotcrete;

(d) Provision of inspectors to monitor shotcrete installation, with the authority to require removal and replacement of defective shotcrete while still plastic;

(e) Regular monitoring of the results of the Contractor's quality control testing;

(f) Implementation of a program for in-place evaluation and acceptance or rejection, where test results indicate shotcrete non-conforming to the project specifications;

(g) Implementation of a program of remedial works by the contractor, where indicated as being necessary from the results of the quality assurance program.

8.2 Quality Control Testing

8.2.1 The Contractor shall establish and maintain a quality control program for the shotcrete work to assure compliance with the contract requirements. Such a program shall include, but not be limited to the following:

(a) Maintenance of test records for all quality control operations;

(b) For site-batched materials, regular monitoring of aggregate gradation and moisture content; one moisture content check shall be made at the start-up of each shotcreting operation and with any changes in aggregate moisture content;

(c) For dry-bagged premix materials, wash-out testing at the frequency *specified by the Contract Documents* to check cementitious content, aggregate gradation, and fiber content of fiber reinforced shotcrete;

(d) For volume-batched shotcrete, mass batch checks of moisture content of aggregates and mixture proportions at the *frequency specified by the Contract Documents*; and

(e) Physical testing for the hardened shotcrete performance parameters specified in the Contract Documents at the frequency *specified by the Contract Documents.*

8.3 Preconstruction Trials

8.3.1 The Contractor shall implement a preconstruction trial to enable the Engineer to evaluate conformance of the proposed materials, shotcrete mixture, equipment and crew to the project specifications. Acceptance of the preconstruction trial results by the Engineer is required prior to performance of any work *detailed in the Contract Documents*.

8.3.2 The preconstruction trial shall be used to prequalify the nozzlemen proposed for use on the project. Nozzlemen who have not been prequalified shall not be permitted to apply shotcrete on the project.

8.3.3 The preconstruction trial shall approximate actual working conditions, configuration, reinforcement, and shooting position as near as possible. The trial shall involve a workmanship demonstration in accordance with Section 2.5 of ACI 506.3R, *Guide to Certification of Shotcrete Nozzlemen*. The trial shall be evaluated by core grading in accordance with ACI 506.2. Cores for grading shall be taken at locations of intersecting reinforcement, *as directed by the Engineer*. Cores from any one panel shall have a mean grade of 2.0 or less. Panels are unacceptable if any of the cores have a grade of 4 or 5 as described in Section 8.3.4.

8.3.4 Core Grading

8.3.4.1 Grade 1: Shotcrete specimens are solid; there are no laminations, sandy areas or voids. Small air voids with a maximum diameter of 3 mm and maximum length of 6 mm are normal and acceptable. Sand pockets or voids behind continuous reinforcing steel are unacceptable. The surface against the form or bond plane shall be sound, without a sandy texture or voids.

8.3.4.2 Grade 2: Shotcrete specimens shall have no more than two laminations or sandy areas with dimensions not to exceed 3 mm thick by 25 mm long. The height, width and depth of voids shall not exceed 10 mm. Porous areas behind reinforcing steel shall not exceed 13 mm in any direction except along the length of the reinforcing steel. The surface against the form or bond plane shall be sound with full paste, without a sandy texture or voids.

8.3.4.3 Grade 3: Shotcrete specimens shall have no more than two laminations or sandy areas with dimensions exceeding 5 mm thick by 32 mm long, or one major void, sand pocket, or lamination containing loosely bonded sand not to exceed 16 mm thick and 32 mm in width. The surface against the form or bond plane may be sandy with voids containing overspray to a depth of 2 mm.

8.3.4.4 Grade 4 core: The core shall meet in general the requirements of Grade 3 cores, but may have two major flaws such as described for Grade 3 or may have one flaw with a maximum dimension of 25 mm perpendicular to the face of the core with a maximum width of 38 mm. The end of the core that was shot against the form may be sandy with voids containing overspray to a depth of 3 mm.

8.3.4.5 Grade 5 core: A core that does not meet the criteria of core grade 1 through 4, by being of poorer quality, shall be classified as Grade 5.

8.3.5 Preconstruction test panels shall be prepared, cured, and tested in accordance with ACI 506.3R.

8.3.6 Three test specimens shall be extracted at each test age from the non-reinforced shotcrete, for testing for the performance parameters specified in Section 5.3, Table 1, except for Rapid Chloride Permeability test, if required, where two specimens shall suffice.

8.3.7 The Engineer shall evaluate the quality of the extracted cores and test panel. When a prequalification test panel is rejected, the nozzleman shall be permitted to shoot two additional test panels. If either of the additional test panels is also rejected, the nozzleman shall not be permitted to shoot on the project until he has successfully completed an appropriate training program and passed a preconstruction trial test.

8.3.8 If the preconstruction test specimens fail to meet the project performance requirements, then the Contractor shall make the necessary adjustments in shotcrete materials, mixture design or application, and re-shoot test panels. No work shall commence on the project until the preconstruction performance testing requirements have been met.

8.4 Construction Testing

8.4.1 One construction test panel shall be shot by each nozzleman for each 20 cubic meters of shotcrete production, but not more than once per day, and at least once per week. The panel shall be shot in the same position as the repair work being done.

8.4.2 Test panels shall be produced in accordance with the requirements of ASTM C 1140, but shall have minimum dimensions of 450 mm x 450 mm x 100 mm deep. They shall be constructed of wood and sealed plywood, with 45-degree sloped edge forms, to permit escape of rebound. Construction test panels shall contain no reinforcement or embedments (other than fiber reinforcement). The panels shall be cored or cut to provide three compression test specimens as described below.

8.4.3 Construction test panels shall be stored, handled and cured in the same manner prescribed for preconstruction test panels. Similarly, test specimens shall be prepared in the same manner prescribed for preconstruction test specimens.

8.4.4 Compressive strength test specimens shall be either:

(a) 75-mm diameter cores with length/diameter ratios preferably 2:1 and not less than 1:1, or

(b) 75-mm cubes.

Compressive strength tests shall be conducted in accordance with ASTM C 42. Measured compressive strengths shall be corrected to equivalent 2:1 (length: diameter) cores, using the core correction factors given in ASTM C 42.

8.4.5 The mean compressive strength for a set of three cores shall equal or exceed f'_c (where f'_c = specified strength). The mean of a set of three cubes shall equal or exceed 1.15 f'_c.

8.4.6 Specimens for boiled absorption and permeable voids testing to ASTM C 642 shall be 75-mm cubes, or extracted 75-mm diameter cores at least 100 mm long. Three specimens shall be tested at age 7 days after shooting.

9.0 SAFETY AND CLEAN-UP

9.1 Preparation

9.1.1 The contractor shall implement a safety program during preparation for shotcreting to ensure that:

(a) The structural integrity of all bridge elements is protected during concrete and reinforcing steel removal operations by shoring or other suitable means;

(b) All personnel are protected from falling debris, blasting grits and high-pressure water jets during concrete removal processes.

9.1.2 The Contractor shall dispose of all debris, blasting grits, hydrodemolition and water jetting slurry in accordance with all local, state, and Federal laws, rules and regulations.

9.2 Shotcrete Application Safety

9.2.1 The Contractor shall implement a safety program to protect all personnel and surrounding property from pneumatically applied shotcrete overspray and rebound materials during the shotcrete application process, using shrouds, screens or other appropriate measures.

9.2.2 Personnel working near the shotcreting operation, including nozzleman, nozzleman's helpers, supervisor and inspectors, shall wear appropriate protective equipment. Such equipment shall include, but not be limited to safety helmet, safety boots, gloves, appropriate clothing, safety eye glasses with side enclosures and dust masks.

9.2.3 Nozzleman's helper shall keep a supply of water, cloth or towel and back-up safety glasses available for nozzleman, so satisfactory vision can be maintained at all times during shooting operations. Sufficient lighting shall be provided to enable the nozzleman to have a clear view of the work.

9.2.4 Eyebaths and wash facilities shall be readily available in the immediate vicinity of the shotcrete application. Shotcrete crew shall apply appropriate skin protection and adopt work hygiene to protect against cement or accelerator alkali burn.

10.0 SHOTCRETE APPLICATION AND FINISHING

10.1 Shotcrete Application

10.1.1 All areas prepared for shotcrete repair shall be reviewed and *approved by the Engineer* prior to application of any shotcrete.

10.1.2 Shotcrete shall be applied in accordance with good practice as detailed in Chapter 8 of ACI 506R. Application requirements of Section 8.5 of ACI 506R apply, except that with silica-fume modified shotcrete it will usually be possible to apply the full thickness of shotcrete in a single pass, without the need for multiple-layer construction. Wherever possible, shotcrete shall be applied to the full thickness in a single layer.

10.1.3 The concrete substrate shall be saturated the day before shotcreting and then re-wetted prior to shooting. At least one hour prior to application of shotcrete, all surfaces to be shotcreted shall be flushed with water of drinking quality standard. Wetted surfaces shall be allowed to dry back to a saturated-surface-dry condition prior to application of shotcrete. If necessary, a blowpipe shall be used to facilitate removal of surface water. Only oil-free compressed air shall be used in the blowpipe. In the event a work stoppage longer than two hours takes place on any shotcrete layer prior to the time it has been built up to required thickness, the surface shall be re-wetted prior to continuing. No shotcrete shall be applied to a dry surface or to a surface with free surface water.

10.1.4 The minimum number of layers required to build up the full thickness of shotcrete without sagging, separation or sloughing shall be used.

10.1.5 When using multiple-layer shotcrete construction, the first layer shall be prepared before application of a subsequent layer by either:

(a) Brooming the stiffening layer with a stiff bristle broom to remove all loose material, rebound, overspray or glaze, prior to the shotcrete attaining initial set; or

(b) If the shotcrete has set, surface preparation shall be delayed at least 24 hours, at which time the surface shall be prepared by sandblasting or high-pressure water blasting to remove all loose material, rebound, hardened overspray, glaze, or other material that prevents adequate bond as *specified in the Contract Documents*.

10.1.6 When successive layers of shotcrete are required to build up the full shotcrete thickness, the first layer shall be prevented from drying out by fogging or wetting. The use of curing compound shall not be permitted between layers, except with the *approval of the Engineer* in writing. If a curing compound is used, it shall be removed by abrasive blast cleaning or high-pressure water blasting, prior to application of the next layer of shotcrete. The first layer of shotcrete shall be free of surface water and in a saturated-surface-dry condition at the time of application of the next shotcrete layer.

10.1.7 Care shall be exercised to protect adjacent surfaces from build-up of rebound and overspray. Rebound shall not be permitted in the completed work. Hardened rebound and hardened overspray shall be removed prior to application of additional shotcrete, using abrasive blast cleaning, chipping hammers, high-pressure water blasting or other suitable techniques.

10.1.8 The Contractor shall provide scaffolding or other temporary support system (e.g., manlifts, suspended work platform, etc.) at each repair location unless otherwise *approved by the Engineer*. Plans for the proposed temporary support system shall be provided to the Engineer for review and approval prior to its installation. No holes shall be drilled into the superstructure to accommodate the support system unless approved in writing by the Engineer. All anchorages placed in the substructure shall be removed when the platform is removed and the substructure repaired at no additional cost.

10.1.9 Sufficient lighting and ventilation shall be installed to provide the nozzleman and helpers with a clear, unhindered view of the shooting area. Work shall be terminated and corrective measures adopted if, in the opinion of the Engineer, visibility is unsuitable for the safe application of quality shotcrete.

10.1.10 Shotcrete nozzling shall follow acceptable shooting practice, as detailed in Section 8.5 of ACI 506R. In particular,

(a) The nozzle shall be generally operated at a distance of one-half to one-and-one-half meters from the receiving surface and shall be oriented at right angles to the receiving surface, except as required to fill corners, cover edges and encase large diameter reinforcing steel;

(b) The combination of air pressure at the nozzle, moisture content of the shotcrete and distance of the nozzle from the receiving surface shall be optimized to achieve maximum compaction of the shotcrete;

(c) Care shall be taken while encasing reinforcing steel and mesh to keep the front face of the reinforcement clean during shooting operations, so that shotcrete builds up from behind, to encase the reinforcement and prevent voids and sand pockets from forming; and

(d) Accumulations of rebound and overspray shall be continuously removed by the blowpipe operator in advance of the deposition of new shotcrete. Rebound material shall not be reused.

10.1.11 Shotcrete shall not be applied during periods of rain or high wind which could interfere with the shotcrete stream unless suitable protective covers, enclosures or wind breaks are installed.

10.1.12 Shotcrete shall be applied to the required line and grade and tolerance *detailed in the Contract Drawings*, using shooting wires, depth gauges, guide strips, forms or other suitable devices that do not entrap rebound. Shotcrete shall be applied to provide the minimum cover to reinforcing detailed in the drawings. A positive means of checking the total thickness of the applied shotcrete shall be provided by the use of shooting wires which shall be removed prior to the final finish coat.

10.1.13 The application of a 5- to 20-mm thick final layer of plain 5-mm maximum size aggregate flash coat of shotcrete shall be permitted over the top of 10-mm maximum aggregate size shotcrete or steel fiber reinforced shotcrete.

10.2 Shotcrete Finishing

10.2.1 Unless finishing is specifically *required in the Contract Documents*, the surface of the shotcrete shall be built up slightly and trimmed to the final surface by cutting with the leading edge of a sharp trowel. Any imperfections shall be floated using a rubber float. Work done to the finished surface shall be limited to correcting imperfections caused by cutting with the trowel.

10.2.2 Where finishing is required, shotcrete shall be cut back to line and grade using trowels, cutting rods, screeds or other suitable devices. The shotcrete shall be allowed to stiffen sufficiently before cutting and trimming so as to prevent the formation of tears, cracks and delaminations. Shooting wires shall be removed on completion of cutting and trimming.

10.2.3 One or more of the following optional finishes may be applied, *as specified in the Contract Documents:*

(a) Wood float finish, either as a preliminary finish for other surface treatments, or as a granular texture finish;

(b) Rubber float finish, applied to either a flash coat or wood float finish, to produce a finer textured granular finish;

(c) Brush finish, a fine hairbrush float finish, leaving a finely textured, sandy finish.

10.2.4 All shotcrete and overspray shall be trimmed back from adjacent non-prepared concrete surfaces. The edges of all shotcrete repairs shall have a minimum square saw-cut edge 15 mm deep and shotcrete shall be finished up to this edge. Featheredging of shotcrete (including flash coats) shall be prohibited.

11.0 CURING AND PROTECTION

11.1 Curing

11.1.1 On completion of finishing, shotcrete shall immediately be prevented from drying out by fogging, wetting or where *permitted by the Contract Documents*, by application of a curing compound.

11.1.2 Curing compounds, if *permitted by the Contract Documents*, shall be removed prior to application of subsequent paints, coatings or additional layers of shotcrete.

11.1.3 Once shotcrete has attained final set, it shall be kept continuously moist for a minimum period of 7 days, unless *the Contract Documents permit* a shorter curing period, or the use of a curing compound. Moist curing shall be accomplished using one or more of the following procedures:

(a) Wrapping the elements in wet burlap which has been presoaked in water for 24 hours prior to installation; wrapping the wet burlap in plastic sheet is useful for retarding the rate of drying of the burlap;

(b) Installation of sprinklers, soaker hoses or other devices which keep the shotcrete repairs continuously wet. The use of intermittent wetting procedures which allow the shotcrete to undergo wetting and drying during the curing period shall be prohibited.

11.2 Hot and Cold Weather Protection

11.2.1 The general requirements for hot and cold weather concreting, detailed in ACI 305R and ACI 306R, shall also apply to shotcrete remedial work except the maximum temperature of the shotcrete shall not exceed 35 degrees C.

11.2.2 If the prevailing ambient conditions (relative humidity, wind speed, air temperature and direct exposure to sunlight) are such that the shotcrete develops plastic shrinkage and/or early drying shrinkage cracking, shotcrete application shall be terminated. The Contractor shall:

(a) Reschedule the work to a time when more favorable ambient conditions prevail; and/or

(b) Adopt corrective measures, such as installation of sun-screens, wind breaks, surface evaporation retardants or fogging devices, to protect the work.

11.2.3 Shotcrete application shall be terminated if the ambient temperature rises above 30 degrees C, unless the Contractor adopts special hot weather shotcreting procedures, which are *approved by the Engineer.*

11.2.4 During periods of cold weather, shotcreting may only proceed if the concrete substrate to which the shotcrete is applied is free of frost and the air temperature in contact with the repair surfaces is above 5 degrees C.

11.2.5 The air temperature in contact with repaired surfaces shall be maintained at 5 degrees C or greater for at least 3 days after application of shotcrete. The means of maintaining the air temperature shall be *approved by the Engineer.* The use of unvented heaters, which give rise to carbonation, shall be prohibited.

11.2.6 The temperature of applied shotcrete shall be preferably in the range of 10 to 20 degrees C but not outside the range of 5 to 35 degrees C. Cooler mix temperatures are preferred during hot weather shotcreting operations and warmer mix temperatures during cold weather shotcreting.

12.0 SHOTCRETE ACCEPTANCE AND REPAIR

12.1 Shotcrete Acceptance

12.1.1 The *Engineer shall have authority* to accept or reject the shotcrete work. Shotcrete which does not conform to the project specifications may be rejected either during the shotcrete application process or on the basis of tests on the test panels or completed work.

12.1.2 Deficiencies observed during the shotcrete application process, such as, but not limited to:

(a) failure to properly control and remove build-up of overspray and rebound;

(b) incomplete encasement of or incomplete consolidation around reinforcing steel, mesh or anchors;

(c) incorporation of sand lenses, excessive voids, delaminations, sags, rebound, and sloughing; or

(d) failure to apply shotcrete to the required line and grade and tolerance

shall constitute cause for rejection of the plastic shotcrete. If plastic shotcrete is rejected the contractor shall stop the work and take all measures necessary to correct deficiencies.

12.1.3 The Contractor shall, whenever possible, perform remedial work to correct deficiencies while the shotcrete is still plastic.

12.1.4 The *Engineer shall examine* the completed shotcrete work. The hardened shotcrete shall be examined for any evidence of cracking, tears, featheredging, sloughs or other deficiencies. Sounding or other non-destructive evaluation (NDE) methods shall be used to check for delaminations at 28 days, or less when approved by the Engineer in writing. Non-conforming shotcrete is any that lacks uniformity; exhibits segregation, honeycombing, or delaminations; has suffered excessive cracking; was not prepared or applied in compliance with these specifications; fails to meet the specified requirements in Table 1; or fails to meet the core grading requirements.

12.1.5 If the results of compliance tests from shotcrete construction test panels, or assessment of the plastic and hardened shotcrete indicate non-conformance of the shotcrete to the project specifications, the contractor shall drill at least three cores from the repaired member. The cores shall penetrate into the existing concrete a minimum of 50 mm. The number and location of the cores shall be at *the discretion of the Engineer*. These cores shall be core graded in accordance with ACI 506.2 and tested for compressive strength, boiled absorption, volume of permeable voids, and rapid chloride permeability, if applicable. The shotcrete shall be accepted if the mean core grade is 2 or less and no individual core grade is 4 or 5, and the test results meet the specified requirements for Boiled Absorption, Volume of Permeable Voids, and Rapid Chloride Permeability, if applicable, in Table 1 and the following compressive strength criteria. The mean compressive strength of a set of three cores shall equal or exceed 0.85 f'_c with no individual core less than 0.75 f'_c. The mean of a set of three cubes shall equal or exceed f'_c with no individual cube less than

0.88 f'_c. All core holes shall be patched as *detailed in the Contract Documents.*

12.1.6 Shotcrete which is determined by the Engineer to be defective or non-conforming to the project specifications based on evaluation of cores from the finished shotcrete shall be repaired or removed and replaced by the contractor at no cost to the Owner. Repairs of non-conforming shotcrete are subject to the same testing, evaluation, and acceptance criteria as the original repair shotcrete.

12.2 Shotcrete Repair

12.2.1 Shotcrete which is identified as being non-conforming while still plastic shall be removed using spades, scrapers or other suitable mechanical devices. High-pressure water jetting may be used, subject to acceptable disposal of the removed shotcrete and slurry.

12.2.2 Hardened shotcrete which is identified as being non-conforming shall be removed using the same basic procedures used for removal of deteriorated concrete. Care shall be taken to avoid damage to reinforcing steel, mesh or anchors. Any embedments damaged during the shotcrete removal process shall be replaced at no cost to the Owner.

12.2.3 All prepared repair areas shall be *inspected and approved by the Engineer* prior to the placement of any repair shotcrete. Repair shotcrete shall be placed, finished, cured and protected in the same manner specified for shotcrete work.

12.2.4 The contractor shall bear the costs for all repair and tests for non-conforming shotcrete.

13.0 MEASUREMENT

13.1 Shotcrete shall be measured by the in-place or volume in cubic meters of applied shotcrete. The depth shall be measured from the original outside concrete face. The Contractor and Engineer shall measure repair quantities after removal of unsound concrete and before application of shotcrete.

13.2 Payment shall be full compensation for furnishing materials, equipment, labor, tools and incidentals required to accomplish temporary work access, preparation of surfaces, application of shotcrete, waste shotcrete and rebound, coring of test samples, testing, replacement of defective shotcrete as specified, clean-up of the area and disposal of waste water, wasted shotcrete and rebound, and all other work and overhead costs necessary to complete the designated pay items.

Pay Item	Unit of Measurement
Shotcrete	Cubic Meter

Part III of the Joint AASHTO-AGC-ARTBA Guide Specifications for

Wet-Mix Shotcrete Repair of Highway Bridges

1.0 GENERAL DESCRIPTION AND REQUIREMENTS

1.1 Scope

1.1.1 This document provides a guide specification for the repair of highway bridges using the wet-mix shotcrete process. It provides guide specifications for: selection of materials; shotcrete mixture proportioning; selection of shotcrete equipment; preparation for shotcreting; quality assurance and quality control testing; safety measures; shotcrete application, finishing and curing procedures; and shotcrete acceptance. If incorporated into the Contract Documents, this document shall become a part of the Contract Documents and the Contractor shall comply with all the provisions in this document unless otherwise specified in the Contract Documents or modified in writing by the Engineer.

1.2 Qualifications

1.2.1 The shotcrete contractor's crew foreman and nozzlemen shall meet the following requirements unless otherwise *specified in the Contract Documents*:

(a) Furnish proof that the shotcrete crew foreman has at least 5 years experience in shotcrete repair work on projects of similar size and character along with 5 references who were responsible for supervision of similar projects. Include name, address, and telephone number of references who will testify to the successful completion of these projects by the shotcrete crew foreman.

(b) Furnish proof that the nozzlemen have successfully completed 3 projects of similar size and character along with 3 references of those responsible for supervision of these projects. The nozzlemen shall also pass a test, described in Section 8.3, demonstrating their competence.

1.3 Requirements

1.3.1 The Contractor shall furnish all labor, materials and equipment for the following:

(a) Removal of all spalled, deteriorated and damaged concrete as detailed in the Contract Documents and directed by the Engineer;

(b) Cleaning corrosion product from corroded in-place reinforcing steel and *where specified* removing and replacing excessively corroded reinforcing steel with new reinforcement;

(c) Preparing concrete surfaces to receive shotcrete by either high-pressure water blasting or abrasive grit blasting;

(d) Installing all new reinforcing steel, mesh and anchors *as detailed in the Contract Documents;*

(e) Supply, application, finishing, curing and protection of shotcrete; and

(f) Provision of a quality control program to ensure compliance of completed shotcrete remedial work with contract documents.

1.3.2 The Contractor shall implement a safety program which shall include but not necessarily be limited to the following:

(a) Ensuring that the structural integrity of all bridge elements is protected during the repairs by shoring or other suitable means *as specified in the Contract Documents*;

(b) Protecting all personnel and the traveling public from falling debris, blasting grits and high-pressure water jets during concrete removal processes;

(c) Protecting all personnel and the traveling public from pneumatically applied shotcrete and rebound materials during the shotcrete application process;

(d) Ensuring compliance with all state and Federal OSHA regulations.

2.0 SUBMITTALS The Contractor shall submit to the Engineer 10 working days before commencement of production shotcreting work written documentation which provides:

2.1 The qualifications of the work crew, including the supervisor, shotcrete nozzlemen, pump operator and shotcrete blowpipe operators, and the references for the supervisor and nozzlemen required in 1.2.1 (a) and (b).

2.2 Test records, showing source and proof of conformance to project specifications of all shotcrete materials, including:

a) Portland cement,

(b) Supplementary cementing materials (silica fume, fly ash, ground blast furnace slag),

(c) Aggregates,

(d) Mix water,

(e) Chemical admixtures, and

(f) Reinforcement, including welded wire mesh fabric, reinforcing steel, fibers.

2.3 Details of proposed shotcrete mixture(s) including shotcrete proportions and means of shotcrete supply.

2.4 Results of the preconstruction testing program and a description of the proposed construction quality control testing program, including the frequency of specific tests.

2.5 Proposed curing procedures and protection to be provided to shotcrete.

2.6 Proposed scaffolding or other temporary support system for workers and inspectors.

2.7 Proposed falsework or temporary support system for all bridge elements which undergo loss of strength or support during concrete removal operations. Design criteria for temporary structural support systems shall be as listed in the Contract Documents.

3.0 REFERENCE DOCUMENTS

3.1 The documents referenced below form a part of this document only to the extent referenced. In the case of conflicts between the referenced portions of these documents and this specification, the requirements of this specification shall take precedence.

3.1.1 American Concrete Institute (ACI)

ACI 305R	Hot Weather Concreting
ACI 306R	Cold Weather Concreting
ACI 506R	Guide to Shotcrete
ACI 506R.3	Guide to Certification of Shotcrete Nozzlemen
ACI 506.2	Specifications for Materials Proportioning and Application of Shotcrete

3.1.2 American Society for Testing and Materials (ASTM)

ASTM A 185	Specification for Steel Welded Wire Fabric, Plain, for Concrete Reinforcement
ASTM A 385	Practice for Providing High-Quality Zinc Coating (Hot Dip)

ASTM A 615	Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement
ASTM A 641	Specification for Zinc-Coated (Galvanized) Carbon Steel Wire
ASTM A 706	Specification for Low-Alloy Steel Deformed Bars for Concrete Reinforcement
ASTM A 767	Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement
ASTM A 775	Specification for Epoxy-Coated Reinforcing Steel Bars
ASTM A 820	Specification for Steel Fibers for Fiber Reinforced Concrete
ASTM C 33	Specification for Concrete Aggregates
ASTM C 39	Test Method for Compressive Strength of Cylindrical Concrete Specimens
ASTM C 42	Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
ASTM C 150	Specification for Portland Cement
ASTM C 260	Specification for Air-Entraining Admixtures for Concrete
ASTM C 387	Standard Specification for Packaged, Dry, Combined Materials for Mortar and Concrete
ASTM C 494	Specification for Chemical Admixtures for Concrete
ASTM C 595M	Specification for Blended Hydraulic Cements
ASTM C 618	Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete

ASTM C 642	Standard Test Method for Specific Gravity, Absorption and Voids in Hardened Concrete
ASTM C 685	Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing
ASTM C 989	Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars
ASTM C 1017	Specification for Chemical Admixtures for Use in Producing Flowing Concrete
ASTM C 1116	Standard Specification for Fiber Reinforced Concrete and Shotcrete
ASTM C 1140	Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels
ASTM C 1202	Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
ASTM C 1240	Specification for Silica Fume for Use in Hydraulic-Cement Concrete and Mortar

3.1.3 American Association of State Highway and Transportation Officials (AASHTO)

AASHTO M 6	Standard Specification for Fine Aggregate for Portland Cement Concrete
AASHTO M 80	Standard Specification for Coarse Aggregate for Portland Cement Concrete
AASHTO M 157	Ready-Mixed Concrete

4.0 MATERIALS

4.1 Cement

4.1.1 Cement shall conform to the requirements of ASTM C 150 or C 595M. Engineer shall select appropriate cement type.

4.2 Supplementary Cementing Materials

4.2.1 *Engineer shall specify* which supplementary cementing materials, if any, are permitted or required for use on project.

4.2.2 Fly ash pozzolan shall conform to the requirements of ASTM C 618.

4.2.3 Granulated slag shall conform to the requirements of ASTM C 989, Grade 100 or 120, ground granulated blast furnace slag.

4.2.4 Silica fume shall conform to the requirements of ASTM C 1240.

4.3 Water

4.3.1 All water used in shotcrete production shall be of drinking water standard and free of oil and chemical or organic impurities.

4.3.2 Similarly, all water used for high-pressure water blasting, predampening of concrete surfaces prior to application of shotcrete, in blowpipes for removal of rebound and overspray, and for shotcrete curing shall be of drinking water standards and free of oil and chemical or organic impurities.

4.4 Aggregates

4.4.1 Aggregates shall be normal weight aggregates conforming to the requirements of AASHTO M 6 for fine aggregate and AASHTO M 80 for coarse aggregate. Gradation of aggregates shall be as required in the Contract Documents or as approved by the Engineer.

4.5 Admixtures

4.5.1 No admixtures shall be added to the shotcrete *without approval of the Engineer.* In particular any admixtures containing chlorides shall not be used. Shotcrete accelerators shall not be used *without written authorization by the Engineer.*

4.5.2 Air-entraining admixtures shall be added to the mix water *if specified in the Contract Documents.* Air-entraining admixtures shall conform to the requirements of ASTM C 260.

4.5.3 Chemical admixtures, if used, such as water reducing and set-retarding admixtures, shall conform to the requirements of

ASTM C 494. Superplasticizing admixtures, if used, shall conform to the requirements of ASTM C 1017.

4.6 Reinforcement

4.6.1 Welded wire mesh fabric shall be welded galvanized steel of dimensions and mass specified in drawings and shall conform to ASTM A 185.

4.6.2 New or replacement reinforcing bars shall be installed *as detailed in the Contract Documents.* Reinforcing bars shall conform to ASTM A 615, A 706, A 767, or A 775.

4.6.3 Inserts for attachment of welded wire mesh fabric to existing concrete shall be galvanized in accordance with ASTM A 385 and A 641, and be of adequate length and strength to resist a 10-kN pull-out force.

4.6.4 Fibers shall conform to the requirements of ASTM C 1116. Fiber type, length and addition rate shall be as *specified in the Contract Documents.*

4.7 Materials Handling and Storage

4.7.1 Portland cement and supplementary cementing materials shall be stored so as to be protected from exposure to moisture and temperatures below 5 degrees C and above 30 degrees C.

4.7.2 All admixtures shall be maintained at temperatures above 5 degrees C and below 30 degrees C at all times.

4.7.3 Aggregates used in site batching of shotcrete shall be stockpiled and handled so as to prevent segregation, and shall be tested to determine percent moisture for use in mix design and calculation of water-cement ratio. Shelters or tarpaulins shall be used to protect the aggregate stockpiles during periods of wet weather.

4.7.4 Fiber shall be stored in dry, sealed containers until ready for batching and shall be free from corrosion, oil, grease or other contaminants.

5.0 SHOTCRETE PROPORTIONING

5.1 Mixture Design

5.1.1 The Contractor shall be responsible for shotcrete mixture proportioning and shall submit the proposed shotcrete mixture proportions *to the Engineer for review and approval* 10 working days prior to application of production shotcrete. As a minimum, for each shotcrete mixture design the following information shall be submitted:

(a) An easily identifiable mix designation, number or code;

(b) Batch quantities of fine aggregate, coarse aggregate, cement, supplementary cementing material, expected water demand (to include all water from moisture in aggregates, and water added at the batch site and on site) and all other shotcrete ingredients, in kg/m^3, based on saturated surface dry aggregates; and

(c) Aggregate source, gradation, relative bulk density (specific gravity) and absorption.

5.1.2 Allowance shall be made for the shooting orientation and rebound in shotcrete mixture proportioning.

5.1.3 Shotcrete shall be proportioned to meet the performance requirements detailed in the project drawings and Section 5.3.

5.1.4 The Contractor shall submit performance test data from previous experience, if available, along with the shotcrete mixture proportions *for review by the Engineer.*

5.1.5 In the absence of suitable shotcrete mixture proportioning experience, the Contractor shall use the nominal trial mixture proportions detailed in Section 5 of the Commentary section of this Guide Specification. Adoption of these nominal trial mixture proportions shall not relieve the Contractor of responsibility for meeting the performance requirements detailed in the Contract Documents.

5.2 Silica Fume Shotcrete

5.2.1 The silica fume content of silica fume shotcrete shall be between 5 and 15 percent by mass of cement content or *as specified in the Contract Documents.*

5.2.2 Silica fume shall be supplied and added to the mixture in either a slurry; loose, uncompacted; or partially compacted form. Densely compacted silica fume shall not be used.

5.2.3 Silica fume shall be used in conjunction with the addition of sufficient superplasticizing and water reducing admixture to control water demand of the mixture. The water demand of wet-mix silica fume shotcrete shall not exceed the water demand of a comparable Portland cement shotcrete mixture without silica fume.

5.3 Performance Requirements

5.3.1 Shotcrete shall conform to the performance requirements in Table 1.

TABLE 1
Wet-Mix Shotcrete Performance Requirements

Test Description	Test Method	Age (Days)	Specified Requirement
Max. Water–Cementitious Materials Ratio		–	0.42
Air Content–As Shot, %	ASTM C 231	–	5 ± 1½
Slump at Discharge into Pump, mm	ASTM C 143	–	60 ± 20
Min. Compressive Strength, MPa (f'_c)	ASTM C 39 ASTM C 42	7 28	28 35
Max. Boiled Absorption, % Max. Vol. of Permeable Voids, %	ASTM C 642	7 7	8 17
Max. Rapid Chloride Permeability, Silica-Fume Shotcrete, Coulombs	ASTM C 1202	7	1500

5.3.2 For wet-mix shotcrete other than silica-fume shotcrete, *the Contract Documents shall establish* maximum permissible rapid chloride permeability coulomb limits.

5.3.3 The air content shall be determined on shotcrete shot into an air pressure meter base.

6.0 SUPPLY AND EQUIPMENT

6.1 Batching, Mixing and Supply

6.1.1 Wet-mix shotcrete shall be batched, mixed and supplied by one of the following methods:

(a) Central mixing with transit mix delivery,

(b) Transit mixing and delivery,

(c) Volumetric batching, mobile mixer unit, or

(d) Dry-bagged premix materials with water added at site.

6.1.2 Central Mixing and Supply

(a) Aggregate, cement and silica fume shall be mass batched in a central mix plant and delivered in a transit mixer in accordance with the requirements of AASHTO M 157. Water and chemical admixtures shall be volumetrically batched. Weighing equipment shall be capable of batching to the accuracy specified in ASTM C 685.

(b) Shotcrete materials shall be added in any sequence which provides uniform mixing and dispersion except that all water reducing admixtures and superplasticizers shall be in the mixer at the time of addition of silica fume powder.

(c) Transit mixers shall be free of excessive accumulations of hardened shotcrete or concrete in the drum or on the blades. Blades shall be free of excessive wear. Transit delivery shall conform to the requirements of AASHTO M 157, Section 10.

(d) One retempering with superplasticizer added directly to the transit mixture during the period of discharge shall be permitted in order to maintain workability (slump) of shotcrete within the specified range of 60 ± 20 mm. Mixing shall continue for a minimum period of five minutes at rated mixing speed after all additions of superplasticizer to the transit mixer.

(e) All shotcrete shall be shot within 90 minutes after addition of mix water to the batch. Shotcrete loads shall be of such batch size that this requirement is met.

6.1.3 Transit Mixing and Supply

(a) The same requirements shall apply as for central mixing except that all ingredients shall be added directly to the transit mixer, instead of the central mixer. Transit mixers shall be charged to not more than 70 percent of their rated capacity, to enable efficient mixing action.

6.1.4 Volumetric Site Batching

(a) The mobile mixer unit for volumetric batching shall conform to the requirements of ASTM C 685. The equipment shall proportion materials to the tolerances specified in ASTM C 685.

(b) The equipment shall be capable of thoroughly mixing materials in sufficient quantity to maintain shotcreting continuity.

(c) The equipment shall be calibrated in accordance with the requirement of ASTM C 685 at the start of every shift or every 30 cubic meters of shotcrete batched, whichever is more frequent, using a mass batch check of the volumetric proportioning.

(d) Feed systems for all materials (cement, silica fume, aggregates, admixtures) shall be interconnected so that if one feed stops, they all stop.

(e) The equipment shall be cleaned thoroughly at least once per shift to prevent accumulation of aged material.

(f) All wet-mix shotcrete shall be applied within 90 minutes of mixing. Aged material shall be discarded and not applied in the work.

6.1.5 Dry-Bagged Premix Supply

(a) The use of dry-bagged premix supply with water addition at the site shall be permitted, provided the Contractor can demonstrate uniform mixing of the shotcrete and satisfactory conformance to all the proper performance requirements.

6.2 Shotcrete Placing Equipment

6.2.1 The shotcrete delivery equipment shall conform to the requirements of Sections 3.3, 3.6, and 3.7 of ACI 506R and shall be capable of delivering a steady stream of uniformly mixed material to the discharge nozzle at the proper velocity and rate of discharge.

6.2.2 The use of positive displacement pumps equipped with hydraulic or mechanically powered pistons (e.g., similar to conventional concrete piston pumps), with compressed air added at the discharge nozzle, is the preferred type of wet-mix shotcrete delivery system. Pneumatic feed guns, rotary type feed guns (similar to dry-mix guns) and peristaltic squeeze-type pumps shall only be used if the Contractor can demonstrate that they produce shotcrete meeting all the performance requirements in this document.

6.2.3 The air ring at the nozzle shall be carefully monitored for any signs of blockage of individual air holes. If non-uniform discharge of shotcrete becomes apparent, shooting shall be stopped, and the air ring cleaned or other appropriate corrective actions taken.

6.2.4 The delivery equipment shall be thoroughly cleaned at the end of each shift. Any build-up of coatings in the delivery hose and nozzle liner shall be removed. The air ring and nozzle shall be regularly inspected and replaced as required.

6.3 Auxiliary Shotcrete Equipment

6.3.1 The Contractor shall supply a clean, dry air supply, capable of maintaining sufficient nozzle velocity for all parts of the work and simultaneous operation of a blowpipe.

6.3.2 The air supply system shall contain a moisture and oil trap to prevent contamination of the shotcrete.

6.3.3 Auxiliary shotcrete equipment such as delivery hose, water hose, water booster pumps, blowpipes, couplings, admixture dispensers and fiber feeders shall conform to the recommendations in Section 3.8 of ACI 506R.

7.0 PREPARATION FOR SHOTCRETING

7.1 Concrete Removal and Preparation

7.1.1 The Contractor, at the *direction of the Engineer,* shall locate and remove all loose, spalled, deteriorated and delaminated concrete. Sounding shall be used to locate delaminated areas. Care shall be exercised not to damage areas of sound concrete or reinforcing steel during concrete removal operations. Unless specifically *directed by the Engineer*, depth of removal shall not exceed 150 mm. Concrete removal shall be in accordance with a sequence approved by the Engineer.

7.1.2 Concrete removal shall be accomplished using one or more of the following methods:

a) Chipping with hand picks, chisels or light-duty pneumatic or electric chipping hammers (not to exceed 7 kg mass);

b) Scarifiers, scabblers or other suitable mechanical means; and/or

c) High-pressure (100 to 275 MPa) water jetting.

7.1.3 If sound concrete is encountered before existing reinforcing steel is exposed, the surface shall be prepared and repaired without further removal of the concrete. When corroded reinforcing steel is exposed, concrete removal shall continue until there is a minimum 20-mm clearance around the exposed, corroded reinforcing bar. Care shall be taken to not damage bond to adjacent non-exposed reinforcing steel during concrete removal processes.

7.1.4 The perimeter of all areas where concrete is removed shall be tapered at an approximately 45-degree angle, except that the outer edges of all chipped areas shall be sawcut to minimum depth of 15 mm to prevent featheredging unless otherwise approved by the Engineer.

7.1.5 After all deteriorated concrete has been removed, the repair surface to receive shotcrete shall be prepared by abrasive blast cleaning or high-pressure (100 to 275 MPa) water jetting. The repair surface shall have an adequate surface roughness determined as three peak-to-valley measurements of 5 mm within 150 mm.

7.1.6 Abrasive blast cleaning or high-pressure water jetting shall remove all fractured surface concrete and all traces of any unsound material or contaminants such as oil, grease, dirt, slurry, or any materials which could interfere with the bond of freshly placed shotcrete. Cleaned areas shall have shotcrete applied within 48 hours or shall be reblasted.

7.1.7 The requirement for abrasive blast cleaning or high-pressure water jetting may be waived by *the Engineer* where concrete removal has been performed with high-pressure water blasting and the prepared surface is free of any residual slurry or other material detrimental to adequate shotcrete bond.

7.1.8 Unless otherwise *specified in the Contract Documents*, all material removed shall become the property of the Contractor and shall be disposed of as approved by the Engineer.

7.2 Reinforcement

7.2.1 All corroded reinforcing steel exposed during concrete removal shall have corrosion products removed by abrasive grit blasting. The exposed reinforcing steel surface that is facing away from the sandblast nozzle shall be cleaned to remove all dust and loose particles.

7.2.2 Reinforcing steel displaying deep pitting or loss of more than 20 percent of cross-sectional area or as *specified in the Contract Documents* shall be removed and replaced or augmented with additional reinforcement, *as detailed in the Contract Documents.*

7.2.3 In cases of isolated pitting, the existing reinforcing steel need not be cut, but shall be reinforced by addition of appropriately placed reinforcing bar of suitable length *as detailed in the Contract Documents.*

7.2.4 The minimum lap splice length of all replacement and new reinforcing steel shall be as *detailed in the Contract Documents.* Such bars shall be placed in accordance with the recommendations of ACI 506R, Sections 5.4 and 5.5. In particular, bars shall not be bundled in lapped splices, but shall be placed such that the minimum spacing around each bar is three times the maximum aggregate size or 20 mm, whichever is larger, to allow for proper encapsulation with shotcrete.

7.2.5 Intersecting reinforcing bars shall be tightly secured to each other using 1.6-mm or heavier gauge tie wire, and adequately supported to minimize vibration during shotcrete placement.

7.2.6 As an alternative to lapped splices, replacement reinforcing steel shall be welded to existing reinforcing, subject to verification of weldability of both existing and new reinforcing steel and as *specified in the Contract Documents.*

7.2.7 Welded wire mesh fabric reinforcement shall conform to the requirements of ASTM A 185 and shall be galvanized.

7.2.8 Welded wire mesh fabric shall be provided as *detailed in the Contract Documents* and at each repair area larger than 0.1 square meter if the depth of the repair exceeds 70 mm from the original dimension of the repaired member. Sheets of adjoining mesh shall be lapped by at least one and one-half spaces at all intersections, in both directions, and be securely fastened. Welded wire mesh fabric shall have a minimum shotcrete cover of 50 mm.

7.2.9 Mesh shall be fastened to preset anchors or existing reinforcing using 1.6-mm or heavier gauge tie wire, on a grid not more than 300 mm square. Large knots of tie wire which could result in sand pockets and voids during shotcreting shall be avoided.

7.2.10 The minimum clearance between installed reinforcing steel or mesh and existing concrete shall be 20 mm.

7.2.11 As an alternative to welded wire mesh fabric, steel or synthetic fiber reinforced shotcrete may be used, as *specified in the Contract Documents.* Fiber reinforced shotcrete shall only be used in conjunction with appropriate anchor and tie-back systems, as *specified by the Contract Documents.*

7.3 Anchors

7.3.1 Anchors shall be positioned at the spacing *detailed in the Contract Documents.* Any given area shall have a minimum of four anchors. The reinforcing shall not vibrate or deform excessively during shotcreting. Unless otherwise specified, the maximum anchor spacing shall not exceed 600 mm on a grid pattern over the entire repair area.

7.3.2 Anchors shall be of the type *specified in the Contract Documents* and shall be either mechanically set or grouted, as specified.

7.3.3 Anchors shall develop the minimum pull-out force *specified by the Contract Documents.* Anchors shall be randomly tested at a frequency *specified by the Contract Documents,* to verify pull-out force. In no case shall the pull-out force be less than 10 kN. If any anchors fail to meet the minimum acceptable pull-out value, corrective measures shall be taken.

7.4 Alignment Control and Cover

7.4.1 Alignment control shall be implemented to establish control over line and grade and ensure that the minimum specified shotcrete thickness and cover to reinforcing steel are maintained.

7.4.2 Alignment control shall be accomplished by means of shooting wires, guide strips, depth gauges or forms. The proposed means of alignment control shall be *submitted to the Engineer for review and approval.*

7.4.3 When shooting wires (also called ground wires) are used, they shall consist of a high-strength steel wire (piano wire) kept taut during shotcreting. Shooting wires shall be removed after completion of shotcreting and screeding operations.

7.4.4 Guide strips and forms shall be of such dimensions and installation configuration that they do not impede the ability of the nozzleman to produce uniform, dense, properly consolidated shotcrete. In particular, installations which are conducive to the formation of sand pockets and voids shall not be used.

7.4.5 When depth gauges are used for alignment control, they shall be installed at a spacing not exceeding 1200 mm on a grid pattern. Metal depth gauges shall be cut back to 5 mm below the finished surface to prevent corrosion staining on the surface.

7.4.6 All repaired members shall be restored as close as practicable to their original dimensions, including chamfered, if detailed. A minimum of 50-mm shotcrete cover shall be provided over reinforcing steel exposed during repair.

8.0 QUALITY ASSURANCE AND QUALITY CONTROL TESTING

8.1 Quality Assurance

8.1.1 The owner shall implement a quality assurance program for the work. Such a program will normally be administered by the Engineer and shall include:

(a) Review of Contractor Submittals;

(b) Review and approval of Contractor's proposed materials, supply, equipment and crew. In particular, all shotcrete nozzlemen proposed for use on the project shall be evaluated in the preconstruction testing program; only nozzlemen approved in writing by the Engineer shall be used on the project;

(c) Examination and approval of all areas prepared for shotcreting, including installation of anchors, reinforcement, and devices to control line and grade, prior to application of any shotcrete;

(d) Provision of inspectors to monitor shotcrete installation, with the authority to require removal and replacement of defective shotcrete while still plastic;

(e) Regular monitoring of the results of the Contractor's quality control testing;

(f) Implementation of a program for in-place evaluation and acceptance or rejection, where test results indicate shotcrete non-conforming to the project specifications;

(g) Implementation of a program of remedial works by the contractor, where indicated as being necessary from the results of the quality assurance program.

8.2 Quality Control Testing

8.2.1 The Contractor shall establish and maintain a quality control program for the shotcrete work to assure compliance with the contract requirements. Such a program shall include, but not be limited to the following:

(a) Maintenance of test records for all quality control operations;

(b) For site-batched materials, regular monitoring of aggregate gradation and moisture content; one moisture content check shall be made at the start-up of each shotcreting operation and with any changes in aggregate moisture content;

(c) For dry-bagged premix materials, wash-out testing at the frequency *specified by the Contract Documents* to check cementitious content, aggregate gradation, and fiber content of fiber reinforced shotcrete;

(d) For volume-batched shotcrete, mass batch checks of moisture content of aggregates and mixture proportions at the *frequency specified in the Contract Documents*; and

(e) Physical testing for the hardened shotcrete performance parameters *specified in the Contract Documents* at the frequency *specified by the Contract Documents.*

8.3 Preconstruction Trials

8.3.1 The Contractor shall implement a preconstruction trial to enable the Engineer to evaluate conformance of the proposed materials, shotcrete mixture, equipment and crew to the project specifications. Acceptance of the preconstruction trial results by the Engineer is required prior to performance of any work *detailed in the Contract Documents.*

8.3.2 The preconstruction trial shall be used to prequalify the nozzlemen proposed for use on the project. Nozzlemen who have not been prequalified shall not be permitted to apply shotcrete on the project.

8.3.3 The preconstruction trial shall approximate actual working conditions, configuration, reinforcement, and shooting position as near as possible. The trial shall involve a workmanship demonstration in accordance with Section 2.5 of ACI 506.3R, *Guide to Certification of Shotcrete Nozzlemen.* The trial shall be evaluated by core grading in accordance with ACI 506.2. Cores for grading shall be taken at locations of intersecting reinforcement, *as directed by the Engineer.* Cores from any one panel shall have a mean grade of 2.0 or less. Panels are unacceptable if any of the cores have a grade of 4 or 5 as described in Section 8.3.4.

8.3.4 Core Grading

8.3.4.1 Grade 1: Shotcrete specimens are solid; there are no laminations, sandy areas or voids. Small air voids with a maximum diameter of 3 mm and maximum length of 6 mm are normal and acceptable. Sand pockets or voids behind continuous reinforcing steel are unacceptable. The surface against the form or bond plane shall be sound, without a sandy texture or voids.

8.3.4.2 Grade 2: Shotcrete specimens shall have no more than two laminations or sandy areas with dimensions not to exceed 3 mm thick by 25 mm long. The height, width and depth of voids shall not exceed 10 mm. Porous areas behind reinforcing steel shall not exceed 13 mm in any direction except along the length of the reinforcing steel. The surface against the form or bond plane shall be sound with full paste, without a sandy texture or voids.

8.3.4.3 Grade 3: Shotcrete specimens shall have no more than two laminations or sandy areas with dimensions exceeding 5 mm thick by 32 mm long, or one major void, sand pocket, or lamination containing loosely bonded sand not to exceed 16 mm thick and 32 mm in width. The surface against the form or bond plane may be sandy with voids containing overspray to a depth of 2 mm.

8.3.4.4 Grade 4 core: The core shall meet in general the requirements of Grade 3 cores, but may have two major flaws such as described for Grade 3 or may have one flaw with a maximum dimension of 25 mm perpendicular to the face of the core with a maximum width of 38 mm. The end of the core that was shot against the form may be sandy with voids containing overspray to a depth of 3 mm.

8.3.4.5 Grade 5 core: A core that does not meet the criteria of core grades 1 through 4, by being of poorer quality, shall be classified as Grade 5.

8.3.5 Preconstruction test panels shall be prepared, cured, and tested in accordance with ACI 506.3R.

8.3.6 Three test specimens shall be extracted at each test age from the non-reinforced shotcrete for testing for the performance parameters specified in Section 5.3, Table 1, except for Rapid

Chloride Permeability test, if required, where two specimens shall suffice.

8.3.7 The Engineer shall evaluate the quality of the extracted cores and test panel. When a prequalification test panel is rejected, the nozzleman shall be permitted to shoot two additional test panels. If either of the additional test panels is also rejected, the nozzleman shall not be permitted to shoot on the project until he has successfully completed an appropriate training program and passed a preconstruction trial test.

8.3.8 If the preconstruction test specimens fail to meet the project performance requirements, then the Contractor shall make the necessary adjustments in shotcrete materials, mixture design or application, and re-shoot test panels. No work shall commence on the project until the preconstruction performance testing requirements have been met.

8.4 Construction Testing

8.4.1 One construction test panel shall be shot by each nozzleman for each 20 cubic meters of shotcrete production, but not more than once per day, and at least once per week. The panel shall be shot in the same position as the repair work being done.

8.4.2 Test panels shall be produced in accordance with the requirements of ASTM C 1140, but shall have minimum dimensions of 450 mm x 450 mm x 100 mm deep. They shall be constructed of wood and sealed plywood, with 45-degree sloped edge forms, to permit escape of rebound. Construction test panels shall contain no reinforcement or embedments (other than fiber reinforcement). The panels shall be cored or cut to provide three compression test specimens as described below.

8.4.3 Construction test panels shall be stored, handled and cured in the same manner prescribed for preconstruction test panels. Similarly, test specimens shall be prepared in the same manner prescribed for preconstruction test specimens.

8.4.4 Compressive strength test specimens shall be either:

(a) 75-mm diameter cores with length/diameter ratios preferably 2:1 and not less than 1:1, or

(b) 75-mm cubes.

Compressive strength tests shall be conducted in accordance with ASTM C 42. Measured compressive strengths shall be corrected to equivalent 2:1 (length:diameter) cores, using the core correction factors given in ASTM C 42.

8.4.5 The mean compressive strength for a set of three cores shall equal or exceed f'_c (where f'_c = specified strength). The mean of a set of three cubes shall equal or exceed 1.15 f'_c

8.4.6 Specimens for boiled absorption and permeable voids testing to ASTM C 642, shall be 75-mm cubes, or extracted 75-mm diameter cores at least 100 mm long. Three specimens shall be tested at age 7 days after shooting.

9.0 SAFETY AND CLEAN-UP

9.1 Preparation

9.1.1 The contractor shall implement a safety program during preparation for shotcreting to ensure that:

(a) The structural integrity of all bridge elements is protected during concrete and reinforcing steel removal operations by shoring or other suitable means;

(b) All personnel are protected form falling debris, blasting grits and high-pressure water jets during concrete removal processes.

9.1.2 The Contractor shall dispose of all debris, blasting grits, hydrodemolition and water jetting slurry in accordance with all local, state, and Federal laws, rules and regulations.

9.2 Shotcrete Application

9.2.1 The Contractor shall implement a safety program to protect all personnel and surrounding property from pneumatically applied shotcrete overspray and rebound materials during the shotcrete application process, using shrouds, screens or other appropriate measures.

9.2.2 Personnel working near the shotcreting operation, including nozzleman, nozzleman's helpers, supervisor and inspectors, shall wear appropriate protective equipment. Such equipment shall include, but not be limited to safety helmet, safety boots, gloves, appropriate clothing, safety eye glasses with side enclosures and dust masks.

9.2.3 Nozzleman's helper shall keep a supply of water, cloth or towel and back-up safety glasses available for nozzleman, so satisfactory vision can be maintained at all times during shooting operations. Sufficient lighting shall be provided to enable the nozzleman to have a clear view of the work.

9.2.4 Eyebaths and wash facilities shall be readily available in the immediate vicinity of the shotcrete application. Shotcrete crew shall apply appropriate skin protection and adopt work hygiene to protect against cement or accelerator alkali burn.

10.0 SHOTCRETE APPLICATION AND FINISHING

10.1 Shotcrete Application

10.1.1 All areas prepared for shotcrete repair shall be reviewed and *approved by the Engineer* prior to application of any shotcrete.

10.1.2 Shotcrete shall be applied in accordance with good practice as detailed in Chapter 8 of ACI 506R. Application requirements of Section 8.5 of ACI 506R apply, except that with silica-fume modified shotcrete it will usually be possible to apply the full thickness of shotcrete in a single pass, without the need for multiple-layer construction. Wherever possible, shotcrete shall be applied to the full thickness in a single layer.

10.1.3 The concrete substrate shall be saturated the day before shotcreting and then re-wetted prior to shooting, as above. At least one hour prior to application of shotcrete, all surfaces to be shotcreted shall be flushed with water of drinking quality standard. Wetted surfaces shall be allowed to dry back to a saturated-surface-dry condition prior to application of shotcrete. If necessary, a blowpipe shall be used to facilitate removal of surface water. Only oil-free compressed air shall be used in the blowpipe. In the event a work stoppage longer than two hours takes place on any shotcrete layer prior to the time it has been built up to required thickness, the surface shall be re-wetted prior to continuing. No shotcrete shall be applied to a dry surface or to a surface with free surface water.

10.1.4 The minimum number of layers required to build up the full thickness of shotcrete without sagging, separation or sloughing shall be used.

10.1.5 When using multiple-layer shotcrete construction, the first layer shall be prepared before application of a subsequent layer by either:

(a) Brooming the stiffening layer with a stiff bristle broom to remove all loose material, rebound, overspray or glaze, prior to the shotcrete attaining initial set; or

(b) If the shotcrete has set, surface preparation shall be delayed at least 24 hours, at which time the surface shall be prepared by sandblasting or high-pressure water blasting to remove all loose material, rebound, hardened overspray, glaze, or other material that prevents adequate bond as *specified in the Contract Documents.*

10.1.6 When successive layers of shotcrete are required to build up the full shotcrete thickness, the first layer shall be prevented from drying out by fogging or wetting. The use of curing compound shall not be permitted between layers, except with the *approval of the Engineer* in writing. If a curing compound is used, it shall be removed by abrasive blast cleaning or high-pressure water blasting, prior to application of the next layer of shotcrete. The first layer of shotcrete shall be free of surface water and in a saturated-surface-dry condition at the time of application of the next shotcrete layer.

10.1.7 Care shall be exercised to protect adjacent surfaces from build-up of rebound and overspray. Rebound shall not be permitted in the completed work. Hardened rebound and hardened overspray shall be removed prior to application of additional shotcrete, using abrasive blast cleaning, chipping hammers, high-pressure water blasting or other suitable techniques.

10.1.8 The Contractor shall provide scaffolding or other temporary support system (e.g., manlifts, suspended work platform, etc.) at each repair location unless otherwise *approved by the Engineer.* Plans for the proposed temporary support system shall be provided to the Engineer for review and approval prior to its installation. No holes shall be drilled into the superstructure to accommodate the support system unless approved in writing by the Engineer. All anchorages placed in the substructure shall be removed when the platform is removed and the substructure repaired at no additional cost.

10.1.9 Sufficient lighting and ventilation shall be installed to provide the nozzleman and helpers with a clear, unhindered view of the shooting area. Work shall be terminated and corrective measures adopted if, in the opinion of the Engineer, visibility is unsuitable for the safe application of quality shotcrete.

10.1.10 Shotcrete nozzling shall follow acceptable shooting practice, as detailed in Section 8.5 of ACI 506R. In particular,

(a) The nozzle shall be generally operated at a distance of one-half to one-and-one-half meters from the receiving surface and shall be oriented at right angles to the receiving surface, except as required to fill corners, cover edges and encase large diameter reinforcing steel;

(b) The combination of air pressure at the nozzle, moisture content of the shotcrete and distance of the nozzle from the receiving surface shall be optimized to achieve maximum compaction of the shotcrete;

(c) Care shall be taken while encasing reinforcing steel and mesh to keep the front face of the reinforcement clean during shooting operations, so that shotcrete builds up from behind, to encase the reinforcement and prevent voids and sand pockets from forming; and

(d) Accumulations of rebound and overspray shall be continuously removed by the nozzleman's helper in advance of the deposition of new shotcrete. Rebound material shall not be reused.

10.1.11 Shotcrete shall not be applied during periods of rain or high wind which could interfere with the shotcrete stream unless suitable protective covers, enclosures or wind breaks are installed.

10.1.12 Shotcrete shall be applied to the required line and grade and tolerance *detailed in the Contract Drawings*, using shooting wires, depth gauges, guide strips, forms or other suitable devices that do not entrap rebound. Shotcrete shall be applied to provide the minimum cover to reinforcing detailed in the drawings. A positive means of checking the total thickness of the applied shotcrete shall be provided by the use of shooting wires which shall be removed prior to the final finish coat.

10.1.13 The application of a 5- to 20-mm thick final layer of plain 5-mm maximum size aggregate flash coat of shotcrete shall be permitted over the top of 10-mm maximum aggregate size shotcrete or steel fiber reinforced shotcrete.

10.2 Shotcrete Finishing

10.2.1 Unless finishing is specifically *required in the Contract Documents*, the surface of the shotcrete shall be built up slightly and trimmed to the final surface by cutting with the leading edge of a sharp trowel. Any imperfections shall be floated using a rubber float. Work done to the finished surface shall be limited to correcting imperfections caused by cutting with the trowel.

10.2.2 Where finishing is required, shotcrete shall be cut back to line and grade using trowels, cutting rods, screeds or other suitable devices. The shotcrete shall be allowed to stiffen sufficiently before cutting and trimming so as to prevent the formation of tears, cracks and delaminations. Shooting wires shall be removed on completion of cutting and trimming.

10.2.3 One or more of the following optional finishes may be applied, *as specified in the Contract Documents*:

(a) Wood float finish, either as a preliminary finish for other surface treatments, or as a granular texture finish;

(b) Rubber float finish, applied to either a flash coat or wood float finish, to produce a finer textured granular finish;

(c) Brush finish, a fine hairbrush float finish, leaving a finely textured, sandy finish.

10.2.4 All shotcrete and overspray shall be trimmed back from adjacent non-prepared concrete surfaces. The edges of all shotcrete repairs shall have a minimum square saw-cut edge 15 mm deep and shotcrete shall be finished up to this edge. Featheredging of shotcrete (including flash coats) shall be prohibited.

11.0 CURING AND PROTECTION

11.1 Curing

11.1.1 On completion of finishing, shotcrete shall immediately be prevented from drying out by fogging, wetting or where *permitted by the Contract Documents*, by application of a curing compound.

11.1.2 Curing compounds, if *permitted by the Contract Documents*, shall be removed prior to application of subsequent paints, coatings or additional layers of shotcrete.

11.1.3 Once shotcrete has attained final set, it shall be kept continuously moist for a minimum period of 7 days, unless *the Contract Documents* permit a shorter curing period, or the use of a curing compound. Moist curing shall be accomplished using one or more of the following procedures:

(a) Wrapping the elements in wet burlap which has been presoaked in water for 24 hours prior to installation; wrapping the wet burlap in plastic sheet is useful for retarding the rate of drying of the burlap;

(b) Installation of sprinklers, soaker hoses or other devices which keep the shotcrete repairs continuously wet. The use of intermittent wetting procedures which allow the shotcrete to undergo wetting and drying during the curing period shall be prohibited.

11.2 Hot and Cold Weather Protection

11.2.1 The general requirements for hot and cold weather concreting, detailed in ACI 305R and ACI 306R, shall also apply to shotcrete remedial work except the maximum temperature of the shotcrete shall not exceed 35 degrees C.

11.2.2 If the prevailing ambient conditions (relative humidity, wind speed, air temperature and direct exposure to sunlight) are such that the shotcrete develops plastic shrinkage and/or early drying shrinkage cracking, shotcrete application shall be terminated. The Contractor shall:

(a) Reschedule the work to a time when more favorable ambient conditions prevail; and/or

(b) Adopt corrective measures, such as installation of sun-screens, wind breaks, surface evaporation retardants or fogging devices, to protect the work.

11.2.3 Shotcrete application shall be terminated if the ambient temperature rises above 30 degrees C, unless the Contractor adopts special hot weather shotcreting procedures, which are *approved by the Engineer.*

11.2.4 During periods of cold weather, shotcreting may only proceed if the concrete substrate to which the shotcrete is applied is free of frost and the air temperature in contact with the repair surfaces is above 5 degrees C.

11.2.5 The air temperature in contact with repaired surfaces shall be maintained at 5 degrees C or greater for at least 3 days after application of shotcrete. The means of maintaining the air temperature shall be *approved by the Engineer.* The use of unvented heaters, which give rise to carbonation, shall be prohibited.

11.2.6 The temperature of applied shotcrete shall be preferably in the range of 10 to 20 degrees C but not outside the range of 5 to 35 degrees C. Cooler mix temperatures are preferred during hot weather shotcreting operations and warmer mix temperatures during cold weather shotcreting.

12.0 SHOTCRETE ACCEPTANCE AND REPAIR

12.1 Shotcrete Acceptance

12.1.1 The *Engineer shall have authority* to accept or reject the shotcrete work. Shotcrete which does not conform to the project specifications may be rejected either during the shotcrete application process or on the basis of tests on the test panels or completed work.

12.1.2 Deficiencies observed during the shotcrete application process, such as, but not limited to:

(a) failure to properly control and remove build-up of overspray and rebound;

(b) incomplete encasement around or incomplete consolidation of reinforcing steel, mesh or anchors;

(c) incorporation of sand lenses, excessive voids, delaminations, sags, rebound, and sloughing; or

(d) failure to apply shotcrete to the required line and grade and tolerance

shall constitute cause for rejection of the plastic shotcrete. If plastic shotcrete is rejected the contractor shall stop the work and take all measures necessary to correct deficiencies.

12.1.3 The Contractor shall, whenever possible, perform remedial work to correct deficiencies while the shotcrete is still plastic.

12.1.4 The *Engineer shall examine* the completed shotcrete work. The hardened shotcrete shall be examined for any evidence of cracking, tears, featheredging, sloughs or other deficiencies. Sounding or other non-destructive evaluation (NDE) methods shall be used to check for delaminations at 28 days, or less if approved by the Engineer in writing. Non-conforming shotcrete is any that lacks uniformity; exhibits segregation, honeycombing, or delaminations; has suffered excessive cracking; was not prepared or applied in compliance with these specifications; fails to meet the specified requirements in Table 1; or fails to meet the core grading requirements.

12.1.5 If the results of compliance tests from shotcrete construction test panels, or assessment of the plastic and hardened shotcrete indicate non-conformance of the shotcrete to the project specifications, the contractor shall drill at least three cores from the repaired member. The cores shall penetrate into the existing concrete a minimum of 50 mm. The number and location of the cores shall be at *the discretion of the Engineer.* These cores shall be core graded in accordance with ACI 506.2 and tested for compressive strength, boiled absorption, volume of permeable voids, and rapid chloride permeability, if applicable. The shotcrete shall be accepted if the mean core grade is 2 or less and no individual core grade is 4 or 5, and the test results meet the specified requirements for Boiled Absorption, Volume of Permeable Voids, and Rapid Chloride Permeability, if applicable, in Table 1 and the following compressive strength criteria. The mean compressive strength of a set of three cores shall equal or exceed 0.85 f'_c with no individual core less than 0.75 f'_c. The mean of a set of three cubes shall equal or exceed f'_c with no individual cube less than

0.88 f'_c. All core holes shall be patched as *detailed in the Contract Documents.*

12.1.6 Shotcrete which is determined *by the Engineer* to be defective or non-conforming to the project specifications based on evaluation of cores from the finished shotcrete shall be repaired or removed and replaced by the contractor at no cost to the Owner. Repairs of non-conforming shotcrete are subject to the same testing, evaluation, and acceptance criteria as the original repair shotcrete.

12.2 Shotcrete Repair

12.2.1 Shotcrete which is identified as being non-conforming while still plastic shall be removed using spades, scrapers or other suitable mechanical devices. High-pressure water jetting may be used, subject to acceptable disposal of the removed shotcrete and slurry.

12.2.2 Hardened shotcrete which is identified as being non-conforming shall be removed using the same basic procedures used for removal of deteriorated concrete. Care shall be taken to avoid damage to reinforcing steel, mesh or anchors. Any embedments damaged during the shotcrete removal process shall be replaced at no cost to the Owner.

12.2.3 All prepared repair areas shall be *inspected and approved by the Engineer* prior to the placement of any repair shotcrete. Repair shotcrete shall be placed, finished, cured and protected in the same manner specified for shotcrete work.

12.2.4 The contractor shall bear the costs for all repair and tests for non-conforming shotcrete.

13.0 MEASUREMENT

13.1 Shotcrete shall be measured by the in-place volume in cubic meters of applied shotcrete. The depth shall be measured from a place at the original outside concrete face. The Contractor and Engineer shall measure repair quantities after removal of unsound concrete and before application of shotcrete.

13.2 Payment shall be full compensation for furnishing materials, equipment, labor, tools and incidentals required to accomplish temporary work access, preparation of surfaces, application of shotcrete, waste shotcrete and rebound, coring of test samples, testing, replacement of defective shotcrete as specified, clean-up of the area and disposal of waste water, wasted shotcrete and rebound, and all other work and overhead costs necessary to complete the designated pay items.

Pay Item	Unit of Measurement
Shotcrete	Cubic Meter

Commentary on the Joint AASHTO-AGC-ARTBA Guide Specifications for

Shotcrete Repair of Highway Bridges

1.0 GENERAL DESCRIPTION AND REQUIREMENTS

1.1 Scope

This Commentary should be read in conjunction with the Joint AASHTO-AGC-ARTBA Guide Specifications for Dry-Mix (or Wet-Mix) Shotcrete Repair of Highway Bridges. The same numbering system has been used in the Commentary and Guide specifications to aid the reader in this process. This Commentary is designed to provide the reader with further amplification and guidance on the shotcrete repair of bridges. Both the wet-mix and dry-mix processes have been used for shotcrete repair of bridges. This Commentary provides information about both dry-mix and wet-mix shotcrete to assist the Specifier in selection of the appropriate process for a specific project. Similarly, this Commentary provides guidance on the relative merits and limitations of conventional, silica fume, and fiber reinforced shotcretes.

The vast majority of shotcrete repair work on bridges is carried out on elements such as girders, stringers, slab soffits, diaphragms, arches, abutments, piers, etc. Shotcrete typically provides a more economical remedial solution for repair of the general thin (surficial) damage encountered in deteriorated bridges, compared to remedial work performed with formed and cast-in-place repair concretes or hand-applied repair materials.

Occasionally, shotcrete is also used for repair of superstructure elements, such as median barriers, curb and gutter, parapets, and towers. Conceptually there is no reason why shotcrete cannot be used for repair of superstructure elements. It should, however, be noted that the shotcrete process is best suited to the repair of overhead, vertical, or steeply sloping surfaces. Gradually sloping or horizontal surfaces are generally more favorably repaired with cast-in-place procedures.

Shotcrete repair of bridge substructures is often done in conjunction with repair of superstructure elements, such as the bridge deck, expansion joints and curb and gutter. The C-SHRP study on the *Durability of Shotcrete Rehabilitation Treatments of Highway Bridges* (Reference 1) demonstrated that the greatest service life of shotcrete repairs of bridge substructure elements is achieved when the cause of the original bridge deterioration is properly addressed. In many cases examined, the prime cause of original bridge deterioration was water and deicing chemical solutions leaking through deck joints and deck draining systems onto substructure elements, resulting in scaling and corrosion-induced deterioration in the reinforced concrete elements. If such sources of moisture and salt were not eliminated in the remedial design, the C-SHRP study (Reference 1) found that, while the shotcrete repairs generally performed well, the surrounding non-repaired original concrete often continued to deteriorate. Thus, the best service life will be achieved in repairs which take into account the original cause of deterioration and incorporate mitigative measures in the remedial design.

1.3 Requirements

The requirements section of the Guide Specification outlines the services typically required to be provided by the Contractor in a shotcrete repair of bridges project. If remedial work and/or mitigative measures are required for the deck and superstructure elements, the Requirements section of the Guide Specifications will have to be expanded.

Emphasis has been placed on the need for the Contractor to implement an appropriate safety program. In the repair of deteriorated bridge elements there is often a need for removal of significant quantities of deteriorated concrete, and sometimes corroded reinforcing steel. It is important that the Contractor provide suitable shoring and support to maintain the structural integrity of the bridge during the concrete removal processes. In some cases this will require sequential concrete removal and shotcrete reconstruction in order to maintain structural integrity; e.g., in removal of deteriorated concrete adjacent to major bearings on pier or abutments. Frequent on-site communication with the Engineer will normally be required in such circumstances.

Emphasis is also placed on other safety aspects of the concrete preparation and shotcrete application processes. These processes typically require the use of blasting grits and/or high-pressure water jets, and the high velocity, pneumatic conveyance of shotcrete materials. The Contractor should implement a safety program which satisfies the requirements of the authorities having jurisdiction over the operation of such equipment.

2.0 SUBMITTALS

Shotcrete rehabilitation of bridges is a specialist trade, which requires the use of appropriate equipment and a knowledgeable work crew, experienced in this specific type of work if the Owner is to obtain a satisfactory end product. In particular, it is important that the shotcrete nozzlemen used on the project have suitable prior experience in this type of work. Thus, it is recommended that the Contractor, at the bid stage, submit proof of qualification of the proposed work crew to perform the required work. It should, however, be recognized that the Contractor may not be able to identify all specific individuals proposed for the work at bid stage.

Some specifications require the nozzleman to be certified in accordance with the ACI 506R.3, *Guide to Certification of Shotcrete Nozzlemen*. Very few nozzlemen are, however, likely to have been "certified" in accordance with ACI 506R.3 unless it was done by an independent lab or agency, or unless the contractor has set up a certification program which has been reviewed and accepted by the owner of the project. Thus, proof of past pertinent experience, including a list of previously completed projects (in conjunction with preconstruction testing), is the best means of evaluating the capability of the crew supervisor and nozzlemen to perform the work.

Other submittals should include the normal materials test records showing proof of conformance of proposed materials to the project specifications. In addition, the Contractor should submit details of the proposed shotcrete mixture design(s), and shotcrete batching, mixing, supply and application equipment. The Contractor should also submit details of the proposed quality control testing procedures, and curing and protection to be provided to the shotcrete. The Engineer should review the conformance of all submittals to the project specifications.

3.0 REFERENCE DOCUMENTS

Pertinent American Concrete Institute (ACI) and American Society for Testing and Materials (ASTM) documents are invaluable for providing background and details of common practice when making decisions about a specific project. However, they are not normally referenced in Specification documents since they are not written in specification format. Of these documents, the most useful is the ACI 506R, *Guide to Shotcrete*. While this document does not specifically address the use of shotcrete for repair of bridges, it contains much useful information which will be of assistance to the Specifier in preparing Contract Documents. The Guide Specifications cite specific chapters in ACI 506R with the intent that the specifier, using the Commentary, will choose the requirements which apply to the project and insert those requirements in the project specifications using appropriate imperative language.

Additional useful information with respect to the dry-mix shotcrete process, particularly with respect to encasement of reinforcing steel, is provided in Reference 2. Other useful referral documents are listed in the references at the end of this Commentary.

4.0 MATERIALS

4.1 Cement

Most shotcrete repair of bridges is carried out with ASTM Type I or II Portland cement. Where there is a requirement for high early strength development (e.g., in bridges carrying traffic during construction), a Type III cement may be specified. For substructure elements, such as abutments, piers and wingwalls in sulfate soil or groundwater conditions, it may be necessary to specify the use of a Type V cement. It should, however, be remembered that Type V cements (with low C_3A contents) are less suited to inhibition of chloride ion penetration than Type I, II or III cements. (See Reference 3.)

4.2 Supplementary Cementing Materials

Pozzolans, such as fly ash, have been used in wet-mix shotcrete repair projects. They are used for many of the same reasons they are used in concrete (Reference 4):

- to provide additional fines to enhance pumpability and adhesion and cohesion of the shotcrete mix, particularly if the sand tends to be coarse;

- to provide enhanced long-term durability through the pozzolanic reactions which reduce permeability and enhance resistance to chloride ion penetration; and

- to reduce heat of hydration in thick-section repairs.

There is very limited experience in the use and performance of blast-furnace slag modified shotcretes. Prototype field tests are thus recommended for such shotcrete before using it for repair of bridges.

By far the most widely used supplementary cementing material in shotcrete is silica fume. Silica fume has been used in shotcretes in Scandinavian countries since the 1970s and found its first use in shotcrete repair of structures in North America in the early 1980s (Reference 5). Silica fume is used in both wet- and dry-mix shotcrete for the benefits it imparts to both the plastic and hardened shotcrete. These benefits are detailed in Section 5.2 of this *Commentary*.

Silica fume shotcrete, particularly applied by the dry-mix shotcrete process, is now finding widespread use for bridge repair in some areas.

4.3 Water

It is important that all mix water used in shotcrete preparation and production processes be of drinking water quality. In particular, water which is muddy, or contains sulfate or chloride salts or other contaminants, should not be used. Wash down with muddy water could leave a fine clay residue on the prepared surface and interfere with shotcrete bond. Water used in preparation of concrete surfaces should be free of oil or other contaminants. Similarly, compressors used for adding air at the air ring at the nozzle in the wet-mix shotcrete process, or pneumatically conveying material in the dry-mix shotcrete process, should have oil and water traps added to prevent contamination of the shotcrete. While it may be acceptable to use water meeting ASTM C 94 requirements as mix water for the shotcrete, it is not acceptable to use water meeting that specification for blast cleaning or wash down, since it may contain sufficient contaminants to affect the bond of the shotcrete to the substrate.

4.4 Aggregates

Only good quality, hard, dense aggregates, conforming to all the requirements of AASHTO M 6 for fine aggregate and AASHTO M 80 for coarse aggregate, should be allowed in shotcrete used to repair bridges. In particular, the use of frost-susceptible or alkali-reactive aggregates should be avoided, in view of the aggressive exposure conditions to which most shotcrete bridge repairs are subjected.

Recommended shotcrete aggregate gradation limits for nominal 10-mm and 5-mm maximum size aggregate gradations are given below. These gradation limits correspond to the ACI 506R, Table 2.1 Gradation No. 2 and No. 1 limits respectively. There tend to be regional preferences regarding whether to use nominal 10-mm or 5-mm maximum size aggregate (MSA) gradation shotcrete for bridge repair. One of these gradations should be specified in the Contract Documents. For the 10-mm nominal maximum aggregate size the 10- to 2.5-mm coarse aggregate fraction should be stockpiled and added separately from the fine aggregate (nominal 5-mm maximum size) during mixing operations.

TABLE 1

Gradation Limits for Nominal 10-mm and 5-mm Maximum Size Aggregate Shotcretes

Metric Sieve Size	Total Passing Each Sieve, % by Mass	
Nominal Maximum Aggregate Size	**5 mm**	**10 mm**
14 mm	100	100
10 mm	100	90–100
5 mm	95–100	70–85
2.5 mm	80–100	50–75
1.25 mm	50–90	35–55
630 mm	25–65	20–35
315 mm	10–35	8–20
160 mm	2–10	2–10

The following tabulation provides an indication of the relative advantages and disadvantages of the different aggregate gradations.

TABLE 2

10-mm Nominal Maximum Aggregate Size	
Advantages	**Disadvantages**
➤ More "concrete-like" mixture, with coarse aggregate component, giving rise to lower water demand and hence reduced shrinkage and cracking potential compared to 5-mm MSA shotcrete. ➤ Larger maximum size aggregate provides better "cleaning" of the shotcrete lines and nozzle in the dry-mix shotcrete process. ➤ Greater momentum of larger aggregate particles helps keep the front face of reinforcing steel "clean" during shooting and facilitates the shotcrete compaction process.	➤ Greater rebound of coarse aggregate, particularly during encapsulation of reinforcing steel using the dry-mix shotcrete process. ➤ Leaves a rough "pock-marked" as-shot finish, which may be less aesthetically acceptable than a 5-mm MSA as-shot finish. ➤ Requires more finishing effort compared to 5-mm MSA shotcrete. ➤ May require application of a 5-mm MSA shotcrete finish coat.
5-mm Nominal Maximum Aggregate Size	
Advantages	**Disadvantages**
➤ Lower rebound than 10-mm MSA shotcrete, particularly when encasing reinforcing steel or mesh. ➤ More easily finished than 10-mm MSA shotcrete; usually does not require a finish coat.	➤ Being a mortar, rather than a more concrete-like mixture, has a higher water demand than 10-mm MSA shotcrete. ➤ Requires higher cementitious content than 10-mm MSA shotcrete to produce a given strength. ➤ Has a higher shrinkage capacity and hence greater cracking potential than 10-mm MSA shotcrete. ➤ More prone to the formation of "sand lenses" or "sand pockets" when encapsulating reinforcing steel or mesh, using the dry-mix shotcrete process.

As a general rule, 10-mm MSA shotcrete is more suited to thicker-section shotcrete repairs and where shotcrete finishing is not required. By contrast, 5-mm MSA shotcrete might be preferred for thin-section repairs and where finished surfaces are required.

4.5 Admixtures

The use of admixtures is generally not required in dry-mix shotcrete, with the possible exception of the addition of air-entraining admixture. Extensive research (References 6, 18) has shown that freeze/thaw durable dry-mix shotcrete can be produced without the addition of air-entraining admixtures, provided the shotcrete is properly proportioned, applied and cured. Recent work at Laval University (Reference 7) has, however, shown that the addition of air-entraining admixture to the mix water added at the nozzle in the dry-mix shotcrete process results in enhanced deicing chemical scaling resistance. This procedure is being used for shotcrete repair of bridges in Québec at an addition rate of 15 ml/l of water. More recently an air-entraining powder has been developed to be mixed with the dry ingredients so that water alone can be added at the nozzle. Air-entraining admixture is not considered necessary for properly applied, well-compacted dry-mix shotcrete in normal applications since it has been shown to contain appropriate air-void parameters resulting from the application process which protect it from freeze-thaw damage.

In wet-mix shotcrete, the use of air-entraining admixtures is considered mandatory for shotcrete exposed to freezing and thawing (Reference 6). It should be noted that approximately half the air content in the mixture is lost during the shotcrete application process; thus the air content in the as-batched shotcrete should be adjusted accordingly. The use of water-reducing admixtures is generally recommended for wet-mix shotcrete, as they reduce the water demand of the shotcrete, thus helping reduce shrinkage. In warm weather the use of set-retarding admixtures may be beneficial. For silica fume modified wet-mix shotcretes, the use of superplasticizing admixture is strongly recommended in order to control water demand and hence strength and shrinkage of the mixture.

The addition of "concrete-type" set-accelerating admixtures may be appropriate for wet-mix shotcrete work conducted in cold weather conditions. Such accelerators should, however, be chloride free. The use of "shotcrete accelerators" (such as those typically used in support of underground openings) is, however, not recommended for shotcrete repair of bridges. Such accelerators typically result in substantial increases in drying shrinkage and hence shrinkage cracking potential. They reduce compressive and flexural strength and markedly increase permeability and susceptibility to chloride ion intrusion (References 5, 18). They also reduce frost-resistance and increase the potential for deterioration from deicing chemicals (Reference 7).

4.6 Reinforcement

Good general guidance regarding the selection, location and fixing of reinforcement for shotcrete applications is provided in the ACI 506R, *Guide to Shotcrete*. In shotcrete repair of bridges it is sometimes necessary to replace existing corroded reinforcing, or add additional reinforcing steel to strengthen the structure (e.g., in seismic retrofit). Good shotcrete practice dictates that small bar sizes be used wherever possible, with 15 M bars being the preferred maximum size. Bars as large as 25 M have been used, but they require special skills on the part of the nozzlemen to achieve full encapsulation with shotcrete.

Placement of reinforcing steel for shotcrete applications differs from conventional concrete reinforcing steel installation requirements in that the bars should always be spaced and arranged to facilitate shotcrete placement and the avoidance of the formation of sand pockets and voids. In particular, direct contact of reinforcing splices should be avoided; lapped bars should be spaced apart at least three times the diameter of the largest bar at the splice. Where double layers of reinforcing are required, the spacing of bars should be offset to permit clear, unobstructed access for shooting to the interior reinforcement. All bars should be securely tied to intersecting bars and anchors to minimize vibration and prevent movement during shooting, which could interfere with bond.

Welded wire mesh fabric is commonly used in shotcrete repair of bridges. It serves two major purposes:

- to mechanically tie back the shotcrete repair to fixed anchors or existing reinforcing steel so that the longevity of the repair is not totally dependent on bond to the substrate concrete (or the continuing integrity of the substrate concrete);
- to enhance the resistance of the shotcrete to thermal and drying shrinkage-induced cracking.

Commonly used welded wire mesh fabric sizes are tabulated below:

TABLE 3

Wire Mesh Fabric Sizes	Metric Designation
50 mm x 50 mm	MW 5.6 x MW 5.6
102 mm x 102 mm	MW 9.1 x MW 9.1
102 mm x 102 mm	MW 13.3 x MW 13.3
152 mm x 152 mm	MW 18.7 x MW 18.7

The Engineer should select the appropriate mesh size for the specific repair application. The smaller diameter, more closely spaced meshes are generally preferred in small patch-type repairs. In larger and deeper repairs, particularly where there is a danger of the mesh vibrating excessively during shotcrete applications, the larger diameter, stiffer meshes are preferred. The use of chain-link mesh (or "chicken-mesh") should not be permitted as it is not conducive to full encapsulation with shotcrete without the formation of sand pockets and voids.

Fiber reinforcement can be used in lieu of mesh reinforcement, but it should be properly mechanically anchored to the existing concrete, using anchors with appropriate shear connectors. Anchoring along the perimeter of the repair is particularly recommended. The use of steel fiber reinforced shotcrete is advantageous, compared to mesh reinforcement, in that it eliminates the requirement for fixing mesh and the difficulties which can sometimes be encountered in fully encasing mesh.

Steel fiber has typically been added to the shotcrete at addition rates varying between 40 and 60 kg/m^3. The exact amount of fiber used depends on the particular type of fiber used and bridge element being repaired. Where fibers are being used primarily for shrinkage crack control, 40-kg/m^3 fiber content may suffice. Where "toughness" enhancing characteristics of the fiber are important (e.g., in strengthening load-bearing precast or cast-in-place deck support elements), the use of 60-kg/m^3 of steel fiber would be more appropriate.

It should be remembered that different levels of performance will be provided by different fiber types. As general guidance, for steel fibers the higher aspect ratio (length/equivalent diameter) deformed types of fiber provide the best performance (References 15, 16). Also, it should be remembered that a higher proportion of steel fibers will rebound in dry-mix, compared to wet-mix shotcretes. It should also be noted that exposed steel fibers in the shotcrete surface may create rust stains. If this is undesirable, stains can be prevented by application of a non-fiber surface coat.

Polypropylene fiber has also been used in shotcrete repair of bridges. While high addition rates (up to 0.6 percent by volume) have been used in some bridge repair (Reference 5), polypropylene fiber has generally been added to shotcrete at low addition rates of 0.1 percent by volume (1 kg/m^3). At these addition rates the polypropylene fiber may provide some resistance to plastic shrinkage cracking. Reference 15 contains additional information about the effect of various addition rates of polypropylene fibers on both crack resistance and toughness.

Polypropylene fiber has been used in both the wet-mix and dry-mix shotcrete processes (Reference 17). However, in the dry-mix shotcrete process it may be difficult to incorporate any significant quantities of some specific types of fiber (say more than 0.1 percent by volume) in the completed work. A significant quantity of the fiber added tends to be carried away in the "return air stream" during the shotcreting process. If more than 0.1 percent of polypropylene fibers are required in the final in-place shotcrete, wash-out tests should be performed to select the specific fiber types which can achieve a higher percentage for the application intended.

Anchors for fixing mesh or mechanically anchoring steel fiber reinforced shotcrete should be carefully designed. If the substrate concrete is of questionable quality, or likely to continue to deteriorate behind the shotcrete repairs because of continuing alkali-aggregate reactivity, or frost action, the anchors should be sufficiently deep seated that the repair shotcrete does not simply slab off with the substrate concrete still adhered to it (Reference 1).

4.7 Materials Handling and Storage

Difficulties can be encountered in shotcrete repair of bridges if the temperature of the shotcrete-making materials is allowed to get excessively low or high. At temperatures below 5 degrees C shotcrete rebound can increase markedly and the shotcrete can be very slow in setting, hardening and gaining early strength. This can result in excessive shut-down periods for bridges under repair, or damage to bond in operating bridges. During cold weather, shotcrete-making materials should be stored in warm enclosures whenever possible, until the time of use. Warm water should be used if necessary to increase the temperature of the in-place shotcrete. Temperatures in excess of 30 degrees C can result in excessively rapid loss of workability in wet-mix shotcretes, limiting time from batching to completion of discharge of shotcrete. High temperatures or low temperatures with low relative humidity can also increase the potential for plastic and early drying shrinkage cracking.

Wide ranges in moisture contents in shotcrete making aggregates should be avoided. This may require storage of aggregates in sheltered enclosures or under tarpaulins, particularly for volumetrically site-batched shotcrete. Excessive moisture contents can result in aggregate "bridging" over gates in hoppers and erratic aggregate feed, with resultant variable shotcrete mixture proportions.

5.0 SHOTCRETE PROPORTIONING

5.1 Mixture Design

The burden for shotcrete mixture design should be placed on the Contractor per the Guide Specification. Most experienced shotcrete contractors will be able to readily submit suitable mixture designs, together with appropriate performance documentation, based on previous bridge or other infrastructure repair experience. In the absence of such experience, the Contractor may select one or more of the following "starting mix" designs, depending on the shotcrete type and performance requirements detailed in the Specifications. Selection of these "starting mix" proportions does not, however, relieve the Contractor of the responsibility of meeting the performance requirements of the specification.

TABLE 4

Typical Remedial Shotcrete Mix Designs, Proportions at the Nozzle in kg/m^3				
Material	Mix Description (Exiting the nozzle — not in-place)			
	Wet-Mix		Dry-Mix	
	Plain	Silica-Fume	Plain	Silica-Fume
Portland Cement	400	350	425	375
Silica Fume	–	47	–	50
10-mm Coarse Aggregate*	460	485	495	490
Concrete Sand*	1260	1215	1215	1205
Water	170	177	165	165
Water Reducing Admixture	Yes	Yes	–	–
Superplasticizer	–	Yes	–	–
Air-Entraining Admixture	Yes	Yes	–	–
TOTAL:	2290	2274	2300	2285

*Proportions based on Saturated Surface Dry (SSD) Aggregate

These proportions are based on nominal 10-mm MSA (Maximum Size Aggregate). For nominal 5-mm MSA mixtures, similar mixture proportions could be used, but it may be necessary to increase the cement content slightly because of the increased water demand (and hence increased water/cement ratio and reduced strength) for the finer aggregate mixture. Also, it should be noted that these are nominal mixture proportions based on combined aggregates with relative bulk density (specific gravity) of about 2.72. The Contractor should design the as-batched mixture to yield correctly. The yield will, of course, be influenced by the actual water demand and air content of the mixture. Mixture design and yield analysis calculations should only be done on the basis of saturated surface dry (SSD) aggregates.

An example of a shotcrete mixture design, and yield analysis for a typical wet-mix, steel fiber reinforced, silica fume shotcrete follows:

TABLE 5

Typical Wet-Mix Shotcrete Proportions and Yield Analysis			
Material	Mass (kg)	Bulk Density (kg/m³)	Volume (m³)
Cement (Type I or II)	350	3150	0.1111
Silica Fume	47	2200	0.0214
Coarse Aggregate (SSD) 10 x 2.5 mm	485	2730	0.1777
Sand (SSD)	1215	2710	0.4484
Water (Estimate)	177	1000	0.1770
Water Reducing Admixture	2000 ml	1100	0.0018
Superplasticizer	5800 ml	1100	0.0053
Steel Fiber	60	7860	0.0076
Air-Entraining Admixture	As required for		
Air Content (As Shot into air pot)	5 ± 1.5%		0.0500
TOTALS:	2342		1.0003
Slump = 60 mm ± 20 mm			
Approximate W/(Cement + Silica Fume) = 0.40			

In wet-mix shotcretes, the in-place shotcrete mixture proportions will be very similar to the as-batched proportions since there is normally very little rebound in the wet-mix shotcrete process (usually less than 5 percent rebound on vertical surfaces and less than 10 percent rebound on overhead surfaces). By contrast, in dry-mix shotcrete, significant rebound is a normal aspect of the shotcrete process. The amount of rebound will depend on many factors, including shotcrete orientation (vertical or overhead surfaces), shotcrete thickness, the presence of reinforcing steel, and whether silica fume is used. For dry-mix silica fume shotcrete, rebound of 20 percent on vertical surfaces and 25 percent on overhead surfaces is not unusual (Reference 8). Substantially higher rebound can be expected in conventional dry-mix shotcrete.

Rebound materials characteristically contain less cementitious material than the as-batched shotcrete. Thus, in-place dry-mix shotcrete characteristically has a higher cementitious content than the as-batched material. This aspect should be taken into consideration during design of dry-mix shotcrete mixtures. It should, however, be remembered that attempts to produce excessively lean (low cementitious material content) dry-mix shotcrete mixtures can be counterproductive. Rebound increases markedly in lean dry-mix shotcrete mixtures.

As-batched cementitious contents of less than 350 kg/m^3 are not recommended for any dry-mix repair shotcrete.

5.2 Silica Fume Shotcrete

Silica fume is finding increasing use in shotcrete for repair of bridges because of the benefits it imparts to both the plastic and hardened shotcrete. In the plastic shotcrete, it results in improved adhesion (to the substrate surfaces) and cohesion (adhesion to itself). This enables the build-up of greater thicknesses of shotcrete in a single pass and reduces or eliminates the need for use of shotcrete accelerators. In many repair applications, it becomes possible to build up the entire thickness of shotcrete in a single pass, thus eliminating the need for multiple-layer shotcrete construction. This is particularly true of the dry-mix shotcrete process, where thicknesses of 500 mm or more on vertical surfaces and 200 mm or more on overhead surfaces have been built up in a single pass. Silica fume additions also enable substantial reductions in rebound in the dry-mix shotcrete process (Reference 8).

Improvements in the hardened shotcrete resulting from the use of silica fume include:

- increases in compressive and flexural strength (particularly evident in wet-mix shotcrete);
- reduced permeability and enhanced resistance to chloride ion penetration (Reference 9);
- improved resistance to deicer salt scaling (Reference 7).

Silica fume is typically incorporated in shotcrete at addition rates between 5 and 15 percent by mass of cement. Addition rates of 8 percent will often suffice for repair of predominantly vertical or sloping surfaces. Addition rates of about 12 percent are generally preferred for predominantly overhead repairs. In operating bridges subjected to vibration or repair in wet areas, such as intertidal zones on piers and caissons, it may be necessary to increase the silica fume content to as much as 15 percent by mass of cement in order to prevent loss of freshly placed shotcrete. This has been done with considerable success in repair of marine structures subjected to wave action (Reference 5).

In dry-mix shotcrete the use of superplasticizing admixtures is not required. In wet-mix shotcrete the use of superplasticizers to control the water demand of the mixture is strongly recommended.

5.3 Performance Requirements

Recommended performance requirements for bridge repair shotcretes are given in the Guide Specification, Table 1. Shotcretes batched to the proportions given in Section 5.1 of this Commentary will normally readily meet these performance requirements provided the shotcrete is batched, mixed, applied and cured in conformance with the requirements detailed in the Guide Specification.

A maximum water-cementitious materials ratio of 0.42 will usually suffice for most strength and exposure conditions. Precise determination of the water-cementitious ratio for dry-mix shotcrete is not easily done and, thus, is seldom used as a routine quality control item. More typically, the water-cementitious materials ratio for the proposed mixture is determined during the preconstruction phase of the project, using a materials balance approach; i.e., recording the mass of shotcrete materials and water consumed over a set shooting period. For wet-mix shotcrete, the precise water-cementitious ratio can, if required, be readily determined by a yield analysis check at the batch plant.

Higher compressive strengths than the 28 MPa at 7 days and 35 MPa at 28 days given in the Guide Specification, Table 1, can be specified if required for structural reasons. There is, however, no benefit in specifying lower compressive strengths. Good quality shotcrete, which displays satisfactory adhesion, cohesion, thickness of build-up and acceptable rebound, requires total cementitious contents which should be more than adequate to meet the 28 MPa at 7 days and 35 MPa at 28 strength requirements. The use of a 7-day strength specification is recommended, since in shotcrete repair of bridges, the entire repair may be completed at 28 days after application of the first shotcrete, in which case it is too late to find out if there is a problem with strength. Even earlier age strength limits could be specified if considered necessary (as is often done in shotcrete support of underground openings).

Specification of maximum limits on the permissible values of boiled absorption and volume of permeable voids, as determined by the ASTM C 642 test, has proven useful as a measure of shotcrete quality (Reference 5). It provides a measure not only of the quality of the shotcrete mixture, but also of the nozzlemanship and adequacy of consolidation of the shotcrete. Defects attributed to causes such as sand pockets, voids of incomplete consolidation, and entrapment of rebound or hardened overspray will be quantified in this test.

The ASTM C 1202, Rapid Chloride Permeability Test, has been adopted by some highway agencies as a quality control measure for bridge repair shotcrete. It provides an indication of the chloride ion intrusion inhibiting characteristics of the shotcrete. It should be noted that conventional shotcrete (no silica fume) will typically display coulomb values which may be as much as an order of magnitude greater than in shotcretes made with silica fume (Reference 9). The limit recommended in the Guide Specification, Table 1, of 1500 coulombs at 7 days for silica fume shotcrete can normally be readily achieved in the field. Limits for other types of shotcrete should be established by the Engineer during preconstruction testing; i.e., values attained in approved preconstruction test panels should be used to set the standard for the work. Rapid Chloride permeability testing is not suitable for use with steel fiber reinforced shotcrete.

6.0 SUPPLY AND EQUIPMENT

Wet-Mix vs. Dry-Mix Shotcrete

The first decision to be made in any shotcrete bridge repair project is whether to use the dry-mix or wet-mix shotcrete process. The dry-mix shotcrete process is best suited to smaller volume repair projects particularly where there is considerable starting and stopping, or a need to frequently relocate during shooting operations. By contrast the wet-mix shotcrete process is better suited to larger volume (say 5 m^3/hr. or more) continuous shooting operations with few interruptions. The dry-mix shotcrete process, compared to the wet-mix process, also tends to be better suited to predominantly overhead repair work because of the greater thicknesses of build-up attainable in a single pass. In some projects the decision as to which process to use may not be clear and, in such circumstances, it may be appropriate to allow both the dry-mix and wet-mix process to be used and let the successful low bidder select the application process.

The following is a brief tabulation of the relative advantages and disadvantages of the dry-mix and wet-mix shotcrete processes for bridge repair work.

TABLE 6

Dry-Mix Shotcrete	
Advantages	**Disadvantages**
➢ Suitable for small volume start/stop type repair operations.	➢ Substantially greater rebound compared to wet-mix shotcrete.
➢ With the exception of the air compressor, requires relatively small, highly mobile equipment.	➢ Highly dependent on the skill of the nozzleman for wetting the shotcrete to the appropriate consistency.
➢ Convenient to frequent relocations during shooting.	➢ More onerous for removing overspray and rebound, particularly when encasing reinforcing steel or mesh.
➢ Allows thicker build-up on vertical and overhead surfaces, particularly when silica fume is used.	➢ Greater potential for formation of sand pockets and lenses and entrapment of rebound.
➢ Equipment is more easily cleaned at completion of daily shotcrete operations.	➢ More rebound to dispose of at completion of shotcreting.
Wet-Mix Shotcrete	
Advantages	**Disadvantages**
➢ Suitable for larger volume, continuous shooting operations.	➢ Not suited to frequent start/stop type operations; shotcrete has finite "pot-life."
➢ Much greater productivity (m^3/hr.)	➢ Limited in thickness achievable on overhead surfaces, particularly with conventional shotcrete.
➢ Nozzleman not concerned with controlling water addition; only has to control air addition at the nozzle and shooting technique.	➢ Requires larger, more costly equipment than for dry-mix process; e.g., transit mixers, pumps, etc.
➢ Markedly less rebound than in dry-mix shotcrete and hence less rebound clean-up required.	➢ Clean-up of pumps and hoses and disposal of waste material at end of day more onerous.

6.1 Batching, Mixing and Supply

Site-batching of dry-mix shotcrete, using either volumetric or mass batching equipment, can be used for shotcrete bridge repair. The volume of shotcrete materials required for most bridge repair contracts is such that it is normally not expedient to establish stockpiles of shotcrete-making materials and batching facilities on site. Most dry-mix shotcrete repair of bridges is performed using either dry-bagged premix materials, or mobile, volumetric site batching. These are the preferred supply systems, as they produce fresh shotcrete on an as-needed basis, with minimal waste. Dry-bagged premix materials are typically supplied in either small (30-kg) paper bags, or large (1600-kg) synthetic cloth bulk bin-bags.

The use of rotary drum, transit-mix batched and supplied dry-mix shotcrete is not recommended for bridge repair. There is a tendency for "balls" or "pellets" of non-homogeneous material to develop in the transit mixer. This negatively impacts the quality of the resultant shotcrete particularly during warm weather or extended discharge periods. Negative influences include marked increases in rebound, reduced application thickness and non-homogeneous in-place shotcrete.

When volumetric site batching is used, quality control checks should be implemented to verify that the batched proportions meet the design mixture proportions. Mass batch checks should be used at an appropriate frequency. For dry-bagged premix materials quality control checks should include wash-out and gradation analyses to verify the as-batched proportions. Such tests should be conducted at the frequency specified by the Engineer.

Wet-mix shotcrete is essentially similar to conventional concrete in terms of batching, mixing and supply. The most common systems are either central mix batched and transit mix supplied shotcrete, or transit mix batched and supplied shotcrete. However, volumetric site batching, using fixed or mobile batching units, can also be used if the batching can be calibrated satisfactorily. Another system which has been used for bridge repair, particularly in remote areas, is dry-bagged premixed shotcrete materials which are discharged into a transit or other suitable mixer with water added at the site. With this system the shotcrete should be given adequate "soak time" to enable absorption of water by the "bone-dry" materials, prior to discharge into the shotcrete pump; otherwise pumping and shotcrete finishing difficulties may be encountered.

6.2 Shotcrete Placing Equipment

There is a wide variety of shotcrete placing equipment which can be used for application of dry-mix and wet-mix shotcrete. ACI 506R, *Guide to Shotcrete*, provides details of some of the different types of equipment available. Equipment manufacturers are continually upgrading and improving their shotcrete application systems and thus it is not appropriate in this document to recommend specific types of equipment.

In the wet-mix system there are two basic types of shotcrete application systems: the conventional or "thick-stream" method and the "thin-stream" method. The "thick-stream" method is most commonly used and typically utilizes conventional concrete-type pumps with air addition at the nozzle at the end of the delivery hose. The delivery hose typically has a 50- or 63.5-mm internal diameter. Hose diameters any larger than this become too heavy for the nozzleman to effectively operate.

The "thin-stream" method normally involves the use of a pressurized chamber to pneumatically convey the shotcrete down the hose to the receiving surface. The "thin-stream" method normally utilizes a hose with an internal diameter of 40 mm or less. It is most suited to the application of mortar-like mixtures (nominal 5-mm MSA) and has low productivity rates. It is thus best suited to small, shallow, patch-type repairs. The "thin-stream" method may not provide suitable impacting velocity to properly encase larger diameter reinforcing steel and should be carefully evaluated before being permitted for use in such an application. The Wet-Mix Guide Specifications do not apply to the "thin-stream" method.

There are a wide variety of dry-mix shotcrete "guns" for shotcrete application, including guns that operate on a rotating barrel-feed system and pressurized chamber type guns. Large capacity air compressors are required to pneumatically convey the shotcrete materials down the line to the nozzle. Water is added partially through the use of damp aggregates, (or in the case of dry-bagged premix materials, in a predampening auger) with the remainder of the required mix water being added at a water ring at the nozzle. The application of dry-bagged premix materials, without the use of a predampening auger, should not be permitted. Such practice results in excessive dust, poor shooting visibility, increased rebound and an increased potential for the formation of sand pockets and dry lenses in the in-place shotcrete.

"Housekeeping," in terms of keeping clean shotcreting equipment, lines and hoses, and particularly the air ring in wet-mix shotcrete, or water ring in dry-mix shotcrete, is important. Work should be stopped and appropriate corrective action taken if non-uniform discharge of shotcrete becomes apparent.

7.0 PREPARATION FOR SHOTCRETING

7.1 Concrete Removal and Preparation

One of the most important aspects of shotcrete repair of bridges is proper preparation of the substrate, prior to shotcrete application. All areas of loose, spalled, delaminated or deteriorated concrete should be removed prior to application of repair concrete. In repair of deteriorated load-bearing elements, it may be necessary to provide shoring and/or carry out the repair work in a sequential manner, with partial concrete removal of more material. In some very old structures, the depth of deterioration may be so great (from influences such as freeze-thaw or alkali-aggregate reactivity induced damage) that it may not be possible to remove all deteriorated concrete. In such circumstances shotcrete "jacketing" is sometimes used to upgrade the structure. Such jacketing should be carefully designed to include suitable reinforcing and deep anchors, such that the integrity of the repair is not solely dependent on bond to the substrate concrete. If this is omitted, slabbing failure of the repair can occur with the shotcrete still adhered to the substrate concrete, and the failure plane is within the substrate concrete (Reference 1).

If inadequate surface preparation is suspected, bond testing may be performed by drilling cores through the shotcrete repair layer. The recommended minimum bond is 1.0 MPa at the shotcrete-substrate interface. If lower test values are obtained when the failure surface extends down into the substrate, the interface bond cannot be determined. The Engineer must then evaluate whether the failure resulted from undetected delaminations, new or growing delaminations, or poor quality concrete to decide if further repair is necessary under contract bid items or by extra work.

Concrete removal can be accomplished using a wide variety of mechanical tools, including chipping hammers, scarifiers, scabblers, etc. However, the use of heavy-duty equipment, which could damage sound concrete beneath the prepared surface, should be avoided. Most mechanical preparation procedures (particularly scabblers and scarifiers) will cause some microfracturing of aggregate (sometimes called "bruising") in the prepared surface. Abrasive blast cleaning using sand-blasting, wet-grit blasting, or closed-loop steel shot blasting, should be used to prepare the surface and remove any "bruised" concrete, unsound material, or contaminants such as oil, grease, slurry or any materials which could interfere with the bond of freshly placed shotcrete.

As an alternative to mechanical concrete removal and final surface preparation, high-pressure (usually 100- to 250-MPa) water jetting hydrodemolition equipment can be used. There is a wide variety of such equipment available for hydrodemolition, but care should be taken to ensure that the system used creates a suitable prepared surface profile. Excessive undercutting of exposed aggregate may create a prepared surface which is not conducive to good shotcrete bond and should be avoided. Low-volume water jetting systems which create lesser volumes of demolition water and slurry are preferred. Proper procedures for containing and disposing of hydrodemolition slurry should be implemented. This is particularly important over waterways.

Similarly, the Contractor should implement appropriate measures for collecting and disposing of removed concrete and blasting grits. The requirements of the authorities having jurisdiction should be followed. Also, it should be recognized that high-pressure water jetting and abrasive grit blasting are potentially dangerous procedures. A rigorous safety program to protect personnel from injury and adjacent property from damage should be implemented by the Contractor when using such equipment.

When corroded reinforcing steel is exposed, concrete removal should continue until there is at least a 20-mm clearance around all exposed reinforcing steel. Research conducted in Sweden (Reference 10) has shown that the interface between old concrete and shotcrete should not coincide with the reinforcement plane. There is a potential for bond failure at this plane, particularly under conditions conducive to repeated dynamic cycling (e.g., bridge deck soffits and support elements). Removing concrete behind existing reinforcing steel also facilitates the removal of any corrosion product on the reinforcement and provides mechanical anchorage for the repair shotcrete.

Proper preparation of the perimeters of all patch-type shotcrete repairs is also an important consideration. Featheredging should be avoided, as the C-SHRP study (Reference 1) showed that this was a major cause of edge delamination in shotcrete repairs. The recommended procedure is to square cut the edge of the repair to about a 15-mm depth using an appropriate saw, and then chip the remainder of the perimeter of the repair on about a 45-degree angle. Deeper square cut edges should be avoided, as they are conducive to entrapment of rebound and overspray during shotcrete application. The square cut edge provides a well-defined boundary for shotcrete finishing operations. It provides a convenient edge to ensure featheredging does not occur and results in a more aesthetic completed repair. If used for aesthetics only, saw cutting can be eliminated if inspection is conducted to assure featheredging does not occur.

7.2 Reinforcement

Reinforcement requirements in shotcrete repairs can include:

- replacement of existing corroded reinforcing steel;
- addition of new reinforcing steel to upgrade or strengthen the structure;
- provision of shrinkage and temperature crack control reinforcement;
- reinforcement to tie-back the shotcrete repair to the existing concrete.

Judiciously designed reinforcement will serve more than one, if not all, of the above functions.

For corroded reinforcing steel, bars which display deep pits or have lost more than 20 percent of their cross-sectional area should be removed and replaced, or supplemented with additional reinforcement. (In some highly stressed structures, Engineers may impose more stringent limits on the allowable loss of cross-sectional area). Placement of replacement or supplemental bars, however, differs from conventional reinforced concrete construction in that bars should not be bundled in lapped splices. The general recommendation is that the minimum spacing around each bar should be three times the maximum aggregate size to allow for proper encapsulation with shotcrete. As an alternative to lapped splice, replacement reinforcing steel may be welded to existing reinforcement, but only subject to verification of the weldability of both new and existing reinforcing steel.

When placing double mats of reinforcing steel, bar spacing should as far as possible be offset, such that the interior layer of reinforcement is clearly visible to the nozzleman during shooting. Shooting through more than two layers of reinforcement should be prohibited. Intersecting bars should be tightly secured to each other at appropriate spacing, using 1.6-mm or heavier gauge of wire. Large knots of tie wire, which could interfere with shotcrete placement, should be avoided. Use should be made of suitable reinforcing chairs, or anchors, to support reinforcing steel and mesh to minimize vibration and "flapping" during shotcrete placement. The minimum clearance behind all reinforcing bars or mesh should be 20 mm. It is difficult to properly encapsulate reinforcing fixed tightly against existing concrete.

As an alternative to welded wire mesh fabric, fiber reinforced shotcrete may be used. Fiber reinforcement has the benefit of dispensing with the need to fix reinforcing mesh. It is also more easily applied and less conducive to the formation of sand pockets and voids (nozzleman does not have to be concerned with proper encapsulation of mesh). The fiber reinforced shotcrete should, however, still be properly mechanically anchored to the substrate concrete, particularly at the perimeter of large repair areas.

7.3 Anchors

It is generally recommended that the maximum anchor spacing for reinforcing steel should not exceed 600 mm. In smaller dimension elements such as beams, girders, columns, etc., it may be necessary to use closer anchor spacing. Anchor spacing should be such that the reinforcing does not vibrate or deform excessively during shotcreting. Small areas should contain at least four anchors.

Anchors may be mechanically set or grouted, depending on the exposure conditions (grouted anchors are preferred in wet conditions) and on the purpose of the anchors. Designed anchors are included on the Contract Drawings when the designer anticipates they will be needed to ensure the integrity and stability of thick shotcrete repair sections. Non-designed anchors are used by the contractor to hold reinforcement in place during the shotcrete application process. A general recommendation is that designed anchors should develop a minimum pull-out force of 10 kN. Larger pull-out force resistance and large-diameter, deep-set designed anchors may be required in jacketed repairs of lower quality concretes. Sufficient testing should be conducted to verify pull-out resistance of designed anchors.

7.4 Alignment Control and Cover

Proper alignment control is required to ensure that the specified tolerance requirements and cover to reinforcing steel are satisfied. Alignment control is normally achieved by means of shooting wires, guide strips or depth gauges. In some cases, forms or other types of devices are used. Edge forms can be particularly beneficial when strict tolerances on the shape and lines of the structure are required for aesthetic reasons (e.g., arches). Careful form design and shotcreting technique is, however, required to prevent entrapment of rebound and overspray. When shooting wires are used, they should consist of a high-strength steel wire (piano wire) at constant tension during the shooting operation. The simple use of fencing wire is not recommended as it tends to detension and sag during the shooting operation.

Depth gauges, such as double-headed nails, are used, but they should be appropriately spaced. Spacing on a grid pattern not exceeding 1200 mm is often specified. On completion of shooting, such depth gauges should be cut back a minimum of 10 mm below the finished surface in order to prevent corrosion staining. General cover to reinforcing steel should be prescribed on the contract plans. In no case should cover to reinforcing be less than 30 mm. With steel fiber reinforced shotcrete it may be desirable, for aesthetic reasons, to apply a "flash-coat" of plain (nominal 5-mm MSA) shotcrete to prevent corrosion staining of the finished surface.

In encapsulating elements such as pier caps, buttresses, parapets, etc., it is important that the shotcrete be designed to completely cap the elements. The C-SHRP study (Reference 1) found that there was a danger of the shotcrete repair acting as a "dam" to promote saturation of the original concrete with water and salts if the shotcrete repair did not completely cap the element. The original concrete then became vulnerable to freeze-thaw and deicing salt scaling deterioration. All caps should be designed with a minimum 3 percent slope, to prevent ponding and facilitate drainage.

Careful consideration should also be given at the design stage to incorporation of drip grooves and reveals on the soffits of elements such as decks, beams and arches, which are exposed to rain and/or deck run-off water and salt solutions. Such details should be designed to prevent water and salts from seeping to the underside of the elements.

8.0 QUALITY ASSURANCE AND QUALITY CONTROL TESTING

8.1 Quality Assurance

As in any engineering project, the Owner should implement a suitable quality assurance program to achieve a satisfactory end product. Shotcrete rehabilitation projects tend to differ from most cast-in-place concrete repair type contracts in that it is often necessary to implement a preconstruction evaluation and testing program to establish that the Contractor's proposed materials, supply, equipment and crew are capable of producing the required end product.

It should also be noted that engineering inspection costs may be higher on a shotcrete rehabilitation contract than in new concrete construction. On many structural repairs, the Engineer is required to make judgment calls relating to strength and safety which require a frequent site presence.

8.2 Quality Control Testing

The Contractor should implement a rigorous program of quality control testing to assure compliance with the contract requirements. The recommended details for such a program are given in the Guide Specification. Any deficiencies noted during shooting operations (e.g., sand pockets, dry lenses, shadowing, voids, etc.) are best corrected while the shotcrete is still plastic. Repair of such defects becomes much more costly if the shotcrete is allowed to harden.

8.3 Preconstruction Trials

It is important that the nozzlemen used on the project demonstrate suitable skills. This is normally done by the Engineer evaluating the performance of the nozzlemen in a preconstruction "shoot." Such an evaluation should require the nozzlemen to do preconstruction trials as required in the Guide Specification. The test panels should be oriented to be representative of the project work. (Different skills are, for example, required in bench-gunning thick vertical surface compared to overhead applications). A minimum of three 100-mm diameter cores should be extracted from locations of intersecting reinforcing steel and mesh to check the adequacy of consolidation of shotcrete around reinforcement. At least one core should be taken at the location of an anchor.

Preconstruction test panels should be field cured in the wooden forms in the same manner as the proposed shotcrete work for a minimum of 24 hours, prior to transport to the test laboratory. Test panels should be transported in their wooden forms, taking care not to crack or damage the shotcrete.

The shotcrete nozzleman should be required to demonstrate his ability to correctly and successfully apply the type of shotcrete specified for the project. Effective nozzling is a skill learned from experience and is physically demanding. Only persons who are physically able and experienced should be allowed to work on the project.

A test panel or test area, simulating a surface on the project, should be shot using the equipment, materials, mix proportions, and reinforcement specified for the project. The test panel should be a minimum of 1 meter square to allow the nozzleman to adequately demonstrate his ability. Provision may be made to accumulate and measure rebound from the panel or test area. Performance requirements may vary from project to project. The contractor should use the proper type of shooting surface for the test panel or area, the proper thickness of the shotcrete application to correlate with acceptable core or cube dimensions, mix proportions for dry-mix or concrete proportions for wet-mix, and similar reinforcement requirements as called for in the project.

The test panel or area should be checked by the Engineer to verify that the forms are adequately braced, reinforcing steel bar laps are spaced 2½ bar diameters apart, mesh is lapped 1½ squares, reinforcement is properly spaced and rigidly tied and secured to avoid movement during the shotcrete operation, and shooting surfaces and reinforcement are clean and properly prepared to receive the shotcrete application.

The surface to be shot against, anchorages, reinforcement, panel orientation (vertical, horizontal, and overhead), total sample thickness, material, and mix shall duplicate job requirements as nearly as practical.

The Engineer may refer to ACI 506R, Chapter 2, Materials, as a guide for quality requirements for shotcrete materials. The Engineer should consult with the shotcrete applicator to establish the materials and the mix proportions for the test.

If sufficient data are available from previous tests of the materials, shotcrete mixture proportions may be selected from such data to produce a given compressive strength.

If insufficient or no previous data are available, at least three shotcrete control test panels with a minimum thickness of 75 mm should be shot by an experienced nozzleman using different proportions. Cores or cubes taken from the test control panels shall be removed and tested in accordance with ASTM C 42.

Based on the compressive strength achieved by the cores or cubes taken from the test control panels, a mixture proportion should be selected for the test which should produce shotcrete with a 28-day compressive strength of at least 35 MPa. Core strengths should be corrected to an L/D of less than 2 in accordance with ASTM C 42. Where quick-setting additives or cements are used, compressive strength and setting time may be adjusted to test for initial set time and initial strength in addition to 28-day compressive strength.

The test should be conducted using equipment of a design and size normally used for the specified type of shotcrete. The Engineer may refer to ACI 506R, Chapter 4, Equipment Requirements, as a guide for recommended equipment requirements for either the dry-mix process or the wet-mix process.

A competent crew, including an experienced gunman or pump operator, blowpipe operator, and possibly a finisher, should be provided to assist the nozzleman in shooting the test panel or area.

The Engineer should carefully observe the shooting of the test panel or area and note if the nozzleman:

1. Cleans shooting surface with air and water prior to shooting;

2. Applies bonding coat on shooting surface ahead of heavier shotcrete applications;

3. Directs shotcrete application around reinforcement in a manner which prevents build-up on the face of the reinforcement and allows shotcrete to flow and compact tightly around the back and remainder of the reinforcement;

4. If applicable, directs finisher or blowpipe operator to cut out any sags or sand pockets; and

5. If applicable, and where necessary, directs the finisher or blowpipe operator to broom the shotcrete surface prior to application of additional layers of shotcrete.

Notes, photographs, or other documentation made by the Engineer during gunning of the test panel or area will be helpful later in testing and analyzing the test panel or area.

The test panel or area should be properly cured in accordance with ACI 506R, Chapter 6, paragraph 6.4, Curing and Cold Weather Protection, and ACI 506.2, paragraph 3.7.

Tests and observations of the test panel or area will be used to evaluate workmanship. A minimum of six cores or cubes should be cut from the test panel or area. Three cores or cubes cut through the unreinforced sections of the test panel or area should be subjected to compressive strength tests. Test results will be compared with the compressive strength requirement established for the tests. At least three cores or cubes should be cut through the reinforcement for analysis of quality and extent of shotcrete encasement and be subjected to the core grading requirements of the Guide Specification or ACI 506.2, paragraph 1.7, Shotcrete Core Grades. All cores or cubes should be examined for evidence of sand pockets, voids or sags. A copy of the core grade photos is available in the 1995 version of ACI 506.2.

Where applicable, the Engineer should also examine the stripped side of the panel for evidence of sags, sand pockets and lack of a bonding coat. Corners and other sections of the panels or areas should be cut or broken open for observation by the Engineer of laminations, sand lenses or other defects.

The Engineer may waive the preconstruction evaluation program if satisfied from previous experience that the Contractor and nozzleman have demonstrated the ability to satisfactorily perform the work. The Contract Documents should specify the conditions under which this will occur. In such circumstances, the Engineer should particularly closely monitor the Contractor's performance at the start of the repair work.

8.4 Construction Testing

Construction testing is required to assess the compliance of the shotcrete to the project specifications. Detailed requirements for construction testing are given in the Guide Specification. Shotcrete testing differs from testing of cast-in-place concrete in that the test specimens are typically diamond drilled or saw cut cores or prisms, extracted from either test panels or the in-place shotcrete, rather than cast specimens. When cores are extracted from cast-in-place concrete, the following must apply:

Concrete represented by the core tests shall be considered structurally adequate:

(a) if the average strength of each set of three cores from the portion of the structure in question is equal to at least 85 percent of the specified strength; and

(b) if no single core is less than 75 percent of the specified strength.

There is a considerable debate in the shotcrete community as to whether these same criteria should be applied to interpretation of the results of quality control tests on shotcrete cores. The existing ACI 506.2, *Specifications for Materials, Proportioning and Application of Shotcrete*, Clause 1.6.3.3 does apply these same criteria to shotcrete. Some authorities require the average compressive strength for a set of three shotcrete cores to meet or exceed the specified strength. The Joint Task Force Guide Specification requires using the full specified compressive strength for acceptance of preconstruction test panel cores and for construction test panel cores. They are normally shot under good conditions and should be expected to meet the specified compressive strength. The Guide Specification recommends applying the ACI criteria shown above in italics for acceptance of cores taken from the in-place production shotcrete, if it is necessary to take cores in an area of suspect quality. It should be made very clear to the Contractor in the Contract Documents which criteria apply.

9.0 SAFETY AND CLEAN-UP

During concrete removal processes, safety measures should be implemented to protect personnel from injury and equipment and adjacent property from damage.

10.0 SHOTCRETE APPLICATION AND FINISHING

General guidance for both dry- and wet-mix shotcrete application is provided in the ACI 506R, *Guide to Shotcrete*. The publication by Crom (Reference 2) provides excellent guidance on proper dry-mix shotcrete nozzling procedures. These documents do not, however, deal in any depth with the more recent innovations in shotcrete repair, such as the use of silica fume or steel fiber reinforcement. More detail concerning the latter types of shotcrete systems in repair applications are given in References 1, 5, 11, 12, 13 and 14.

Shotcrete should be applied in accordance with the general requirements detailed in ACI 506R and the Crom publication (Reference 2) except that with silica fume shotcrete it is often possible to build up the full thickness of the repair in a single layer, even on overhead surfaces. This particularly applies to silica fume shotcrete applied by the dry-mix shotcrete process. It is technically desirable to build up the full thickness in a single layer, provided rebound and overspray are properly dealt with and the shotcrete does not lose adhesion and slough, sag or delaminate. Rebound should be removed from surfaces to receive shotcrete; this is best done while the material is still plastic using blowpipes, scrapers, wire brushes, or other suitable tools. Single-layer construction eliminates the requirement for preparing each layer of shotcrete to receive a subsequent layer, and enhances productivity. With conventional shotcrete, the layer thickness on overhead surfaces will generally be limited to 50 mm or less. Thicknesses of 200 mm or more in a single pass on overhead surfaces have been achieved in certain dry-mix silica fume shotcrete repair projects. Thicknesses of 600 mm or more have been achieved in repair of vertical surfaces, using steel fiber reinforced, dry-mix silica fume shotcrete (Reference 14).

General recommendations for shotcrete application in bridge repair projects is provided in the Guide Specification. Items which are important to the provision of quality shotcrete are emphasized, such as:

- provision of suitable scaffolding or elevating devices to provide the nozzleman with good access for proper nozzle orientation to the receiving surface;
- sufficient ventilation and lighting to provide clear, unhindered view of the shooting area;
- use of predampeners in applying dry-bagged premix shotcrete, to minimize dust formation and enhance homogeneity of the in-place shotcrete.

Excess shotcrete or overspray should be removed from non-prepared concrete surfaces adjacent to repair edges. Thin skim coats should not be applied to non-prepared concrete surfaces to "even-out" the appearance between shotcrete patches. Such material is highly vulnerable to delamination and peeling.

11.0 CURING AND PROTECTION

Proper curing is one of the most important requirements for a successful repair. Most shotcrete displays very little bleeding, particularly silica fume shotcrete. Such shotcrete is vulnerable to plastic shrinkage and early age drying shrinkage cracking, unless appropriate protection and curing measures are taken.

On warm, windy days, with high evaporation rates, on cold days with low relative humidity, and on surfaces exposed to direct sunlight during shotcreting, it may be necessary to use special shades, wind breaks, fogging equipment, or surface evaporation retardants, or a combination of these. Alternatively, the shotcrete work may have to be rescheduled to night shifts or more favorable ambient conditions. Shotcrete applied under the above conditions is very vulnerable to cracking, especially when applied to surfaces in a combination of direct sunlight, a breeze, and temperatures above about 25 degrees C. In severe conditions, good results have been obtained by applying a finishing compound made specifically to reduce moisture loss as an interim measure before wet curing can be applied.

The best means of curing is to keep the shotcrete continuously saturated with water for a minimum period of 7 days. This enables the shotcrete to gain strength before being subjected to pronounced drying shrinkage stresses. Means of accomplishing this are given in the Guide Specification. In some circumstances the use of moist curing is impractical; and curing compounds must be removed by grit blasting or high-pressure water blasting if subsequent shotcrete layers, paints or coating are to be applied to the shotcrete. Under favorable conditions of wind, humidity and temperature, the wet curing time may be reduced to a minimum of 4 days based on a local history of acceptable performance.

The normal requirements for hot and cold weather concreting also apply to shotcrete. In cold weather shotcreting operations, it is recommended that shotcrete not be applied if the substrate concrete temperature is below 5 degrees C. The air temperature in contact with the shotcrete should be above 10 degrees C. Otherwise, the shotcrete can be very slow in setting and hardening, and bond to the substrate could be damaged, particularly on overhead surfaces (such as soffits of bridge decks) subjected to vibration from traffic.

12.0 SHOTCRETE ACCEPTANCE AND REPAIR

It is highly desirable that the Engineer provide a knowledgeable inspector to monitor the shotcrete repair work. This is particularly important at start-up of the project so that any observed deficiencies can be corrected before the work progresses too far. The Engineer or his designated inspector should review and approve all prepared shotcrete surfaces, anchors and fixed reinforcing steel or mesh, prior to the placement of any shotcrete. Shotcrete application should be carefully monitored and any deficiencies observed during the shotcrete application process should be immediately addressed. Preferably, any defective shotcrete should be removed while the shotcrete is still plastic, as it becomes much more costly to remove once hardened.

When shotcrete test panels or examination and sounding of the hardened shotcrete provide indications of non-compliance with the project specifications, a program should be implemented to evaluate the quality of the in-place shotcrete. Such a program will usually involve diamond core drilling, sometimes in conjunction with other non-destructive test procedures. The ACI 506 Shotcrete Committee has adopted a "Core Grade System" to quantify the quality of in-place shotcrete. This system is new; however, it is the best available rational criterion to be used for shotcrete acceptance/rejection and is highly recommended.

When shotcrete is required to be removed and repaired, the same basic procedures specified for original concrete repair should be followed. In most contracts, the Contractor is required to bear all costs accrued for testing and repairing defective shotcrete.

REFERENCES

1. Morgan, D. R. and J. Neill, *Durability of Shotcrete Rehabilitation Treatments of Highway Bridges in Canada*, Transportation Association of Canada Annual Conference, Winnipeg, Manitoba, September 17, 1991, p. 36.

2. Crom, T. R., *Dry Mix Shotcrete Nozzling*, Gainesville, Florida, U.S.A., Crom Corporation, 1985, p. 39.

3. Rasheeduzzafar, F. D. and K. Mukarram, *Influence of Cement Composition and Content on the Corrosion Behavior of Reinforcing Steel in Concrete*, Vol. 2, ACI SP-100, 1987, pp. 1477–1502.

4. Morgan, D. R., Use of Supplementary Cementing Materials in Shotcrete, *Proceedings. International Workshop on the Use of Fly Ash, Slag, Silica Fume and other Siliceous Materials in Concrete*, W. G. Ryan, Ed., Sydney, Australia: Concrete Institute of Australia, July 4–6, 1988, pp. 403–432.

5. Morgan, D. R., New Developments in Shotcrete for Repairs and Rehabilitation. Presented at CANMET International Conference on Advances in Concrete Technology, V. M. Malhotra, Ed., Athens, Greece, May 1992, pp. 669–740.

6. Morgan, D. R., "Freeze-Thaw Durability of Shotcrete." *Concrete International*, Vol. 11, No. 8 (August 1989): pp. 86–93.

7. Beaupré, D., M. Pigeon, C. Talbot, and M. Gendreau, "Deicer Salt Scaling Resistance of Dry- and Wet-Process Shotcrete," *ACI Materials Journal* (Sept./Oct., 1994), pp. 487–494.

8. Morgan D. R., J. Neill, N. McAskill, and N. Duke, Evaluation of Silica Fume Shotcrete. CANMET/CSCE International Workshop on Silica Fume in Concrete, Montreal, Québec, May 4–5, 1987, 34 pp.

9. Morgan, D. R. and J. Wolsiefer, *Wet-Mix Silica Fume Shotcrete: Effect of Silica Fume Form*, Vol. 2, ACI SP-132, 1992, pp. 1251–1271.

10. Silfwerbrand, J., Concrete Repair with Shotcrete, *Bulletin No. 153*, Department of Structural Mechanics and Engineering. Royal Institute of Technology, Stockholm, Sweden, 1988.

11. Gilbride, P., D. R. Morgan, and T. W. Bremmern, *Deterioration and Rehabilitation of Berth Faces in Tidal Zones at the Port of Saint John.* American Concrete Institute SP-109, Detroit, 1988, pp. 199–225.

12. Carter, P., Bridge Repairs with Steel Fibre Shotcrete, Alberta Transportation report presented at American Concrete Institute, 1985 Fall Convention, Seminar on Concrete Rehabilitation with Shotcrete, Chicago, 1985, 16 pp.

13. Morgan, D. R., "Dry-Mix Silica Fume Shotcrete in Western Canada." *Concrete International,* Vol. 10, No. 1 (January 1988): pp. 24–26.

14 Anderson, B. C., Shotcrete Repairs to Skeena River Crossing Tower Pier Foundations, Canadian Electrical Association Meeting, Vancouver, B.C., March 1987, 17 pp.

15. Grzybowski, M., Determination of Crack Arresting Properties of Fiber Reinforced Cementitious Composites. Publication TRITA-BRO-8908, ISSN 1100-648X, Department of Structural Engineering. Royal Institute of Technology, Stockholm, Sweden, June 1989, 190 pp.

16. Morgan, D. R. and Mowat, D. N., *A Comparative Evaluation of Plain, Mesh, and Steel Fibre Reinforced Shotcrete*, American Concrete Institute SP-81, 1984, pp. 307-324.

17. Morgan, D. R., N. McAskill, B. W. Richardson, and R. C. Zellers, A Comparative Evaluation of Plain, Polypropylene Fibre, Steel Fibre, and Wire Mesh Reinforced Shotcrete. In *Transportation Research Record 1226*, TRB, National Research Council, Washington, D.C., 1989, pp. 78–87.

18. Gebler, S. H., A. Litvin, W. J. McLean, and R. Schutz, "Durability of Dry-Mix Shotcrete Containing

Accelerators," *ACI Materials Journal*, Vol. 89, No. 3 (May/June, 1992): pp. 259–262.

19. Austin, S. and P. Robins, *Sprayed Concrete: Properties, Design, and Application*. Caithness, Scotland: Whittles Publishing, 1995, pp. 382.

20. Morgan, D. R., *Recommended Practice for Shotcrete Repair of Highway Bridges*. Prepared under the auspices of the Canadian Strategic Highway Research Program study titled *Durability of Shotcrete Rehabilitation Treatment of Bridges*. Transportation Association of Canada, Ottawa, Canada.