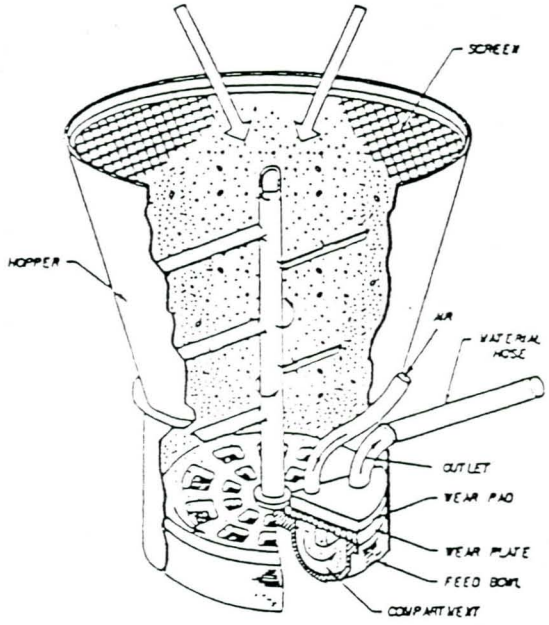
TECHNICAL ENGINEERING AND DESIGN GUIDES
AS ADAPTED FROM THE
US ARMY CORPS OF ENGINEERS, NO. 11

STANDARD PRACTICE FOR



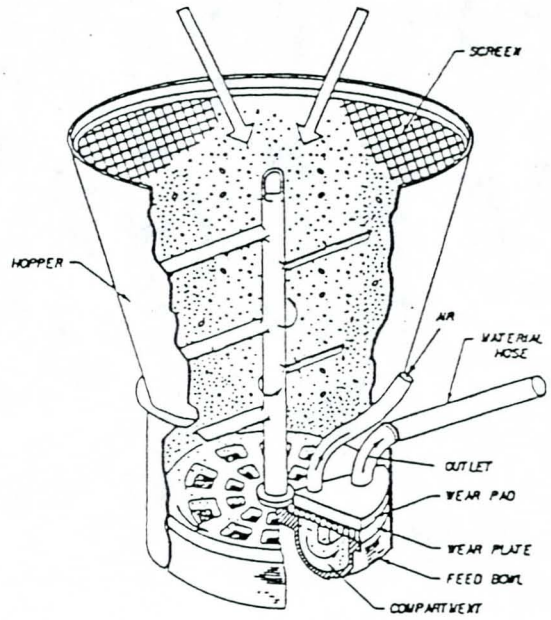
SHOTCRETE

AMERICAN SOCIETY OF CIVIL ENGINEERS

ASCE PRESS

TECHNICAL ENGINEERING AND DESIGN GUIDES
AS ADAPTED FROM THE
US ARMY CORPS OF ENGINEERS, NO. 11

STANDARD PRACTICE FOR



SHOTCRETE

AMERICAN SOCIETY OF CIVIL ENGINEERS

ASCE PRESS

TECHNICAL ENGINEERING AND DESIGN GUIDES
AS ADAPTED FROM THE
US ARMY CORPS OF ENGINEERS, NO. 11

STANDARD PRACTICE FOR SHOTCRETE

Published by
ASCE Press
American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398

ABSTRACT

This manual, *Standard Practice for Shotcrete*, provides information and guidance on the selection, proportioning, and application of shotcrete. It is intended for use by engineers and technical staff tasked with the planning, design, contract preparation, and construction management phases of a shotcrete project. A quality assurance chapter is included which details necessary technical activities during the construction phase. Subjects discussed include shotcrete and applications, materials, equipment and crew, preconstruction testing and evaluation, placement, quality control, and quality assurance.

Library of Congress Cataloging-in-Publication Data

Standard practice for shotcrete.
p. cm. — (Technical engineering and design guides as adapted from the U. S. Army Corps of Engineers; no. 11)
ISBN 0-7844-0068-7
1. Gunite. 2. Concrete construction. I. American Society of Civil Engineers. II. Series.
TA446.S73 1995 95-11427
624.1'834—dc20 CIP

The material presented in this publication has been prepared in accordance with generally recognized engineering principles and practices, and is for general information only. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application.

The contents of this publication are not intended to be and should not be construed to be a standard of the American Society of Civil Engineers (ASCE) and are not intended for use as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document.

No reference made in this publication to any specific method, product, process or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASCE.

ASCE makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability or utility of any information, apparatus, product, orprocess discussed in this publication, and assumes no liability therefor.

Anyone utilizing this information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

Photocopies. Authorization to photocopy material for internal or personal use under circumstances not falling within the fair use provisions of the Copyright Act is granted by ASCE to libraries and other users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee of $2.00 per article plus $.25 per page copied is paid directly to CCC, 222 Rosewood Drive, Danvers, MA 01923. The identification for ASCE Books is 0-7844-0068-7/95 $2.00 + $.25. Requests for special permission or bulk copying should be addressed to Permissions & Copyright Dept., ASCE.

Copyright © 1995 by the American Society of Civil Engineers,
exclusive of U.S. Army Corps of Engineers material.
All Rights Reserved.
Library of Congress Catalog Card No: 95-11427
ISBN 0-7844-0068-7
Manufactured in the United States of America.

Printed on recycled paper. 85% recovered fiber and 15% post-consumer waste.

recycled paper

TABLE OF CONTENTS

Chapter 1. Introduction

1-1	Purpose	1
1-2	Applicability	1
1-3	References	1
1-4	Glossary	1
1-5	Background	1
1-6	Activities and Documentation	1
1-7	Point of Contact	2

Chapter 2. Types of Shotcrete and Applications

2-1	Why Shotcrete	3
2-2	Applications	3
2-3	Shotcrete Processes	4
2-4	Fiber-Reinforced Shotcrete	5
2-5	Silica-Fume Shotcrete	6
2-6	Polymer-Modified Shotcrete	6
2-7	Accelerated Shotcrete	6

Chapter 3. Materials, Proportioning, and Properties

3-1	Cementitious Materials	7
3-2	Aggregate	8
3-3	Water	8
3-4	Chemical Admixtures	8
3-5	Reinforcing Steel	9
3-6	Fiber Reinforcement	10
3-7	Proportioning Shotcrete	10
3-8	Properties of Shotcrete	12

Chapter 4. Equipment and Crew

4-1	General Equipment	15
4-2	Dry-Mix Process	15
4-3	Wet-Mix Process	15
4-4	Auxiliary Equipment	17
4-5	Special Equipment	20
4-6	Crew Composition	20

Chapter 5. Preconstruction Testing and Evaluation

5-1	General	23
5-2	Nozzleman Certification	23
5-3	Mixture Proportioning Evaluation	23
5-4	Preconstruction Demonstration and Testing	23
5-5	Alternate Considerations	26

Chapter 6. Placement

6-1	Preparations	29
6-2	Batching and Mixing	30
6-3	Shotcrete Application Techniques	31
6-4	Rebound	35
6-5	Finishing	36
6-6	Curing and Protection	36
6-7	Repair of Surface Defects	37

Chapter 7. Quality Control

7-1	General Considerations	39
7-2	Preproduction Phase	39
7-3	Production Phase	40
7-4	Corrective Actions	42

Chapter 8. Quality Assurance

8-1	General Considerations	43
8-2	Preproduction Phase	43
8-3	Production Phase	43

Appendices

Appendix A	References	45
Appendix B	Glossary of Terms	49
Appendix C	Shotcrete Applications—Corps of Engineers Projects	51
Appendix D	Mixture Proportioning Sample Submittal	53

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
WASHINGTON, D.C. 20314-1000

REPLY TO
ATTENTION OF:

Mr. Stafford E. Thornton
President, American Society
of Civil Engineers
345 East 47th Street
New York, New York 10017

Dear Mr. Thornton:

I am pleased to furnish the American Society of Civil Engineers (ASCE) a copy of the U. S. Army Corps of Engineers Engineer Manual, EM 1110-2-2005, Standard Practice for Shotcrete. The Corps uses this manual to provide information on the selection, proportioning, and application of shotcrete as a construction material.

I understand that ASCE plans to publish this manual for public distribution. I believe this will benefit the civil engineering community by improving transfer of technology between the Corps and other engineering professionals.

Sincerely,

Arthur E. Williams
Lieutenant General, U. S. Army
Commanding

CHAPTER 1

INTRODUCTION

1-1. PURPOSE.

This manual provides information and guidance on the selection, proportioning, and application of shotcrete. It is intended for use by engineers and technical staff tasked with the planning, design, contract preparation, and construction management phases of a shotcrete project. A quality assurance chapter is included which details necessary technical activities during the construction phase. Subjects discussed include shotcrete and applications, materials, equipment and crew, preconstruction testing and evaluation, placement, quality control, and quality assurance. This manual does not provide guidelines for structural analysis of shotcrete applications. Refer to EM 1110-2-2000 for additional general guidance on concrete.

1-2. APPLICABILITY.

This manual is applicable to all HQUSACE/OCE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having civil works responsibilities.

1-3. REFERENCES.

Appendix A consists of a list of cited references that appear in the body of the text as well as a selected bibliography pertaining to the use of shotcrete. The reader is encouraged to study applicable references to supplement the guidance provided by this manual. In particular, the reader is encouraged to refer to American Concrete Institute (ACI) Committee Report 506R-90, "Guide to Shotcrete" (paragraph A-1, ACI (1991d)), and other ACI 506 documents (paragraph A-1, ACI (1991e), paragraph A-2, ACI (1991c and 1991d)).

1-4. GLOSSARY.

Appendix B consists of definitions of terms commonly used in shotcrete.

1-5. BACKGROUND.

A. Special Equipment and Techniques. Equipment for pneumatically applying a fine aggregate cement mixture was first introduced in 1910. Since that time, many improvements have been made in the equipment and in the specialized techniques required for application of pneumatically applied mortar or concrete. The wide acceptance of shotcrete for slope and surface protection, swimming pool construction, tunnel lining, special architectural features, and renovating existing structures has resulted in the availability of a wide variety of manufactured pneumatic placement equipment.

B. Shotcrete Denotes Various Mixtures. Shotcrete has been referred to by such terms as Gunite, formerly a tradename for pneumatically applied mortar or concrete, sprayed concrete, spraycrete, air-blown mortar and concrete, gunned concrete, and others. In some areas "gunite" has been used to denote small-aggregate shotcrete and mortar mixtures, and "shotcrete" to denote large-aggregate mixtures. The preferred term today for all gunned material is shotcrete, regardless of the aggregate size.

C. Specialty Shotcretes. While most shotcrete placed is the traditional dry-mix and wet-mix shotcrete, the use of specialty shotcretes has become common. The addition of accelerators, fibers, and silica fume can provide shotcrete with significantly enhanced performance.

D. Varied Applications. Typical applications for Corps of Engineers (Corps) projects further discussed in Chapter 2 include slope protection and stabilization, temporary excavation protection, tunnel support, and various structural and remedial applications. Appendix C provides a listing of some Corps projects that have used shotcrete for various applications.

1-6. ACTIVITIES AND DOCUMENTATION.

Involvement in shotcrete activities ranges from preliminary planning studies through the engineering

and design phases, preparation of contract documents, to construction management. During these activities the engineer or other professional must perform investigations, prepare documents, and review design requirements. These activities often result in the production of the following documents:

1. Shotcrete Investigation Report.
2. Technical Specifications.
3. Engineering Considerations and Instructions for Field Personnel.

A. Shotcrete Investigation Report. The information listed is to be included in a shotcrete investigation report and prepared either as a separate report or part of a design memorandum, as a preparatory step to the production of technical specifications. The formalization of such a report depends on the size and complexity of the shotcrete project:

1. Shotcrete quantity to be used and quality required.
2. Climatic and service conditions to which the shotcrete will be subjected.
3. Types of shotcrete processes and delivery equipment to be used.
4. Types, kinds, and sources of cementitious materials to be specified, including special requirements.
5. Potential aggregate sources, quality, and constituents.
6. Grading of aggregate to be specified.
7. Types and kinds of admixtures to be specified, including test requirements.

B. Technical Specifications. Civil Works Guide Specification CW 03361 provides a basis for preparation of a specification for shotcrete.

C. Engineering Considerations and Instruction for Field Personnel. In accordance with EM 1110-2-2000, the designer should provide explanation of the intent of the shotcrete application, special precautions, critical items to monitor, and any other information that may be beneficial to the field staff.

1-7. POINT OF CONTACT.

Questions or discussion concerning this manual should be directed through Headquarters, U.S. Army Corps of Engineers, ATTN: CECW-EG.

CHAPTER 2

TYPES OF SHOTCRETE AND APPLICATIONS

2-1. WHY SHOTCRETE.

A. Importance of Proper Application. Properly applied shotcrete is a structurally sound and durable construction material which exhibits excellent bonding characteristics to existing concrete, rock, steel, and many other materials. It can have high strength, low absorption, good resistance to weathering, and resistance to some forms of chemical attack. Many of the physical properties of sound shotcrete are comparable or superior to those of conventional concrete or mortar having the same composition. Improperly applied shotcrete may create conditions much worse than the untreated condition.

B. Advantages of Shotcrete. Shotcrete is used in lieu of conventional concrete, in most instances, for reasons of cost or convenience. Shotcrete is advantageous in situations when formwork is cost prohibitive or impractical and where forms can be reduced or eliminated, access to the work area is difficult, thin layers or variable thicknesses are required, or normal casting techniques cannot be employed. Additional savings are possible because shotcrete requires only a small, portable plant for manufacture and placement. Shotcreting operations can often be accomplished in areas of limited access to make repairs to structures.

C. Strength of Bonding. The excellent bonding of shotcrete to other materials is often an important design consideration. The force of the impact of this pneumatically propelled material on the surface causes compaction of the shotcrete paste matrix into the fine surface irregularities and results in good adhesion to the surface. Within limits, the material is capable of supporting itself in vertical or overhead applications.

2-2. APPLICATIONS.

The selection of shotcrete for a particular application should be based on knowledge, experience, and a careful study of required and achievable material performance. The success of the shotcrete for that application is contingent upon proper planning and supervision, plus the skill and continuous attention provided by the shotcrete applicator. The following paragraphs discuss the use of shotcrete in several of the more common applications. A number of shotcrete applications by the Corps of Engineers are listed in Appendix C.

A. Repair. Shotcrete can be used to repair the damaged surface of concrete, wood, or steel structures provided there is access to the surface needing repair. The following examples indicate a few ways in which shotcrete can be used in repairs:

(1) Bridges. Shotcrete repair can be used for bridge deck rehabilitation, but it has generally been uneconomical for major full-thickness repairs. It is very useful, however, for beam repairs of variable depths, caps, columns, abutments, wingwalls, and underdecks from the standpoint of technique and cost.

(2) Buildings. In building repairs, shotcrete is commonly used for repair of fire and earthquake damage and deterioration, strengthening walls, and encasing structural steel for fireproofing. The repair of structural members such as beams, columns, and connections is common for structures damaged by an earthquake.

(3) Marine structures. Damage to marine structures can result from deterioration of the concrete and of the reinforcement. Damaging conditions are corrosion of the steel, freezing and thawing action, impact loading, structural distress, physical abrasion from the action of waves, sand, gravel, and floating ice, and chemical attack due to sulfates. These problems can occur in most marine structures such as bridge decks, piles, pile caps, beams, piers, navigation locks, guide walls, dams, powerhouses, and discharge tunnels. In many cases, shotcrete can be used to repair the deteriorated surfaces of these structures.

(4) Spillway surfaces. Surfaces subject to high-velocity flows may be damaged by cavitation erosion or

abrasion erosion. Shotcrete repairs are advantageous because of the relatively short outage necessary to complete the repairs.

B. Underground Excavations. For the most part, shotcrete is used in underground excavations in rock; but on occasion, it has been successfully used in the advancement of tunnels through altered, cohesionless, and loose soils. Typical underground shotcrete applications range from supplementing or replacing conventional support materials such as lagging and steel sets, sealing rock surfaces, channeling water flows, and installing temporary support and permanent linings.

C. Slope and Surface Protection. Shotcrete is often used for temporary protection of exposed rock surfaces that will deteriorate when exposed to air. Shotcrete is also used to permanently cover slopes or cuts that may erode in time or otherwise deteriorate. Slope protection should be properly drained to prevent damage from excessive uplift pressure. Application of shotcrete to the surface of landfills and other waste areas is beneficial to prevent surface water infiltration.

D. New Structures. Shotcrete is not necessarily the fastest method of placing concrete on all jobs, but where thin sections and large areas are involved, shotcreting can be used effectively to save time. The following paragraphs describe some of the applications involved with construction of new structures.

(1) Pools and tanks. Shotcrete has been used extensively to construct concrete swimming pools. More recently, large aquariums have been constructed using shotcrete.

(2) Shotcrete floors and walls. Shotcrete floors in tanks and pools on well compacted subbase or on undisturbed earth have generally given excellent service. Vertical and overhead construction for walls, slabs, columns, and other structural members has been frequently shotcreted.

(3) Shotcrete domes. Construction techniques using inflatable air-forming systems have made the construction of shotcrete shells or domes practical. These large structures have been used for residential housing, warehousing, bridge, and culvert applications.

2-3. SHOTCRETE PROCESSES.

Shotcrete can be applied by two distinct application techniques, the dry-mix process and the wet-mix process.

A. Dry-Mix Shotcrete. The cementitious material and aggregate are thoroughly mixed and either bagged in a dry condition, or mixed and delivered directly to the gun. The mixture is normally fed to a pneumatically operated gun which delivers a continuous flow of material through the delivery hose to the nozzle. The interior of the nozzle is fitted with a water ring which uniformly injects water into the mixture as it is being discharged from the nozzle and propelled against the receiving surface.

B. Wet-Mix Shotcrete. The cementitious material, aggregate, water, and admixtures are thoroughly mixed as would be done for conventional concrete. The mixed material is fed to the delivery equipment, such as a concrete pump, which propels the mixture through the delivery hose by positive displacement or by compressed air. Additional air is added at the nozzle to increase the nozzle discharge velocity.

C. Comparison of Dry-Mix and Wet-Mix Processes. Shotcrete suitable for most requirements can be produced by either the dry-mix or wet-mix process. However, differences in the equipment cost, maintenance requirements, operational features, placement characteristics, and product quality may make one or the other more attractive for a particular application. A comparative summary of the advantages and disadvantages of the processes is given in Table 2-1.

(1) Bond strengths of new shotcrete to existing materials are generally higher with dry-mix shotcrete than with wet-mix shotcrete. Both shotcrete mixtures often provide significantly higher bond strengths to existing materials than does conventional concrete.

(2) Typically, dry-mix shotcrete is applied at a much slower rate than wet-mix shotcrete. Dry-mix shotcrete is often applied at a rate of 1 or 2 cubic yards per hour compared to wet-mix shotcrete applied at a rate of up to 7 or 8 cubic yards per hour. Depending on the application, the in-place production rate may be significantly lower because of obstacles, rebound, and other features which may cause delays.

(3) Rebound is the shotcrete material that "bounces" off the shooting surface. Rebound for conventional dry-mix shotcrete, in the best of conditions, can be expected to be at least 20 percent of the total material passed through the nozzle. Wet-mix shotcrete rebounds somewhat less than dry-mix shotcrete.

(4) The use of air-entraining admixtures (AEA) in shotcrete is practical only in wet-mix shotcrete. When batched properly, AEA forms an air-void system suitable for providing frost resistance to wet-mix shotcrete. The

TABLE 2-1. Comparison of Features of Dry-Mix and Wet-Mix Shotcrete Processes

Dry-mix process (1)	Wet-mix process (2)
Mixing water instantaneously controlled at the nozzle by operator to meet variable field conditions	Mixing water controlled at plant and measured at time of batching
Longer hose lengths possible, if necessary	Normal pumping distances necessary
Limited to accelerators as the only practical admixture	Compatible with all ordinary admixtures. Special dispensers for addition of accelerators are necessary
Use of air-entraining admixture not beneficial. Resistance to freezing and thawing is poor	Air entrainment possible. Acceptable resistance to freezing and thawing
Intermittent use easily accommodated within prescribed time limits	Best suited for continuous application of shotcrete
Exceptional strength performance possible	Lower strengths, similar to conventional concrete
Lower production rates	Higher production rates
Higher rebound	Lower rebound
Equipment maintenance costs tend to be lower	Equipment maintenance costs tend to be higher
Higher bond strengths	Lower bond strengths, yet often higher than conventional concrete

formation of an air-void system in dry-mix shotcrete is not possible. However, dry-mix shotcrete, when properly proportioned and applied, will have a compressive strength exceeding approximately 7,000 pounds per square inch (psi). It has performed well in moderate exposures to freezing and thawing.

2-4. FIBER-REINFORCED SHOTCRETE.

A. Unreinforced shotcrete, like unreinforced conventional concrete, is a brittle material that experiences cracking and displacement when subjected to tensile stresses or strains. The addition of fibers to the shotcrete mixture adds ductility to the material as well as energy absorption capacity and impact resistance. The composite material is capable of sustaining postcrack loadings and often displays increased ultimate strength, particularly tensile strength. Fibers used in shotcrete are available in three general forms: steel fibers, glass fibers, and other synthetic fibers. Natural fiber, a fourth form, is not commonly used in shotcrete and will not be discussed.

B. The use of steel fibers has evolved rapidly since its inception in the late 1950's. The present third-generation steel fibers are greatly superior to the earlier fibers. Early mixing and handling problems which hampered uniform distribution of fibers in a mixture have been minimized by the manufacture of fibers with low-aspect ratios (ratio of length to diameter), surface deformations, and improved shape.

C. The use of glass-fiber-reinforced shotcrete (GFRS) is an adaptation of the technology of using chopped glass fibers and a resin binder. The equipment and process to apply glass-fiber shotcrete is not a conventional shotcrete operation, but requires a special gun and delivery system. This process termed "spray-up" is used extensively in the construction of lightweight panels for building cladding and special architectural features and is usually applied in a plant production situation. A common onsite application is the construction of simulated rock structures for animal exhibits at zoos. The fibers are made from a special zirconium alkali-resistant (AR) glass to resist deterioration in the highly alkaline portland-cement environment. Guidelines for

the use of glass-fiber spray-up are provided by the Prestressed Concrete Institute (PCI) (1981).

D. Other synthetic fibers are composed of nylon, polypropylene, polyethylene, polyester, and rayon. The predominant fiber used for shotcrete has been of polypropylene produced in a collated fibrillated form. The primary benefit of synthetic fiber additions to shotcrete is to decrease width of shrinkage cracks in the material.

E. Typical applications for fiber-reinforced shotcrete are for tunnel linings, surface coatings on rock and soil, slopes, structures, embankments, or other structures that may be subject to high deformations or where crack control is needed.

2-5. SILICA-FUME SHOTCRETE.

A. Silica fume is a very fine noncrystalline pozzolanic material composed mostly of silica. Silica fume is used in concrete and shotcrete to increase strength, decrease permeability, and enhance cohesion and adhesion. Specific advantages of silica fume in shotcrete are the improved bond strength of shotcrete to substrate surfaces, the improved cohesion of the shotcrete, and the resulting ability to apply thicker layers of shotcrete in a single pass to vertical and overhead surfaces. The material is more resistant to "washout," where fresh shotcrete is subject to the action of flowing water, and rebound is significantly reduced. Shotcrete containing silica fume may have improved resistance to aggressive chemicals.

B. In general, silica-fume shotcrete produces unhardened and hardened material properties which, among other uses, make it suitable as a substitute for polymer-modified shotcrete and accelerated shotcrete applications. Use of silica-fume shotcrete should be considered for many applications that presently use conventional shotcrete because of its bond and strength performance.

C. Silica-fume shotcrete has been widely used in tunnel construction often combined with fibers to control shrinkage cracking. Because of inherent improvements in permeability, silica-fume shotcrete has been used to cap landfills and other waste areas to be sealed from surface water infiltration. Performance in high-strength applications is more easily accomplished with silica-fume shotcrete.

2-6. POLYMER-MODIFIED SHOTCRETE.

A. Polymers are incorporated into shotcrete in two ways. In one method, the entire binder is composed of a polymer material. This is no longer a hydraulic-cement product but a polymer shotcrete. The more common use of polymers is the addition of a polymer emulsion to the hydraulic-cement mixture, as with a partial replacement of the mixing water, or as total replacement, which disperses throughout the mixture forming a continuous polymer matrix. This is termed polymer-portland-cement shotcrete.

B. The emulsified polymer for use in shotcrete has usually been styrene butadiene. Acrylic polymer latexes and epoxy resins are less frequently used products for portland-cement systems. The advantage of polymer-modified systems are that the polymers improve flexural and tensile strengths, improve bond, and reduce absorption because of lower permeabilities.

2-7. ACCELERATED SHOTCRETE.

A. Accelerating admixtures are used extensively in shotcrete. Highly effective accelerators have been developed for rapid setting of shotcrete. Often considered "super-accelerators," these are commonly used with dry-mix shotcrete. With the increasing use of silica fume, the use of accelerators may decline somewhat. In the past, these accelerators were exclusively powdered materials added to dry-mix shotcrete materials. Now both powdered and liquid admixtures are used in both dry-mix and wet-mix shotcrete. The use of these accelerators with a wet-mix process requires that the accelerator be added at the nozzle rather than batched with the other materials.

B. Applications include tunnel support and linings, seawalls, portions of dams, roof construction, slope protection, and water-retention structures such as canals, thick concrete sections applied vertically or overhead, rapid repairs, and leaks sealed with flashset shotcrete. Accelerated shotcrete is particularly beneficial in tunnel support because it allows rapid section buildup, early strength development, and seals water leakage. For applications in the splash zone of marine structures, an accelerating admixture may be used to prevent freshly placed shotcrete from being washed away by the incoming tide or by wave action.

CHAPTER 3

MATERIALS, PROPORTIONING, AND PROPERTIES

The materials, mixture proportions, and properties of shotcrete are similar in many respects to conventional concrete. Much of the guidance of EM 1110-2-2000 for conventional concrete applies to shotcrete as well.

3-1. CEMENTITIOUS MATERIALS.

A. Portland Cement.

(1) Cement requirements for shotcrete are similar to those for conventional concrete. Portland cement must meet the requirements of CRD-C 201 (All CRD-C designations are to *Handbook for Concrete and Cement*, 1949, U.S. Army Engineer Waterways Experiment Station. Parenthetical references are ASTM equivalents.)(American Society for Testing and Materials (ASTM) C 150), Type I or II. Where the shotcrete will be exposed to soil or water high in soluble sulfates, Type II or V should be used as described in EM 1110-2-2000. Blended cement must meet the requirements of CRD-C 203 (ASTM C 595), Type IP or IS, and moderate sulfate resistance may be specified by adding the suffix MS to the type designation. Where structural requirements require high early strength, Type III meeting the requirements of CRD-C 201 (ASTM C 150) cement should be considered.

(2) Low-alkali cement must be specified when the aggregates used are regarded as chemically reactive with the alkalies in the cement (see EM 1110-2-2000).

(3) Air-entraining cement has been used with the wet-mix process and has achieved varied results, with the air content generally much lower than in conventional concrete. Generally, the use of air-entraining cement is not recommended, since in-place air contents are affected by external factors such as air pressure, hose lengths, and equipment type. AEA's allow flexibility to compensate for these factors.

B. Pozzolan. When added to a portland-cement matrix, pozzolan reacts with the calcium hydroxide and water to produce more calcium silicate gel. Consequently, shotcretes with pozzolan may exhibit improved long-term strength performance and lower permeability. Pozzolan is sometimes added to wet-mix shotcrete to enhance workability, improve pumpability, increase resistance to sulfate attack, and reduce expansion caused by the alkali-silica reaction. The use of fly ash facilitates pumping shotcrete long distances. Portland cement replacement with pozzolan should be carefully considered, since early age strength development is delayed. Pozzolans should conform to CRD-C 255 (ASTM C 618). Natural pozzolans and fly ash are not typically used with dry-mix shotcrete. However, silica fume is often used in dry-mix shotcrete and does not delay strength development.

C. Silica Fume.

(1) Silica fume is an extremely fine, amorphous pozzolanic material which is a waste product of the silicon, ferrosilicon, or other silicon alloy production in submerged-arc electric furnaces. The silica fume condenses from the exhaust gases forming extremely minute spherical particles. The material is over 85 percent silica dioxide, is approximately 100 times finer than portland cement, and has a specific gravity ranging from 2.1 to 2.6.

(2) Silica-fume additions create several favorable conditions in shotcrete. Because of the pozzolanic nature of silica fume, its addition results in improved strength and durability. Because of the its extreme fineness, silica fume particles fill the microscopic voids between cement particles further reducing permeability and increasing the density of the shotcrete. Shotcrete mixtures with silica-fume additions display increased adhesion and cohesion.

(3) Since silica fume is so fine, the material cannot be effectively handled in its dry, natural form. Consequently, silica fume is commercially available in several processed forms. In one form, silica fume is densified to 30 to 40 pounds per cubic foot (pcf) loose bulk density. Further modifications include the addition of powdered water-reducing admixtures (WRA) to produce a formulated product. Silica fume is also available in a pellet-

ized form. Significant mixing action is necessary to completely break down and dissolve the pellets. Slurried silica fume is produced by mixing nearly equal weights of silica fume and water. Slurries are also further modified to include water-reducing admixtures.

(4) Silica-fume additions to wet-mix shotcrete must be made in conjunction with the addition of normal and high-range WRA's. Silica-fume additions without WRA's would necessitate large water additions to maintain a suitable workability level. The additional water increases the water-cement ratio and negates the benefits of the silica-fume addition. On the other hand, WRA's are not recommended for silica-fume additions to dry-mix shotcrete since the total mixture is in contact with water for only the time when the mixture exits the nozzle and impacts the shooting surface. The use of WRA's into dry-mix shotcrete would cause the compacted shotcrete to slough and sag on the surface as the admixture takes effect.

(5) For wet-mix shotcrete, any of the packaging processes are applicable. If the silica fume is not prepackaged with a WRA, such an admixture must be batched. Dry-mix shotcrete is best proportioned using dry processed products of silica fume.

3-2. AGGREGATE.

A. Aggregate should comply with the quality requirements of CRD-C 133 (ASTM C 33). Table 3-1 shows acceptable grading limits. Grading No. 1 should be used if a mortar mixture is desired. Gradings No. 2 and 3 contain coarse aggregate; the latter is similar to a conventional 19.0-mm (3/4-inch) nominal maximum size aggregate, except for a reduction in the larger sizes to minimize rebound. Aggregate failing to comply with these gradings may be used if preconstruction tests demonstrate that it gives good results. However, a uniform grading is essential. Coarse and fine aggregate should be batched separately to avoid segregation.

B. Fine aggregate for finish or flash coats and certain other special applications may be finer than Grading No. 1. Finer fine aggregates, however, generally produce shotcretes having greater drying shrinkage, while coarser sands result in more rebound.

C. Lightweight-aggregate shotcrete is most practical for the dry-mix process. Since moisture and aggregate contact is initiated at the nozzle, the severe workability reductions common in conventional lightweight concrete production do not occur.

3-3. WATER.

A. Mixing Water. Potable water should be used. If this is not available, the proposed water source should be tested according to CRD-C 400.

B. Curing Water. No special requirements are necessary for curing water applied to shotcrete (ASTM 1978). Water for curing of architectural shotcrete should be free from elements that will cause staining.

3-4. CHEMICAL ADMIXTURES.

A. Use of Admixtures. Because of shotcrete equipment limitations, the use of admixtures in shotcrete is not the same as in conventional concrete. Admixtures should be tested in the field prior to use on large jobs to ensure that the desired properties are achieved. Chemical admixtures used in shotcrete should comply with the appropriate requirements given in CRD-C 625 (ASTM C 1141). ACI 212.3R (paragraph A-1, ACI (1991a)), "Chemical Admixtures for Concrete," contains detailed information on general use in concrete.

TABLE 3-1. Grading Limits for Aggregate

Sieve size (1)	Percent by Mass Passing Individual Sieves		
	Grading No. 1 (2)	Grading No. 2 (3)	Grading No. 3 (4)
3/4-inch	—	—	100
1/2-inch	—	100	80–95
3/8-inch	100	90–100	70–90
0.19 inch (No. 4)	95–100	70–85	50–70
0.093 inch (No. 8)	80–100	50–70	35–55
0.046 inch (No. 16)	50–85	35–55	20–40
0.024 inch (No. 30)	25–60	20–35	10–30
0.012 inch (No. 50)	10–30	8–20	5–17
0.006 inch (No. 100)	2–10	2–10	2–10

B. Air-Entraining Admixture (AEA). The use of AEA's in shotcrete is practical only in wet-mix shotcrete. Due to the loss of air during the gunning process of the wet-mix shotcrete, the AEA should be batched so that the measured air contents in the plastic mix prior to pumping are twice the desired hardened shotcrete air content. The mixing process required to form the air bubbles does not occur in the dry-mix process, hence a suitable air-void system is not generated using the admixture. Air entrainment has slightly reduced rebound.

C. Water-Reducing and Retarding Admixtures. WRA's meeting the requirements of CRD-C 87 (ASTM C 494) are readily adapted to the wet-mix process but are not used in dry-mix shotcrete due to the ineffectiveness of the admixture when adding the admixture and water at the nozzle. Retarding admixtures are seldom used in shotcrete, except for near horizontal surfaces where subsequent finishing of the shotcrete surface is required.

D. Accelerators.

(1) Accelerators are essential in some shotcrete applications, such as tunnel support, where rapid section buildup and rapid strength development are necessary. Early accelerators were powders consisting of soluble aluminates, carbonates, and silicates. Modern accelerators, both powdered and liquid, fall into a wide assortment of chemical makeups. Accelerators have different effects depending on their chemistry, the chemistry of the cement, and the dosage rate of the admixture. Some of the commercial accelerators contain calcium chloride. Many are caustic, particularly the powdered materials, although not as caustic as in the past.

(2) Tests should be made to establish the compatibility of the particular accelerator with the cement proposed for use on the project and to determine the amount of such accelerator required. Many accelerators reduce 28-day strengths by 25 to 40 percent, depending upon the compatibility of the accelerator and cement. Where the aggregate is reactive, the alkali content of the admixture added to that of the cement should not exceed 0.6 percent by mass of the cement.

(3) Accelerators may reduce the frost resistance of the shotcrete. Some may be very caustic and therefore are a safety hazard. For these reasons and because of their cost, accelerators should only be used where necessary and then only in the minimum quantity necessary to achieve the desired results.

(4) Calcium chloride, an accelerator, should never be used in an amount greater than 2 percent by mass of the cement, except where "flash set" is needed for stoppage of leaks. It should not be used in sulfate exposures, nor where the shotcrete encases dissimilar metals (such as aluminum and steel) in contact with each other. No admixtures containing calcium chloride should be used where the shotcrete is in contact with prestressing steel.

(5) Liquid accelerators are generally added at the nozzle for dry-mix or wet-mix shotcrete. Powdered accelerators are generally used only for dry-mix shotcrete, added as a powder to the dry ingredients. Accelerators used in wet-mix shotcrete produce quick stiffening, then initial set. However, the final set usually occurs much later than for dry-mix shotcrete. The time of set can be varied widely with these materials, including initial set in less than 1 minute, and final set in less than 4 minutes. Some of these materials can also be used to create a "flash set" for special applications.

E. Polymers. The addition of certain latex emulsions to a conventional portland-cement shotcrete has increased both tensile and flexural strength, improved bonding, and decreased permeability. One common use of these materials has been in the repair of concrete structures in marine environments and those subject to chemical attack. A latex with favorable properties should be selected and the field personnel must be instructed in its behavior.

F. Bonding Compounds. Bonding compounds are generally not recommended in shotcrete work, because the bond between shotcrete and properly prepared substrates is normally excellent. When improperly used, bonding compounds can act as bond breakers. Bonding agents should not be used in shotcrete work without an investigation into their effectiveness in each case.

3-5. REINFORCING STEEL.

A. Reinforcing bars for shotcrete should meet the same specifications as for conventional concrete. Because of the placement method, the use of bars larger than No. 5 or heavy concentrations of steel are not practical. Large bars make it difficult to achieve adequate build-up of good quality shotcrete behind the bar and heavy concentrations of steel interfere with the placement of shotcrete. In general, bar spacings of 6 to 12 inches are recommended for shotcrete reinforcement.

B. It is often advantageous to specify as welded wire fabric, reinforcement either uncoated, galvanized, or epoxy coated. Flat stock should usually be specified in lieu of rolled fabric. Because of the rolled configura-

tion, rolled welded wire fabric is difficult to place at specified locations. Wire spacing should be as wide as possible to allow shotcrete to be built up behind. Spacing of 6 inches is recommended, however wire spacing as low as 2 inches has been used with 4 inches being more typical.

C. In repair work, a thin shotcrete coating may not require reinforcement. When reinforcement is exposed in the old concrete, but not severely corroded, it may be the only reinforcement necessary. In other cases, additional reinforcement (bars or wire mesh) may be required to replace corroded steel to control temperature cracking, if not to satisfy structural considerations.

3-6. FIBER REINFORCEMENT.

A. Steel Fiber Reinforcement. Steel fibers have been used in shotcrete to increase its ductility, toughness, impact resistance, and reduce crack propagation. The fibers are commercially available in lengths ranging from 1/2 to 3 inches. Typical fiber lengths for shotcrete range from 3/4 to 1-1/2 inches and are used in the amount of 1 to 2 percent by volume of the shotcrete. The fibers have little effect on compressive strength and produce only modest increases in flexural strength. However, they provide continued and, at times, improved load carrying capacity after the member has cracked.

B. Steel Fiber Source. Steel fibers are manufactured in several ways. Wire fibers are produced from drawn wire that has been subsequently cut or chopped. Flat steel fibers are cut or slit from sheet of steel or by flattening wire. The melt-extraction process is used to "cast" fibers by extracting fibers from a pool of molten steel. Consequently, fibers are round, flat, or irregular in shape. Additional anchorage is provided by deformations along the fiber length or at the ends. Deformations can be natural irregularities, crimps, corrugations, hooks, bulbs, and others. Collated fibers and fibers with noncircular cross sections reduce the handling and batching problems common with straight, round fibers.

C. Polypropylene-Fiber Reinforcement. Collated fibrillated-polypropylene (CFP) fibers are used in shotcrete. Fiber lengths of 1/2 to 2-1/2 inches have been the most common in use. The common application has been 1 to 2 pounds of polypropylene fibers per cubic yard of shotcrete. The primary benefit is to control thermal and drying shrinkage cracking. More recently, polypropylene doses of up to 10 pounds per cubic yard have been used successfully yielding shotcrete toughness performance approaching that of some steel fiber shotcrete (Morgan et al. 1989). The hazard from rebound is much less when polypropylene is used. The most common specified length for polypropylene is 1-1/2 inches, although longer lengths are no problem.

D. Glass Fiber Source. Glass fibers are made from high zirconia alkali-resistant glass designated AR glass. Glass fibers, used for fiberglass reinforcement, are designated E glass and should not be used in a portland-cement matrix. While glass fibers may be as small as 0.0002 inch, they are usually bonded together into elements having a diameter of 0.0005 to 0.05 inch. Glass fiber lengths are typically 1 to 2 inches, but a wide range of lengths is possible.

E. Applicable Technology. ACI 506.1R, "State-of-the-Art Report on Fiber Reinforced Shotcrete" (ACI 1991e), is a comprehensive document covering the full range of fiber shotcrete technology.

3-7. PROPORTIONING OF SHOTCRETE.

A. Considerations. In general, conventional concrete technology may be applied to shotcrete proportioning. Prior to mixture proportioning, the following should be considered:

1. Type of dry-mix or wet-mix shotcrete appropriate for the work.
2. The specific job constraints on the shotcrete work.
3. The type of specification.
   — Performance versus prescription.
   — Contractor versus Government mixture proportioning.

A mixture proportioning sample submitted is presented in Appendix D.

B. Mixture Proportioning Trial Batching.

(1) Since shotcrete performance is highly dependent on application procedures, trial batching and testing is a critical operation in verifying mixture performance. The batching and mixing of wet-mix shotcrete is practically identical to conventional concrete; only the fabrication of specimens is different. However, dry-mix is a distinct process. It is normal procedure to obtain trial mixture proportions for shotcrete from the contractor. Along with the proportions, test panels and cores of the shotcrete are highly recommended, as discussed in Chapter 5.

(2) Test panels are particularly important for dry-mix shotcrete because laboratory mixtures cannot duplicate as-shot dry-mix shotcrete. Typically, a performance specification of 12-hour, 7-day and/or 28-day compres-

sive strengths will be specified, along with a grading for the aggregate. Both the wet- and dry-mix methods will yield a higher as-shot cement content and lower coarse aggregate content, due to rebound of the aggregate.

C. Chlorides. The total chloride ion (Cl^-) from all sources including mixing water, cement, admixture, and aggregate should not exceed 0.06 percent by mass of cement for prestressed members. For other reinforced shotcrete applications, this limit is increased to 0.10 percent in a moist environment exposed to chloride and 0.15 percent in a moist environment not exposed to chloride.

D. Nominal Maximum Size Aggregate (NMSA). The selection of NMSA depends on several factors. The major factors are the allowable shrinkage performance, size of the placement, and the rigidity of the substrate. The amount of rebound, inherent in the shotcrete process, depends on the ability of the substrate and the placed shotcrete to cushion subsequently placed shotcrete. Shotcrete for thin linings on rock or concrete experiences high rebound. Thicker sections and sections on soil structures experience lower rebound. For placements of thin layers on hard surfaces, coarse aggregate should be minimized or eliminated in the mixture to minimize rebound.

E. Wet-Mix Proportioning. Mixture proportioning procedures for the formulation of conventional concrete for pumping applications are applicable for wet-mix shotcrete. The nominal maximum aggregate size is usually 3/4 inch or smaller. The batched cement content will typically range from 500 to 700 pounds per cubic yard. Rich mixtures are common for shotcrete, especially if vertical or overhead shotcrete placement is required. The limiting factor for cement content in a mixture is often governed by the amount of cement necessary for the shotcrete to adhere to a wall or ceiling, not the specified compressive strength. It is not unusual for shotcrete used in vertical and overhead placement to have 28-day strengths in excess of 4,500 psi, due only to the amount of cement necessary to make the shotcrete adhere.

(1) Workability. The slump for wet-mix shotcrete should be near the minimum that the pump will handle. A 3-inch slump should normally be considered the maximum slump to be used. Excess slump will yield lower-strength shotcrete which will tend to slough off of vertical and overhead surfaces.

(2) Entrained air. If air entrainment is to be used, an air content ranging from 8 to 12 percent prior to pumping is typical. The in-place shotcrete will have about one-half of the entrained air that was recorded at the pump.

(3) Admixtures. Additional admixtures generally behave the same in wet-mix shotcrete as they do in conventional concrete. Any admixture should be tested in the mixture proportioning studies and on the test panels prior to usage.

F. Dry-Mix Proportioning. There is no established method of proportioning dry-mix shotcrete. Since it is not practical to perform laboratory trial mixtures for dry-mix shotcrete, field testing of dry-mix proportions is highly advisable, especially if no field data exist for a given dry-mix. The in-place aggregate grading will be finer than the batched grading due to rebound, especially if larger aggregate sizes are used. As with wet-mix shotcrete, the in-place cement factor will be higher also.

(1) Compressive strength. ACI 506 (paragraph A-1, ACI (1991d)), reports typical data on strength versus cement content of dry-mix shotcrete as shown in Table 3-2.

TABLE 3-2. Strength Versus Cement Content, Dry-Mix Shotcrete, Typical Data

28-day compressive strength psi (1)	Cement content lb (2)
3,000	500–650
4,000	550–700
5,000	650–850

(2) Workability. The workability of the shotcrete is controlled by the nozzleman at the placement. Water adjustments may be made instantaneously at the placement by adjustment of the water valve.

(3) Entrained air. Air-entraining admixtures have little effect on dry-mix shotcrete since there is no mixing of admixture water and aggregate until impact on the shooting surface. Some contractors prefer to add an air-entraining admixture to a mix to improve workability.

(4) Admixtures. Accelerators are typically the only admixtures that are used in dry-mix shotcrete. These should be tested to determine that they are compatible with the cement being used and produce the required accelerated times of setting.

(5) Cement content. Cement contents are similar to those used in wet-mix shotcrete. Batch weights for

cement of 500 to 700 pounds per cubic yard are typical, with 28-day compressive strengths of more than 4,500 psi common for the mixtures used for vertical and overhead placement.

(6) Water-cement ratio. The batched water-cement ratio for coarse aggregate dry-mix shotcrete typically varies between 0.30 to 0.40.

G. Fiber-Shotcrete Proportioning.

(1) Steel fiber lengths for shotcrete are typically 1 inch but often range from 3/4 inch to 1-1/2 inches. The fiber should be at least 1/4 inch longer than the diameter of the maximum aggregate size. Shorter fibers are more easily pumped through the system, although more are required for equivalent performance. Fiber batch quantities are dependent on required shotcrete properties. Typical fiber proportions range from 0.5 to 2.0 percent by volume of shotcrete. Deformed fibers and fibers with end anchorage provisions produce shotcrete with properties equivalent to straight fibers at much lower fiber loadings. Since fibers tend to rebound at a greater rate than does aggregate, the fiber batch quantity should be adjusted accordingly.

(2) Proportioning mixtures using glass fibers is discussed by the PCI (1981). Proportioning mixtures using polypropylene fibers is discussed by Morgan et al. (1989).

H. Silica-Fume Shotcrete Proportioning. Silica fume is added to a shotcrete mixture as a cement replacement or in addition to cement. Batch quantities range from 7 to 15 percent by mass of cement. Strength enhancement and decreased permeability is apparent at the lower dosages. Reductions in rebound and increases in cohesiveness for thick applications do not occur until silica-fume dosages exceed approximately 14 percent. Further mixture adjustments to wet-mix shotcrete may be necessary to attain the required workability level.

I. Polymer-Modified Shotcrete. Polymer emulsions are typically 50 percent solids and 50 percent water. The liquid portion of the emulsion replaces the equivalent volume of water, and the solid portion replaces the same volume of combined solids. Additional adjustments to attain desired workability levels may be required.

3-8. PROPERTIES OF SHOTCRETE.

As is the case with conventional concrete, shotcrete properties vary dramatically depending on water-cement ratio, aggregate quality, size, and type, admixtures used, type of cement used, and construction practices. The proper use of admixtures, fibers, silica fume, and polymers can improve certain properties. Depending on the needs of the particular application, properties of the shotcrete materials and mixtures should be tested prior to final application.

A. Strength. In terms of compressive and flexural strength, shotcrete can produce strength generally equivalent to conventional concrete. Compressive strengths of up to 12,000 psi have been reported from drilled cores from test panels, and 10,000 psi is often quoted in the literature as a typical high strength. The practicality of strengths over 5,000 psi should be established by laboratory or field testing prior to final use. The ratio between compressive and flexural strength appears to be the same as for conventional concrete. Relationships between water-cement ratio and strength also appear to follow normal patterns, with higher strength associated with lower water-cement ratios. Early strength of shotcrete can be very high, reaching 1,000 psi in 5 hours and 3,000 psi in 24 hours.

B. Bond Strength. Although few data on bond strength appear to exist, bond strength with other materials is reported to be generally higher than can be achieved with conventional concrete. ACI 506R (paragraph A-1, ACI (1991d)) and Mahar, Parker, and Wuellner (1975) provide some data on bond strengths of shotcrete to various substrates.

C. Shrinkage. Drying shrinkage is most influenced by the water content of the mixture. Typical values of unrestrained shrinkage range from 600 to 1,000 millionths. Shrinkage is reduced in coarse-aggregate shotcrete and increased in shotcrete without coarse aggregate or shotcrete subject to high rebound. Shotcrete containing silica fume has a tendency to exhibit more shrinkage before setting than shotcrete without silica fume. Procedures similar to those outlined by Holland (1987) to prevent plastic shrinkage cracking should be implemented.

D. Resistance to Freezing and Thawing. Wet-mix shotcrete frost resistance is ensured by entraining a proper air-void system. Typically, an air content of 8 to 12 percent in the mixture results in in-place shotcrete having a proper air-void system. Although many dry-mix applications have performed well when subjected to mild freezing and thawing, dry-mix shotcrete is more subject to problems from freezing and thawing than wet-mix shotcrete. This is due to the difficulty in entraining air and creating an adequate air-void system in dry-mix shotcrete.

E. Density and Permeability of shotcrete can be excellent, provided good practices are followed in the field.

F. Toughness. The addition of fibers to shotcrete can result in a product displaying significant load carrying capability after the occurrence of the first crack. The relationship of post-crack load capacity to load capacity at first crack is defined as toughness. The type, size, shape, and amount of fiber determines the extent of this performance. The use of the toughness index by load-deflection testing, CRD-C 65 (ASTM C 1018), provides a rational means of specifying and comparing performance. However, recent concerns have developed over the specifics of applying this testing procedure (Gopalaratnam et al. 1991). The reader is advised to consider the cited references and contact CECW-EG for further guidance.

CHAPTER 4

EQUIPMENT AND CREW

4-1. GENERAL EQUIPMENT.

There are two basic types of shotcrete delivery equipment known as guns: dry-mix guns and wet-mix guns. Although either type may be used for most shotcrete work, each has its limitations. It is important to select equipment which is capable of placing the job mixture and maintaining an adequate production rate.

4-2. DRY-MIX PROCESS.

Cement and damp aggregate are thoroughly mixed, or premixed, and prebagged cement and aggregate are fed through a premoisturizer. The cement-aggregate mixture is then fed into the gun. The mixture is introduced into the delivery hose via a metering device such as a feed wheel. Compressed air is added at the gun and the mixture is carried through the delivery hose to the nozzle. The nozzle is fitted inside with a perforated water ring through which water and admixtures are introduced under pressure and intimately mixed with the other ingredients as they go through the nozzle. The concrete is propelled from the nozzle at high velocity onto the receiving surface.

A. Description of Guns. Dry-mix guns are divided into two classifications, the double chamber gun and the continuous feed gun, each of which is capable of delivering mixtures in a wide range of consistencies.

(1) Double chamber. The first gun developed was the double chamber or pot type, introduced in the early 1900's, shown in Figure 4-1. Although the material enters the upper chamber in batches, the valve arrangement is such that the discharge from the lower chamber is continuous. Until recent years, this gun had been used only for mortar mixtures and the production rate was low, but larger, high-production units which will handle coarse aggregate up to about 3/4 inch are now available.

(2) Continuous feed. The continuous-feed gun was introduced about 1960 and is shown in Figure 4-2. Most of these guns will handle mortar or concrete mixtures with aggregate up to about 3/4-inch and will produce shotcrete at production rates up to 2 cubic yards per hour.

B. Plant Layout. A typical plant layout for a dry-mix shotcreting operation, including air and water supplies, gun, delivery hose, and nozzle, is shown in Figure 4-3.

4-3. WET-MIX PROCESS.

Cement, aggregates, and admixtures (except accelerators) are thoroughly mixed. The mixture is fed into the gun and propelled through the delivery hose to the nozzle by compressed air or pneumatic or mechanical pumping. Air is injected at the nozzle to disperse the stream of concrete and generate the velocity for shotcrete placement.

A. Description of Guns.

(1) Pneumatic-feed. In the pneumatic-feed equipment shown in Figure 4-4, the premixed mortar or concrete is conveyed from the gun through the delivery hose to the nozzle by slugs of compressed air. At the nozzle additional air may be added if needed to increase the velocity and improve the gunning pattern. This equipment can handle mixtures of a consistency suitable for general shotcrete construction, using mixtures containing up to 3/4-inch aggregate. Guns with a dual mixing chamber and a two-way valve allow mixing of materials and a continuous flow operation.

(2) Positive displacement. In the positive displacement equipment shown in Figure 4-5, the concrete is pumped or otherwise forced through the delivery hose without the use of compressed air. Air is injected at the nozzle to disperse the stream of concrete and impart the velocity necessary for shotcrete placement. Positive displacement delivery equipment requires a wetter mixture than pneumatic-feed equipment, and the velocity of the shotcrete being applied is lower. It is difficult to apply shotcrete to vertical and overhead surfaces by this method unless a suitable accelerator is used. This equipment can also satisfactorily shoot material containing 3/4-inch aggregate.

B. Plant Layout. A typical plant layout for each of the wet-mix processes is given in Figures 4-6 and 4-7.

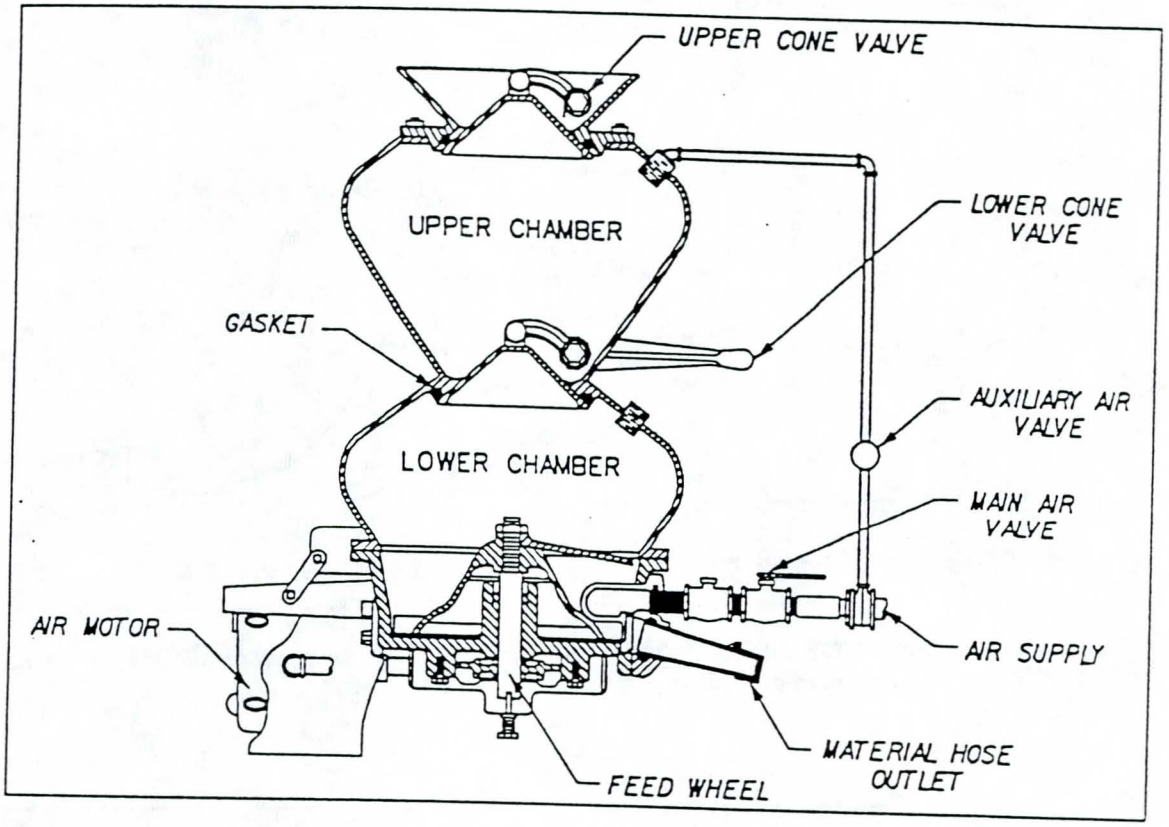


Figure 4-1. Cross section of typical double-chamber dry-mix gun (Crom 1966; copyright permission granted by ACI)

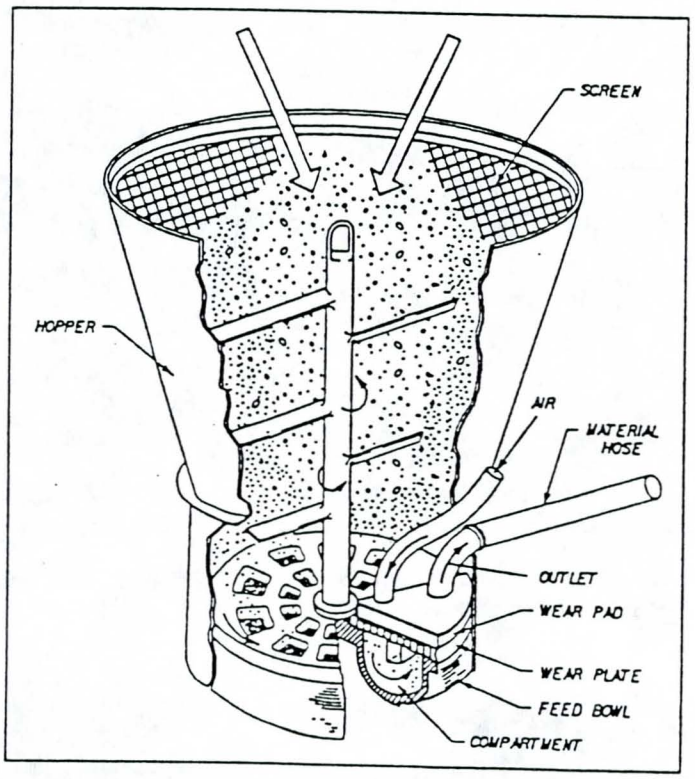


Figure 4-2. Cross section of typical continuous-feed dry-mix gun (Mahar, Parker, and Wuellner 1975)

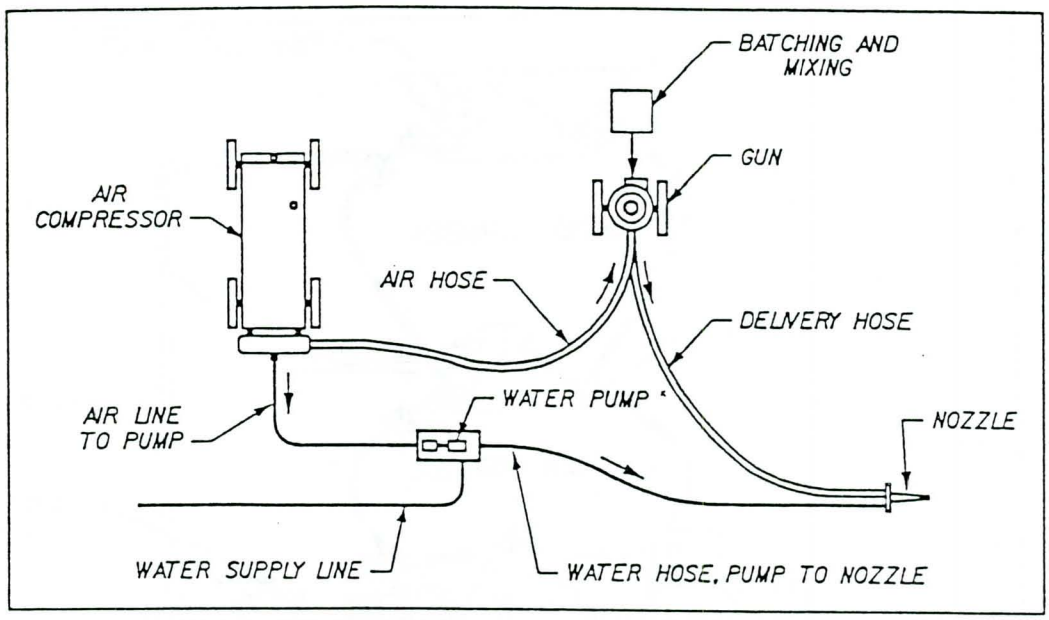


Figure 4-3. Typical plant layout for dry-mix shotcreting (Crom 1966; copyright permission granted by ACI)

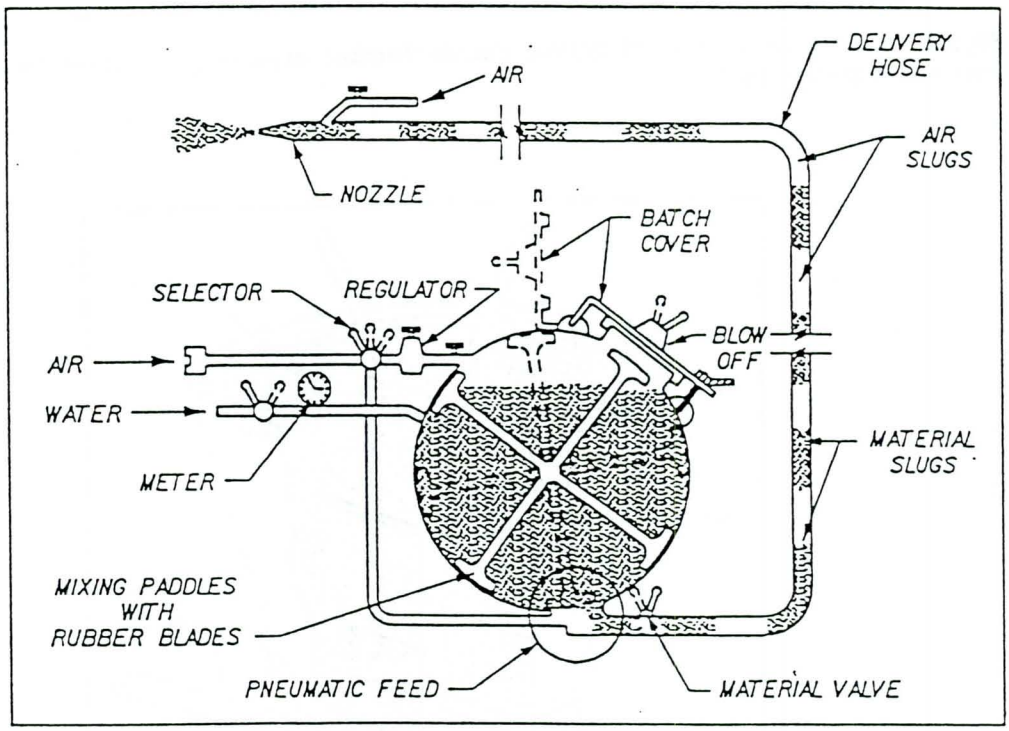


Figure 4-4. Cross section of pneumatic-feed shotcrete gun (Hoffmeyer 1966; copyright permission granted by ACI)

4-4. AUXILIARY EQUIPMENT.

A. Batching and Mixing Equipment. Most shotcrete is batched and mixed in the field using portable mixing equipment or delivered in mixer trucks from a local ready-mixed concrete plant. Mixing equipment for shotcrete is of the batch or the continuous type. Where ready-mixed concrete is used, it should conform to CRD-C 31 (ASTM C 94). Equipment for the batch type should conform to CRD-C 31 (ASTM C 94). In the

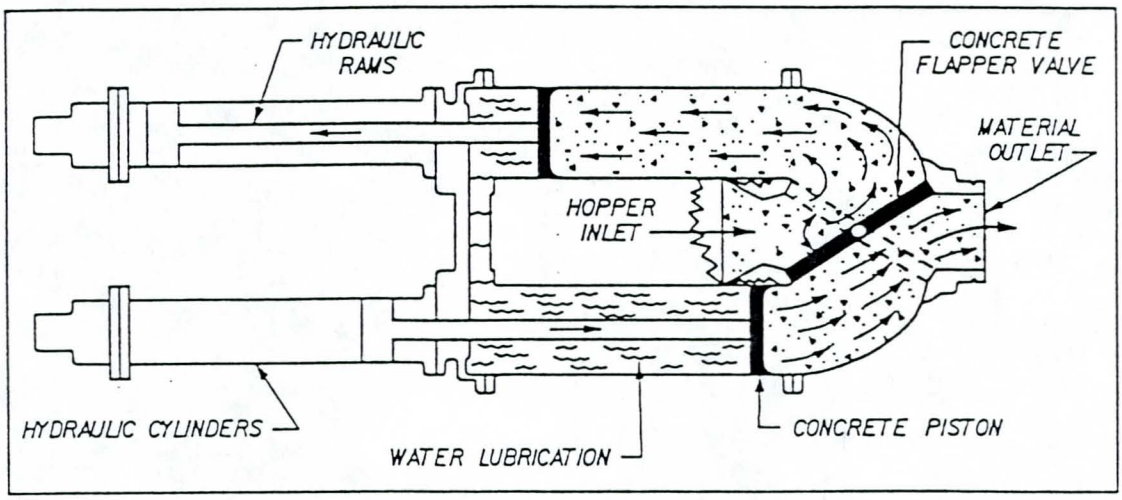


Figure 4-5. Schematic of positive displacement pump (Fredricks, Saunders, and Broadfoot 1966; copyright permission granted by ACI)

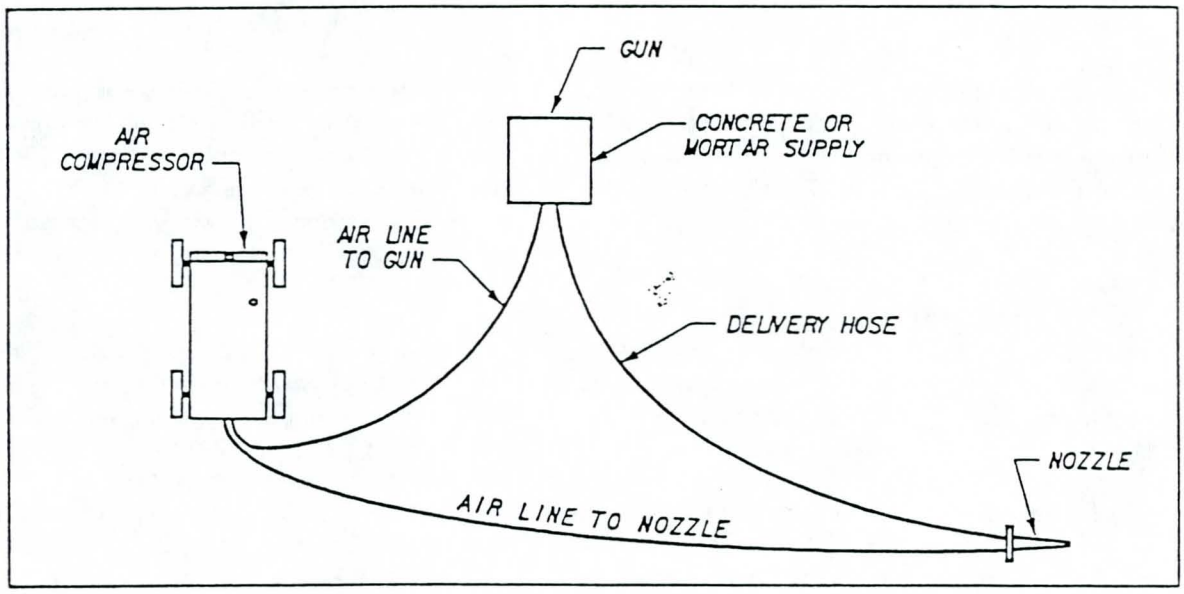


Figure 4-6. Typical plant layout for wet-mix pneumatic-feed equipment

continuous type, individual ingredients are fed to a mixer screw by means of variable speed augers, belt-feed systems, or a combination of both. This equipment should conform with CRD-C 98 (ASTM C 685). A hopper is sometimes used in high production units of both these types to collect and feed the mixture as required. Water-metering systems are also available to redampen the mixture. Batching and mixing equipment must be capable of maintaining an adequate and continuous flow of homogeneous material. Batching by mass is preferred and will normally be required. Water may be batched by mass or volume. For small jobs, approval may be given to batching by a volumetric container, provided periodic weight checks are made. Since many shotcrete jobs have a low production rate and are in isolated locations, mixing is often done by a small drum mixer at the jobsite.

B. Admixture Dispensers. Admixtures may be added when needed during mixing or at the nozzle, depending on their properties and the type of shotcrete process (dry or wet).

(1) In the dry-mix process, dry (powder) admixtures are usually introduced into the mixture during batching. If a continuous feed gun is being used, they may also be added directly into the gun hopper by a special dispenser, usually an auger-type dry dispenser

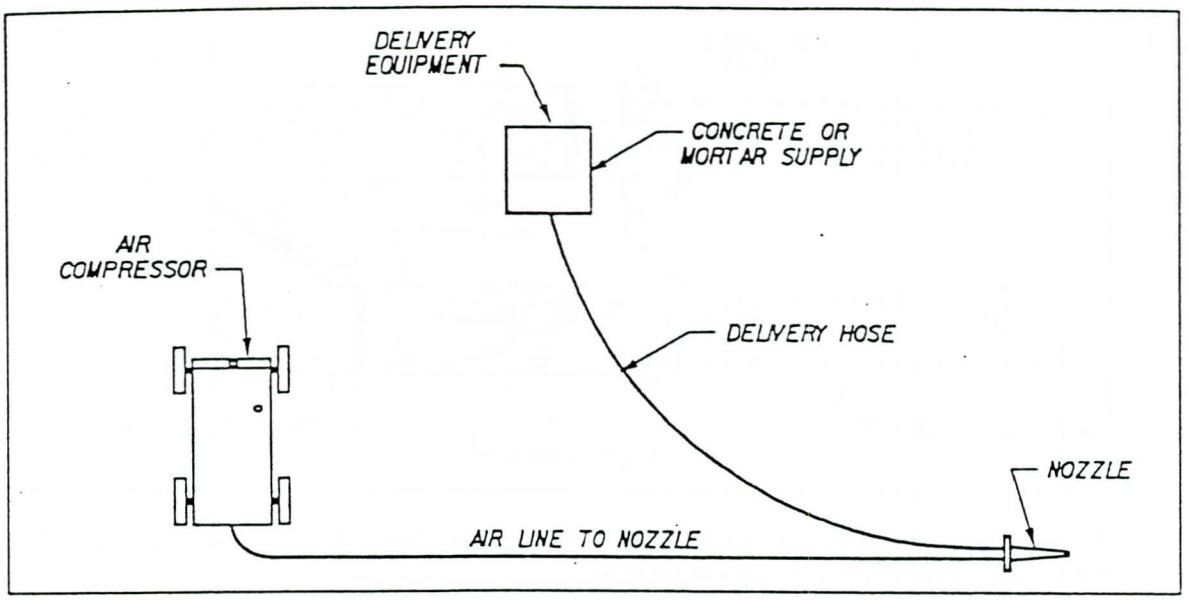


Figure 4-7. Typical plant layout for wet-mix positive displacement equipment

driven by and calibrated to the gear train of the shotcrete machine. The dispenser should be capable of metering a precise quantity of admixture, usually 1 to 4 percent by mass of the cement, into the mixture, and must be capable of accurately varying the ratio of accelerator to cement.

(2) In the dry-mix process, liquid admixtures must be introduced at the nozzle through the mixing water. The admixture may be premixed with water and pumped to the nozzle or added directly to the mixing water at the nozzle.

(3) In the wet-mix process, dry or liquid admixtures may be added to the mixture when batching provided the pumping properties are not adversely altered. As an example, an accelerator would create problems if added during batching, while a high-range water reducing admixture (HRWR) might have beneficial effects. In wet-mix applications, only liquid admixtures may be added to the air supply at the nozzle. They are proportioned to the delivery rate of the mixture through the material hose.

C. Air Compressor. A properly operating air compressor of ample capacity is essential to a satisfactory shotcreting operation. The compressor should maintain a supply of clean, dry, oil-free air adequate for maintaining sufficient nozzle velocity for all parts of the work while simultaneously operating all air-driven equipment and a blowpipe for cleaning away rebound.

(1) Table 4-1 gives recommendations for compressor capacity, diameter of delivery hose, and maximum production rate for the dry-mix process. The operating air pressure is the pressure driving the material from the delivery equipment into the hose and is measured by a gage near the material outlet of the gun. The air pressure should be steady (nonpulsating). A compressor of adequate capacity will ensure that the operating air pressure is sufficient.

(2) The values shown in Table 4-1 are based on a hose length of 150 feet, with the nozzle not more than 25 feet above the delivery equipment. Operating pressures should generally not be less than 40 psi, when 100 feet or less of shotcrete hose is used. Operating pressures are generally increased about 5 psi for each additional 50 feet of hose and about 5 psi for each 25 feet that the nozzle is raised above the gun.

(3) Air requirements for the wet-mix process have not been thoroughly studied. In general, however, the values for the pneumatic-feed type are a little lower than those shown, but back pressures are higher. Positive displacement equipment requires at least 105 ft^3/min. at 100 psi at the air ring for proper operation.

(4) Certain moisture conditions will cause an increase of water vapor in the compressed air stream which will adversely affect the shotcrete operation. A moisture trap or filter should always be installed in the supply line from the compressor.

D. Water Supply for Dry-Mix Equipment. Water supply booster pumps should be capable of supplying at least a 10-gallon/minute flow at 60 psi at the nozzle for standard nozzles. The water pressure

TABLE 4-1. Compressed Air Required for Dry-Mix Guns

Compressor capacity at 100 psi (ft^3/min) (1)	Inside diameter of delivery hose (in.) (2)	Maximum production rate (yd^3/hr) (3)
365	1	4
425	1.25	6
500	1.5	9
700	1.75	10
900	2	12
1,000	2.5	15

must be constant and must be 15 to 30 psi or more greater than the operating air pressure.

E. Aggregate Premoisturizer. It is common practice in large volume dry-mix shotcrete projects to prebag all the shotcrete materials together in a dry condition at the site. It is advantageous to premoisturize this material to 3 to 6 percent, by dry mass, prior to entering the shotcrete gun. A premoisturizer is a piece of equipment staged just before the shotcrete gun that uniformly distributes and mixes water to a continuous feed of dry materials.

4-5. SPECIAL EQUIPMENT.

A. Steel Fiber-Reinforced Shotcrete. It is critical that fibers be uniformly distributed throughout the mixture. Proper batching procedures and equipment can prevent the possible problems of fibers tangling together into fiber balls. For small projects, no special equipment is necessary. Fibers can be manually added to the mixture at an appropriate rate to prevent balling of fibers. Larger dry-mix shotcrete projects use prebagged material, including predistributed fibers. Specialized fiber feeder equipment, consisting of a drum and screen mechanism that uniformly screens the individual fibers into the shotcrete mixture, is available for continuous production of shotcrete. As with other continuous-feed systems, calibration of the system is mandatory to achieve proper proportions.

B. Silica-Fume Shotcrete. No special equipment is necessary for batching and mixing silica-fume shotcrete. Densified or slurried packaging eases manual batching methods common for low production-rate projects. Higher production-rate projects use bin systems similar to flash-feed systems, liquid pumping systems similar to liquid admixture systems, or prebagged materials.

C. Nozzles. A dry-mix nozzle typically consists of a tip, water ring, control valve, and nozzle body arranged in a wide variety of nozzle tips, nozzle sizes, and configurations. Figure 4-8 shows a section of a dry-mix nozzle. A wet-mix nozzle usually consists of a rubber nozzle tip, an air injection ring, a control valve, and nozzle body. Figure 4-9 shows an example of a wet-mix nozzle section. Some investigations have shown improved mixing action and less rebound for dry-mix shotcrete when a special prewetting nozzle is used and the water ring is placed in the hose 1 to 8 feet before of the nozzle. This has been particularly effective for silica-fume shotcrete.

D. Remote-Controlled Nozzles. During recent years, the use of remote-controlled nozzles has become increasingly popular, particularly for underground work. These machines are truck-mounted and include a boom-mounted nozzle, a gun, and an air compressor. The remote controls allow the nozzleman to rotate the nozzle in an 18-inch-diameter circle to allow proper application technique. The nozzleman can also swing the nozzle around 360 degrees and maneuver it closer to or farther from the surface being shot. Significant economy is realized because of higher placement rates and reduced crew size. Because of the remote location of the operator, some safety benefits can be realized from avoiding rebound of aggregates and fibers.

4-6. CREW COMPOSITION.

A. The quality of shotcrete depends largely on the skill of the application crew. The shotcrete crew may consist of four to eight individuals, depending on the size of the operation and the type and setup of equipment. A typical crew may include the foreman, nozzleman, delivery equipment operator, and nozzleman's helpers. Additional personnel such as a delivery equipment operator helper and operator for

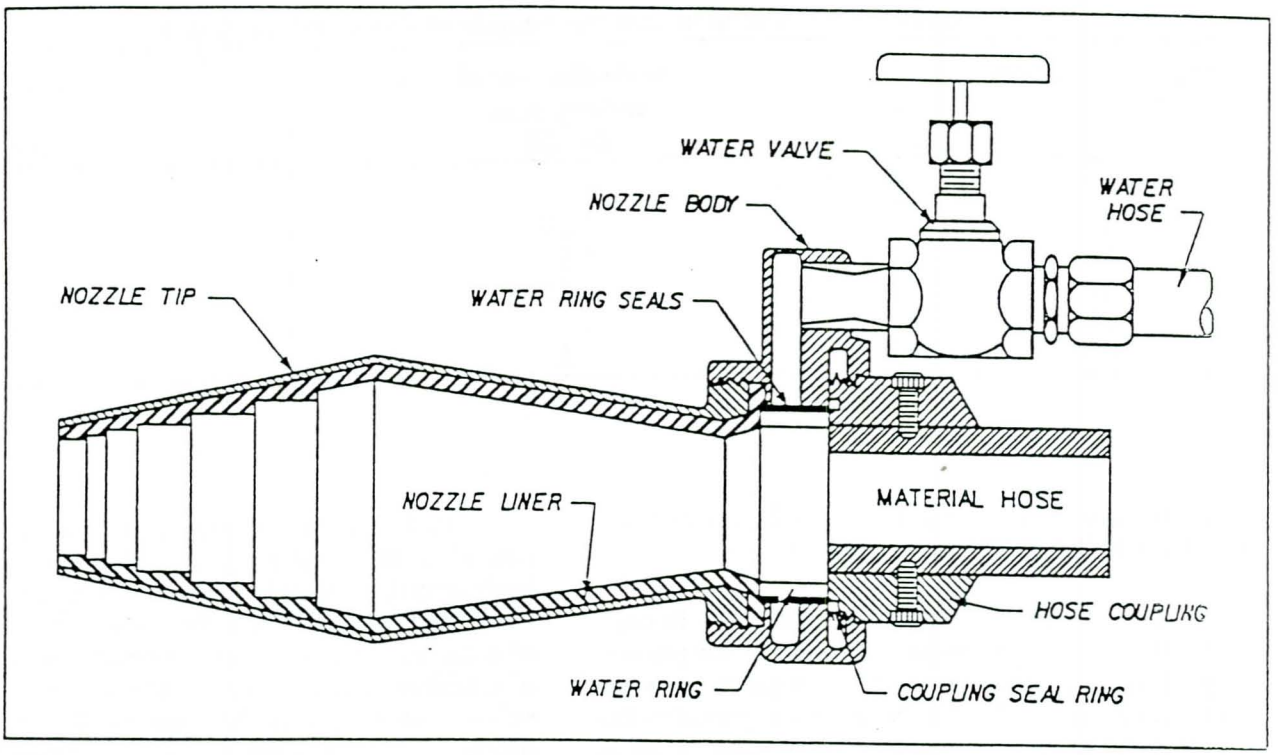


Figure 4-8. Typical dry-mix nozzle (paragraph A-2, ACI 1991c; copyright permission granted by ACI)

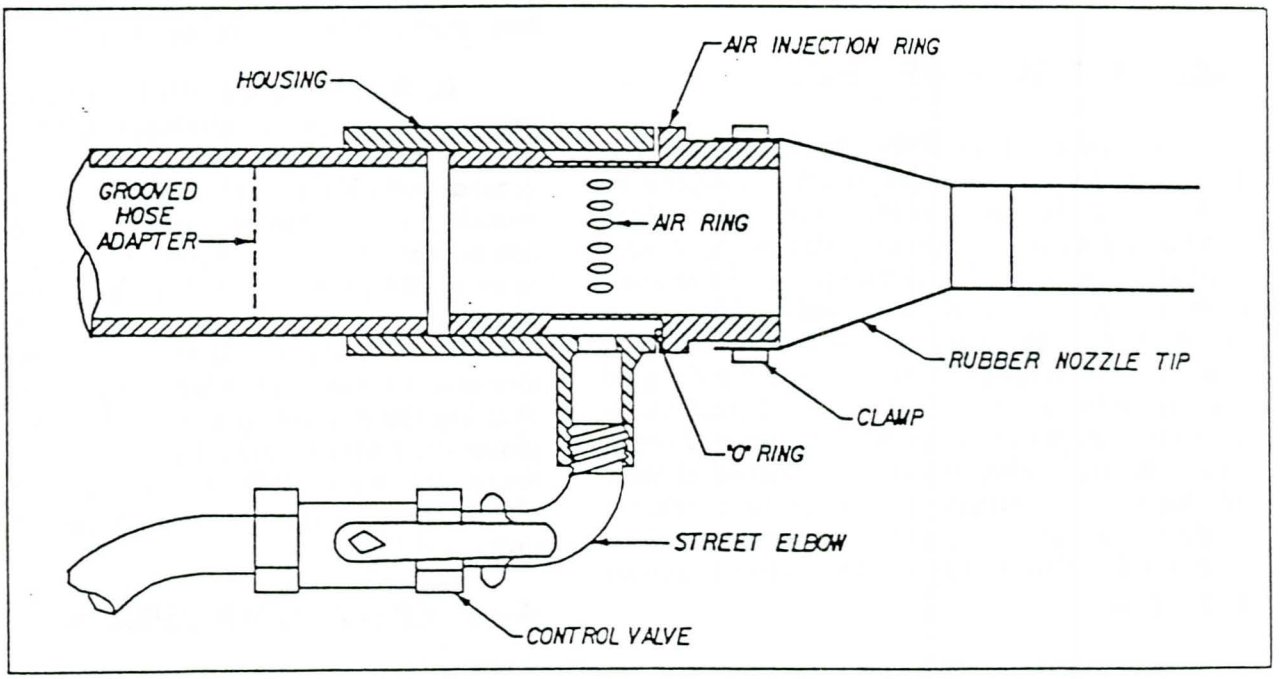


Figure 4-9. Typical wet-mix nozzle (paragraph A-2, ACI 1991c; copyright permission granted by ACI)

haulage of materials may also be necessary. By far, the most important member of the crew is the nozzleman.

B. The success of the shotcrete crew depends largely on the ability of the nozzleman since he controls the surface preparation, the material delivery rate, the

impingement of the shotcrete particles on the surface, the thickness, and, in the dry-mix process, the water-cement ratio. The nozzleman should have served an apprenticeship on similar applications and should be certified, as discussed in Chapter 5, for his ability to satisfactorily perform his duties and to gun shotcrete of the required quality. During production he will perform the following duties:

1. Ensure that all surfaces to be shot are clean and free of laitance or loose material, using air and air-and-water blast from the nozzle as required.

2. Ensure that the operating air pressure is uniform and provides proper nozzle velocity for good compaction.

3. Regulate the water content so that the mixture will be plastic enough to give good compaction and a low percentage of rebound, but stiff enough not to sag. (In the dry-mix process the nozzleman actually controls the mixing water, while in the wet-mix process he directs changes in consistency as required.)

4. Hold the nozzle at the proper distance and as nearly normal to the surface as the type of work will permit to secure maximum compaction with minimum rebound.

5. Follow a sequence that will fill corners with sound shotcrete and encase reinforcement without voids behind the steel, using the maximum practicable layer thickness.

6. Determine necessary operating procedures for placement in close quarters, at extended distances, or around unusual obstructions where placement velocities and mixture consistency must be adjusted.

7. Direct the crew to start and stop the flow of material and stop the work when material is not arriving uniformly at the nozzle.

8. Ensure that sand lenses, slough pockets, or laminations are cut out for replacement.

9. Bring the shotcrete to finished lines in a neat and workmanlike manner.

10. Assume responsibility for safety in the area where shotcrete is applied. He must be aware of other people in his immediate vicinity and take care not to direct the shotcrete stream irresponsibly. He should always maintain a firm grip on the nozzle and plan his movements so that he does not lose control of the material hose.

C. The nozzleman's apprentice or helper operates an air blowpipe at least 3/4 inch in diameter to assist the nozzleman in keeping all rebound and other loose or porous material out of the new construction (except in classes of work where the trapped rebound can readily be removed by the nozzleman). He also assists the nozzleman in moving hoses and in other assignments as required.

CHAPTER 5

PRECONSTRUCTION TESTING AND EVALUATION

5-1. GENERAL.

Regardless of the size of the project, some form of preconstruction testing and evaluation must be done to assure that competent personnel, equipment, and materials are provided. Prior to application of shotcrete, the quality assurance team must assess the suitability of the shotcrete nozzleman, the materials and mixture proportions, the equipment, crew, and application process. These are confirmed by submittal or performance of:

1. Nozzleman Certification.
2. Mixture Proportioning Testing and/or Data.
3. Preconstruction Demonstration and Testing.

5-2. NOZZLEMAN CERTIFICATION.

A. The success of any shotcrete application is dependent, in large part, on the skills and abilities of the nozzleman. It is imperative that only qualified individuals perform this work. Unlike some other work processes, the application of shotcrete cannot tolerate inexperience or marginal workmanship.

B. The ACI has an ongoing Nozzleman Certification Program. Specifications should require that all nozzlemen hold such certification. Certification requires the successful completion of a two-part written examination on general shotcrete knowledge and specific application knowledge. A shotcrete demonstration, the construction of test panels which are subsequently evaluated for strength, uniformity, and other applicable properties, is also required.

C. Final approval of ACI certified nozzlemen must be contingent on successful demonstration of abilities by applying shotcrete to preconstruction test panels.

5-3. MIXTURE PROPORTIONING EVALUATION.

Unlike the evaluation of conventional concrete mixtures, shotcrete testing is difficult to perform in a laboratory environment. The equipment and technique are integral factors in the performance of the mixture. The mixture proportioning study should therefore be conducted under field conditions insofar as practicable. Mixture proportions are submitted in one of two ways, trial batching or historical data submission.

A. Trial Batching. Mixture proportions or materials, which have had no previous use, are accompanied by data verifying material properties, mixture proportions, field conditions, test data, and performance. This work is performed specifically for the project on which it will be used. This process requires significant lead time, often in excess of 45 days, to attain the required 28-day strength results. More extensive testing will add more time to this process. This is not a laboratory exercise but a full-scale production of test panels with actual equipment, personnel, and materials. Test panels should be fabricated as described in paragraph 5-4: Preconstruction Demonstration and Testing.

B. Historical Data. Often, materials and mixture proportions that will meet the requirements for the current project are available from use on previous projects. If past documentation and performance is acceptable, no further testing is necessary. Submission of the historical mixture proportions will suffice. This process greatly reduces the lead time required of the contractor. A historical data submittal includes all material data, mixture proportions, field conditions, and test reports or data summaries.

5-4. PRECONSTRUCTION DEMONSTRATION AND TESTING.

A. Acceptable Equipment and Personnel. Prior to placement of any shotcrete for payment, the contractor should demonstrate the acceptable performance of equipment and personnel. This is done by the fabrication of a series of test panels for each nozzleman. These test panels may also serve for approval of the materials and mixture proportions.

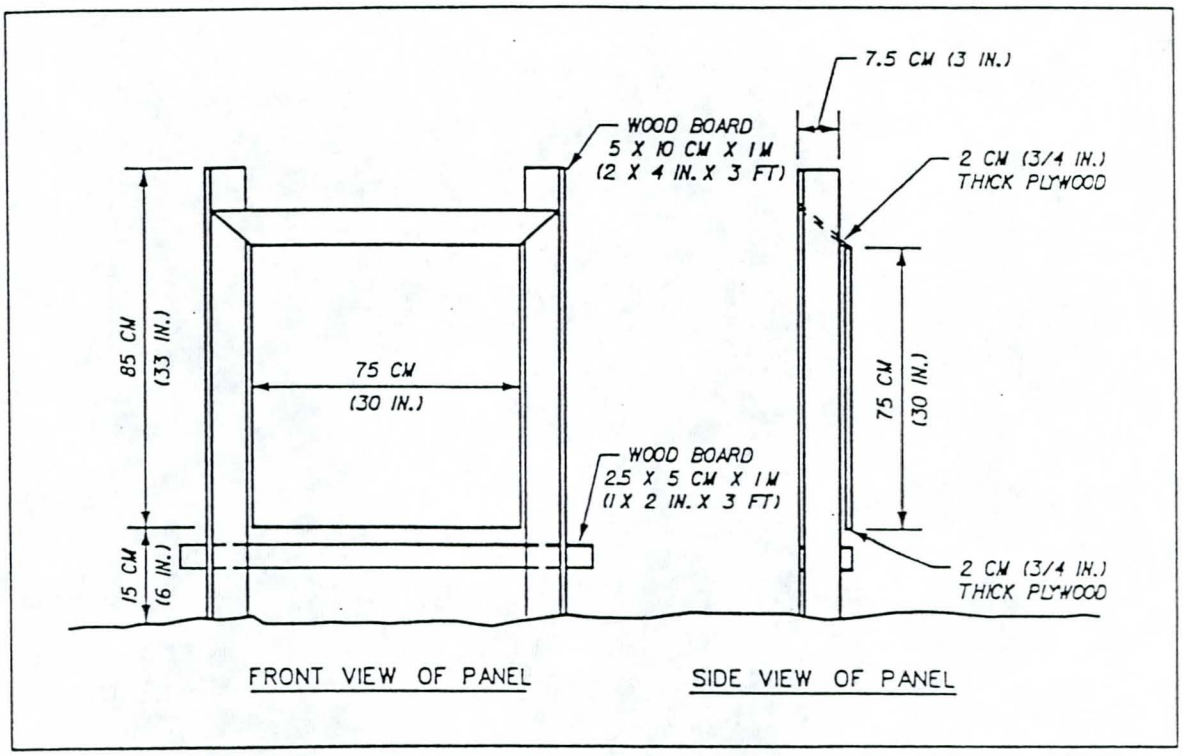


Figure 5-1. Test panel support system (Mahar, Parker, and Wuellner 1975)

B. Test Panels. Fabrication of test panels mounted in a framework is the typical way to evaluate the shotcrete process (Figures 5-1 and 5-2). A separate panel should be fabricated for each nozzleman, for each shooting position to be encountered in the structure; e.g., slab, vertical, or overhead. Where the field shotcrete will contain reinforcement, this should be duplicated in at least part of the panels to show whether sound shotcrete is obtained behind reinforcing bars or wire fabric. Each panel should be large enough to obtain all the test specimens needed and also large enough to indicate what quality and uniformity may be expected in the structure: not less than 30 inches square for mortar mixtures and not less than 36 inches square for concrete mixtures. The thickness should equal that of the structure but should measure no less than 3 inches.

C. Specimen Testing.

(1) At least five cubes or cores (Figure 5-3) should be extracted from the interior (at least 4 inches from the edge) of each panel for testing. Cores should have a minimum diameter of 3 inches and a length-to-diameter ratio (L/D) of at least one, if possible. Core strengths should be corrected for L/D as described in CRD-C 27 (ASTM C 42). Cube strengths may be reported as determined, or converted to cylinder (L/D = 2) strengths by multiplying by the factor 0.85.

(2) Panels should be cored or sawn no sooner than after 7 days of standard curing. The specimens should be tested in compression at 28 days to evaluate the mixture performance. It is not necessary to test at such a late age to evaluate the process. Depending on the expected strengths, testing at 7 or 14 days is adequate to determine the suitability of the nozzlemen and process.

(3) Beams for toughness evaluation and flexural strength testing can be sawn from the test panels. Typical beam dimensions are 4 by 4 by 16 inches. Beams must be sawn from the interior of the panel and not closer than 4 inches from any edge. Beams must be tested in the same orientation as shotcrete on the structure. For example, shotcrete for thin linings results in a fiber orientation parallel to the finished surface. Beams sawn from test panels should be tested with the shot surface normal to the load application.

D. Visual Examination. Visual examination of sawn surfaces is the best method of determining the uniformity of the shotcrete. Panels should be sawn into quadrants after 7 days of standard curing. The cut surfaces of the specimens should be carefully examined, and additional surfaces should be exposed by sawing the panel when this is considered necessary to check the soundness and uniformity of the material. Figure 5-4 shows some problem conditions that may be encoun-

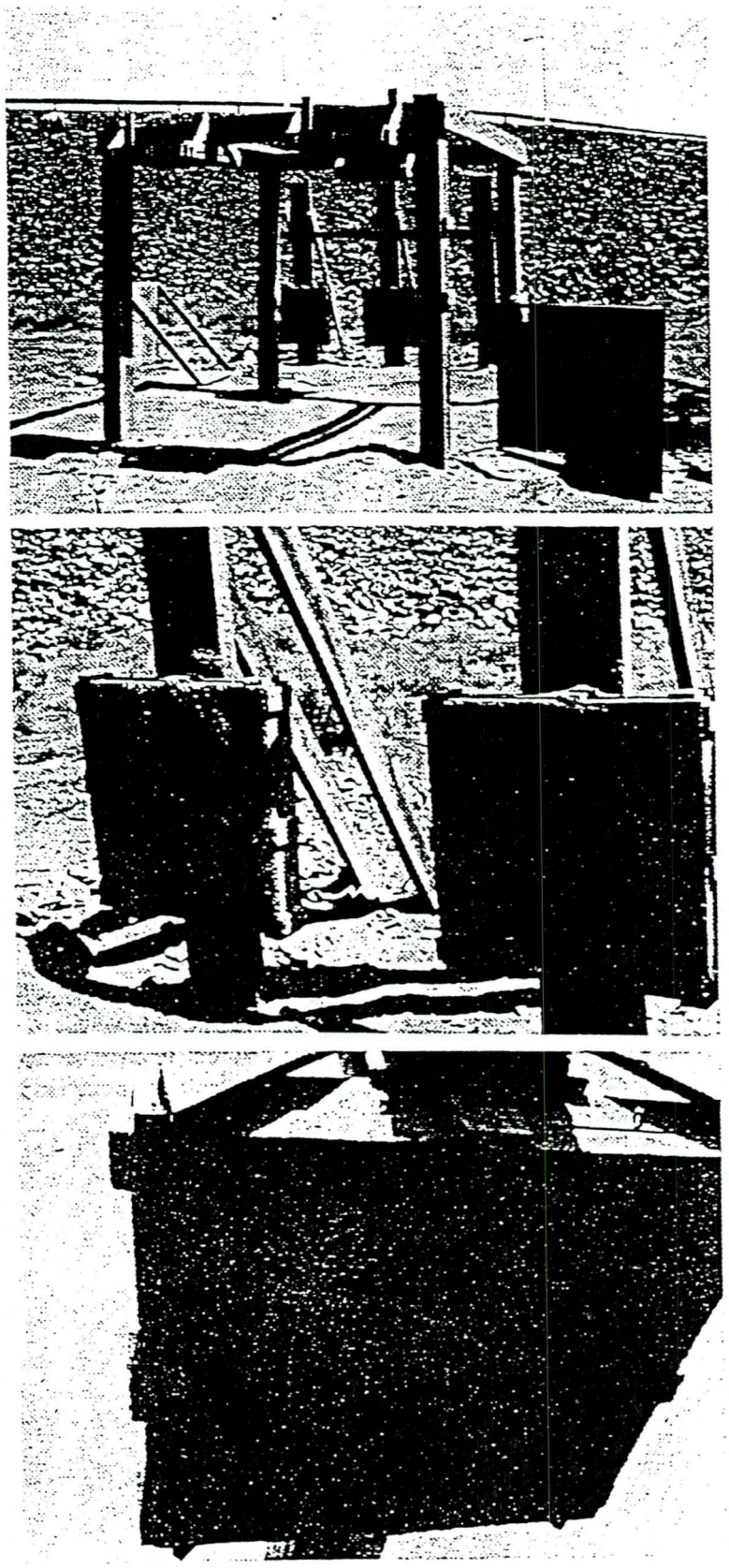
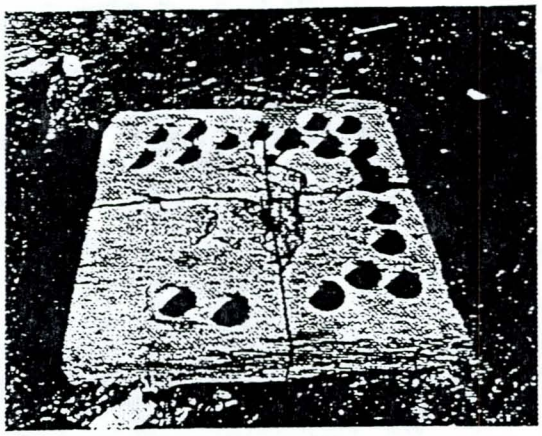
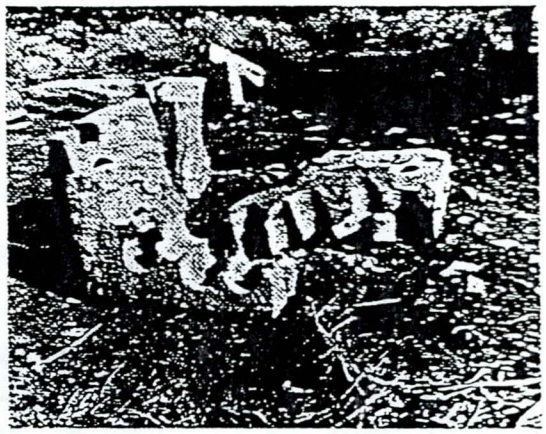


FIG. 5-2. Test Panel Frame System.





tered. All cut and broken surfaces should be dense and substantially free from laminations and sand pockets.

E. Accelerated Testing. Often it is advantageous to correlate accelerated strength development of the shotcrete mixtures with the standard laboratory strength development. This correlation will allow determination of mixture performance at ages of 3 to 5 days. Special equipment and extensive laboratory evaluations are necessary prior to construction for this testing procedure.

F. Load Deflection Testing. Fiber shotcrete performance should be specified by use of toughness index values as determined by CRD-C 65 (ASTM C 1018). The test procedure should be done using the specified equipment, preferably a deflection control testing machine of sufficient stiffness to not bias the results. Toughness index values, termed I5, I10, and I20, should be selected to be compatible with project service conditions. Designers should avoid specifying minimum limits for the I5 index and instead specify limits for the I10 or I20 indexes.

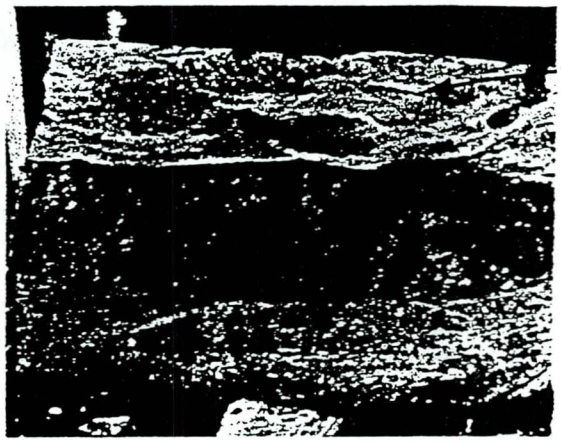
G. Other Tests. Tests for absorption, drying shrinkage, resistance to freezing and thawing, and other properties may also be made if desired, using appropriate specimens cored or sawed from the panels.

5-5. ALTERNATE CONSIDERATIONS.

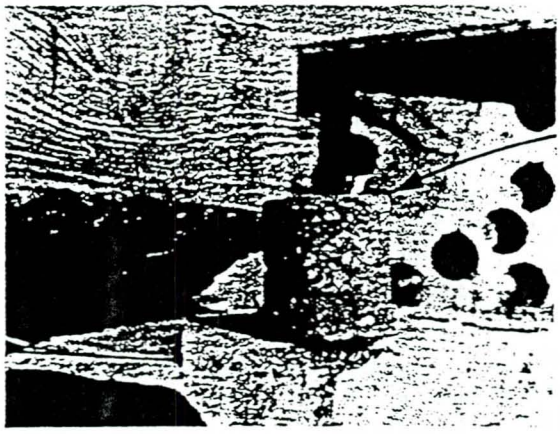
A. Typically, preconstruction testing and evaluation must precede the actual work by more than 30 days to allow time for nozzleman certification at the start and ending with strength testing at 28 days. This protracted start-up period may add significant costs to a small repair contract and may delay the start of actual construction.

B. In the case where previous acceptable mixture proportions information is available for the proposed materials and proportions, it may be advantageous to eliminate the later-age testing of the shotcrete mixture. Some contracting organizations have found it cost effective to evaluate the nozzleman and equipment at a site convenient to the contractor, often in conjunction with the contractor's ongoing work, to eliminate the early mobilization and extended standby time of equipment and personnel.

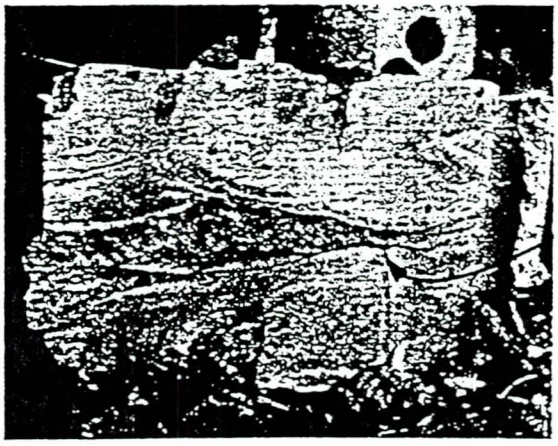
C. The designer must always consider the criticality of the shotcrete placement and the qualifications of the nozzleman when considering whether or not to waive some of the preconstruction requirements.



VOIDS OR "SAND LENSES" CREATED DURING LAYERING PROCESS



DELAMINATED FLASH COAT ON FINISHED SURFACE OF SHOTCRETE



VOIDS BEHIND REINFORCING STEEL

Figure 5-4. Shotcrete problems obvious from a visual inspection

Specimens should be sawn or cored from the test panel to verify the contract requirement for strength. The specimens and the test panel should be visually examined for signs of laminations, sand streaks, aggregate pockets, reinforcing steel not completely surrounded by shotcrete, and any other indications of either mixture proportion problems or nozzleman workmanship.

7-3. PRODUCTION PHASE.

An ongoing program of testing should be performed by the Contractor to verify that the materials, methods, and in-place shotcrete meet the requirements of the contract documents. The specifications should clearly state the minimum types of tests that are required, the minimum frequency of performing each test, a procedure for reporting the results of the tests, and a procedure for correcting any deficiencies (Table 7-1).

A. Materials.

(1) Cementitious materials. Manufacturer's certified test results for the cement, pozzolan, and appropriate test data for silica fume should be furnished at the interval specified and whenever a change in the appearance or performance of the material is suspected.

(2) Aggregates.

a. Quality. Test data should be furnished to verify that the quality of the aggregates meets the requirements of the specifications. Test data should be submitted at established intervals and whenever a change in the appearance or performance of the material is suspected.

b. Grading. The grading of each aggregate group should be verified by testing according to CRD-C 103 (ASTM C 136) at established intervals and whenever a change in the appearance or performance of the material is suspected. Changes in the grading of an aggregate will cause a change in the water requirements of the mixture with attendant changes in the strength and placing characteristics of the shotcrete.

c. Moisture content. The moisture content of each aggregate group must be known to calculate the amount of free water to be added to each batch of shotcrete. The

TABLE 7-1. Quality Control Testing Requirements — Guide to Testing Frequency

Property/activity (1)	Test procedure (2)	Frequency (3)	Comment (4)
Cementious Materials	Mill Test	per 400 tons of cement	—
Aggregate Quality	—	—	—
Quality	CRD-C 133 (ASTM C 33)	Initial	Increase if necessary
Grading	CRD-C 133 (ASTM C 33)	Per shift	—
Particle Shape	CRD-C 119 (ASTM D 4791)	Initial	—
Moisture Content	CRD-C 113 (ASTM C 566)	Daily	—
Unhardened Properties	—	—	—
Air Content	CRD-C 41 (ASTM C 231)	Per batch	Wet-mix only
Slump	CRD-C 5 (ASTM C 143)	Per batch	Wet-mix only
Mix Proportions	—	Per shift	—
Rebound	per specs	Daily	—
Thickness	per specs	Per 50 ft²	Probe shotcrete or check gauge wires
Hardened Properties	—	—	—
Fabricate Test Panels	per specs	Per shift	—
Drill In-situ Cores	CRD-C 27 (ASTM C 42)	3 per 2,500 ft²	—
Compression Stength	CRD-C 14 (ASTM C 42/C 39)	3 per 2,500 ft²	—
Flexural Strength	CRD-C 16 (ASTM C 42/C 78)	2 per 5,000 ft²	—
Toughness	CRD-C 65 (ASTM C 1018)	3 per 5,000 ft²	Fiber-reinforced shotcrete only
Surface Roughness	per specs	2 per 1,000 ft²	—
Delaminations	per specs	1 per 25 ft²	—

Note: Table values are only a guide. Testing frequency must be based on an evaluation of testing costs, criticality of performance, and the nature of the application.

moisture contents should be established prior to start of each shift and whenever a change is made in stockpile sources.

(3) Admixtures and curing compound. Manufacturers' certificates of compliance for the air-entraining admixture, retarding admixture, water-reducing admixture, accelerating admixture, and curing compound should be furnished at an established interval and whenever a change in the appearance or performance of the material is suspected.

B. Surface Preparation. The Contractor's ability to prepare surfaces according to the requirements of the specifications should be verified during each shift. No shotcrete should be placed until surface preparations are completed. Bonding of the shotcrete layer to the underlying stratum is essential for proper performance and longevity.

C. Shotcrete.

(1) Strength. The strength of the shotcrete should be verified at established intervals. The method of obtaining samples, the method of testing, the frequency of testing, and the required strength should be clearly stated in the contract specifications.

a. Test panels. A test panel should be shot at least once a shift. The panel should be shot by a nozzleman who is placing shotcrete in permanent work shotcrete. The panel should be at least 18 by 18 by 3 inches. The test panel should be cured at the project site in accordance with the contract requirements until it has attained sufficient strength to allow movement to the testing laboratory. Curing should continue in the test laboratory until specimens are obtained from the panel. Cores or beams should be taken from the panel in accordance with the provisions of CRD-C 27 (ASTM C 42). Cores are used to verify the compressive strength of nonfiber reinforced shotcrete, and beams are used to verify the flexural strength of fiber-reinforced shotcrete.

b. In-place samples. At established intervals and whenever deemed necessary by the Contracting Officer, cores or beams should be obtained from the in-place shotcrete to verify the strength. The samples should be cured and tested in a manner similar to that of test panel samples.

(2) Mixture proportions. The mixture proportions of the shotcrete should be checked regularly to verify that the original proportions are being maintained. This is generally accomplished by verifying that the batch weights, especially the cementitious materials and water weights, are as required.

(3) Air content. Wet-mix shotcrete is generally required to have a specified air content as determined by CRD-C 41 (ASTM C 231). The air content should be determined at regular intervals and at locations as specified. The air content specified in the contract documents is higher than required for durable conventional concrete and allows for about 50 percent of the air to be lost during the delivery and shooting of the shotcrete. The specification must detail how air content is to be determined. If sampled at the pump, the test is performed as detailed in CRD-C 41 (ASTM C 231).

(4) In-place thickness. Gauge wires or studs should be set prior to placing shotcrete to facilitate placing of the required thickness. It is best to verify thickness by measuring the offset of the gauge wires since later probing of the in-place shotcrete may be very difficult. The in-place thickness of the shotcrete may be verified by probing the fresh shotcrete with a sharp tool. Thin areas should be corrected by immediate application of additional material. Cores of hardened shotcrete may be directed to be taken by the Contracting Officer to verify areas of suspect thickness.

(5) Rebound testing. It is advantageous to periodically determine the amount of shotcrete that is rebounding from the placement surfaces. This can be done by designating a placement area and collecting all the rebound material after the placement is complete. The percent of rebound can be calculated by determining the volume of material shot and the volume of material collected.

(6) Curing and protection. The contractor should verify that the required curing and protection of the shotcrete is being furnished. Proper curing is important due to the generally low water content of shotcrete. Any premature drying could impair the hydration process. Proper protection during hot or cold weather is essential to proper hydration of shotcrete.

(7) Nondestructive testing. The uniformity and quality of in-place shotcrete may be assessed by nondestructive testing devices such as impact hammers or probes (CRD-C 22 (ASTM C 805) and CRD-C 59 (ASTM C 803)), ultrasonic equipment (CRD-C 51 (ASTM C 597)), and pull out devices (CRD-C 78 (ASTM C 900)). The use of such devices should be at the direction of the Contracting Officer and should be used to identify areas of suspect quality and relative strength, not for actual strength determination.

(8) Delamination testing. Where appropriate, complete shotcrete coatings should be checked for complete bond to the substrate and bond between

each shotcrete layer. This can be done using a small hammer on the surface. The contract should require that all delaminated areas be removed and shotcrete reapplied.

(9) Surface tolerances. Some applications may require that exacting surface variation tolerances be met. Verifying that a surface meets a tolerance is best done using the specified length straight-edge and measuring the gap below the edge. The specification should be clear that this method will be the verification method.

(10) Visual inspection. The quality of the shotcrete should be thoroughly evaluated by visual inspection. Surfaces should be inspected for uniformity, voids at the surfaces, varying finish conditions, dry conditions, seepage of water, cracking, and damaged sections.

7-4. CORRECTIVE ACTIONS.

When a submittal or test report indicates that a material or product fails to meet the contract requirements, the corrective actions specified in the contract documents should be initiated immediately.

CHAPTER 8

QUALITY ASSURANCE

8-1. GENERAL CONSIDERATIONS.

A. Quality Assurance (QA) activities on a shotcrete project should be directed to obtaining compliance with the contract requirements. The quality of the materials used in the production of the shotcrete and of the in-place shotcrete are established during the design stage of the project and should have been clearly stated in the contract documents.

B. A memorandum entitled "Engineering Considerations and Instructions for Field Personnel" should be prepared by the designer in accordance with EM 1110-2-2000. This memorandum outlines the designer's intent and highlights the areas of special concern during construction. If any doubts exist by construction personnel as to the required quality, they should be resolved with the designer as early in the project as possible.

C. Qualified QA personnel with previous experience on shotcrete projects should be assigned to the project. ER 1180-1-6 should be followed in preparing a QA Plan. The following discussions pertain to technical aspects of shotcrete and should be incorporated into the plan.

8-2. PREPRODUCTION PHASE.

A. Submittals. Prior to start of production of shotcrete for any permanent work, the required material, equipment, and procedural submittals should be reviewed by the appropriate Corps of Engineers representatives to verify compliance with the contract requirements. On larger projects, government verification of cementitious materials properties should be considered.

B. Mixture Proportioning Evaluation. Test panels shot to verify the proposed mixture performance should be visually examined by QA personnel to confirm uniformity of the shotcrete. Specimens should be taken from the test panels to verify that the specified strength is being attained. The specimens may be taken by either QC or QA personnel, but strength testing should be performed by a Corps of Engineers division laboratory or the project laboratory.

C. Nozzleman Certification. All nozzlemen shall be ACI certified. Test panels shot to evaluate a nozzleman's qualifications should be thoroughly examined by a QA representative experienced in shotcrete work. Some panels should contain reinforcing or embedded items that will be included in the permanent work. Panels should be sawn into strips to allow examination of the interior portions of the panels. Panels should be homogeneous without lenses or pockets of aggregate and all reinforcing and embedded items should be completely encased in dense shotcrete. The quality of dry-mix shotcrete is particularly dependent on the skill of the nozzleman, because his ability to control the amount of water being added to the mixture and to shoot test panels to quality is essential.

D. Shotcrete Demonstration. The same test panel evaluation to certify the nozzleman serves to approve the production and placement process.

8-3. PRODUCTION PHASE.

An ongoing program of QA inspections and testing will be required to verify continued conformance with the contract requirements. Consistent materials, mixture proportions, and production methods are necessary for uniform in-place shotcrete.

A. Submittals.

(1) Manufacturer's certificate. Manufacturer's certified test results for the cementitious materials, admixtures, curing materials, reinforcement, and fibers should be reviewed to verify continued conformance with the contract requirements. Any changes in the appearance or performance of any of these materials should require additional verification by the supplier or testing by the QC laboratory.

(2) Test reports. Data from test reports must be reviewed to determine contract compliance and, more importantly, product performance. Consistent and vigilant review of data is the best method to spot trends in material quality that may later become a problem.

B. Testing. Depending on the size and criticality of the project, QA testing of materials and shotcrete may be required to verify compliance with contract requirements. These tests are in addition to QC tests. They will also serve to verify the ability of the QC laboratory to produce valid test data.

C. Visual Inspection. The quality of the shotcrete should be thoroughly evaluated by visual inspection. Surfaces should be inspected for uniformity, voids at the surfaces, varying finish conditions, dry conditions, seepage of water, cracking, and damaged sections.

APPENDIX A

REFERENCES

A-1. REQUIRED PUBLICATIONS.

[1]**ER 1180-1-6.** "Construction Quality Management."

[1]**EM 385-1-1.** "Safety and Health Requirements Manual."

[1]**EM 1110-2-2000.** "Standard Practice for Concrete."

[1]**CW-03361.** "Shotcrete."

[2]**U.S. Army Engineer Waterways Experiment Station 1949.**
U.S. Army Engineer Waterways Experiment Station. 1949. *Handbook for Concrete and Cement,* with quarterly supplements (all CRD-C designations), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

[3]**American Concrete Institute 1991a.**
American Concrete Institute. 1991a. "Chemical Admixtures for Concrete," ACI Report No. 212.3R-89, *ACI Manual of Concrete Practice,* Part 2, Detroit, MI.

[3]**American Concrete Institute 1991b.**
American Concrete Institute. 1991b. "Guide for Measuring, Mixing, Transporting, and Placing Concrete," ACI Report 304R-89, *ACI Manual of Concrete Practice,* Part 2, Detroit, MI.

[3]**American Concrete Institute 1991c.**
American Concrete Institute. 1991c. "Standard Practice for Curing Concrete," ACI Report No. 308R-86, *ACI Manual of Concrete Practice,* Part 2, Detroit, MI.

[3]**American Concrete Institute 1991d.**
American Concrete Institute. 1991d. "Guide to Shotcrete," ACI Report No. 506R-90, *ACI Manual of Concrete Practice,* Part 5, Detroit, MI.

[3]**American Concrete Institute 1991e.**
American Concrete Institute. 1991e. "State-of-the-Art Report on Fiber Reinforced Shotcrete," ACI Report No. 506.1R-84, (Reapproved 1989), *ACI Manual of Concrete Practice,* Part 5, Detroit, MI.

[1]Reference published by Department of the Army and available through U.S.ACE Command Information Management Office sources.

[2]All Corps of Engineers publications are available on interlibrary loan from the Research Library, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-IM-MI-R, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

[3]Reference available through American Concrete Institute, PO Box 19150, Detroit, MI 48219.

American Society for Testing and Materials.

[4]**ASTM C 33 (CRD-C 133).** "Standard Specification for Concrete Aggregates."

[4]**ASTM C 42 (CRD-C 27).** "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete."

[4]**ASTM C 94 (CRD-C 31).** "Standard Specification for Ready-Mixed Concrete."

[4]**ASTM C 136 (CRD-C 103).** "Standard Method for Sieve Analysis of Fine and Coarse Aggregates."

[4]**ASTM C 150 (CRD-C 201).** "Standard Specification for Portland Cement."

[4]**ASTM C 231 (CRD-C 41).** "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method."

[4]**ASTM C 494 (CRD-C 87).** "Standard Specification for Chemical Admixtures for Concrete."

[4]**ASTM C 597 (CRD-C 51).** "Standard Test Method for Pulse Velocity Through Concrete."

[4]**ASTM C 618 (CRD-C 255).** "Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete."

[4]**ASTM C 685 (CRD-C 98).** "Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing."

[4]**ASTM C 803 (CRD-C 59).** "Standard Test Method for Penetration Resistance of Hardened Concrete."

[4]**ASTM C 805 (CRD-C 22).** "Standard Test Method for Rebound Number of Hardened Concrete."

[4]**ASTM C 900 (CRD-C 78).** "Standard Test Method for Pullout Strength of Hardened Concrete."

[4]**ASTM C 1018 (CRD-C 65).** "Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)."

[4]Reference available through American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

[4]**ASTM C 1141 (CRD-C 625).** "Standard Specification for Admixture for Shotcrete."

A-2. RELATED PUBLICATIONS.

[3]**American Concrete Institute 1974.**
American Concrete Institute. 1974. "Use of Shotcrete for Underground Structural Support," Publication SP-45, Detroit, MI.

[3]**American Concrete Institute 1980.**
American Concrete Institute. 1980. "Performance of Concrete in Marine Environment," Publication SP-65, Detroit, MI.

[3]**American Concrete Institute 1981a.**
American Concrete Institute. 1981a. "Shotcrete Applications," *Concrete International: Design and Construction,* Vol. 3, No. 1, pp. 23–109, Detroit, MI.

[3]**American Concrete Institute 1981b.**
American Concrete Institute. 1981b. "Application and Use of Shotcrete," Compilation No. 6, Detroit, MI.

[3]**American Concrete Institute 1991a.**
American Concrete Institute. 1991a. "Specifications for Structural Concrete for Buildings," ACI Report No. 301R-89, *ACI Manual of Concrete Practice,* Part 3, Detroit, MI.

[3]**American Concrete Institute 1991b.**
American Concrete Institute. 1991b. "Standard Specification for Bonding Plastic Concrete to Hardened Concrete with a Multi-Component Epoxy Adhesive," ACI Report No. 503.2-79 (Revised 1986), *ACI Manual of Concrete Practice,* Part 5, Detroit, MI.

[3]**American Concrete Institute 1991c.**
American Concrete Institute. 1991c. "Specification for Materials, Proportioning, and Application of Shotcrete," ACI Report No. 506.2-90 (Revisions), Copyright 1972, 1982, *ACI Manual of Concrete Practice,* Part 5, Detroit, MI.

[3]**American Concrete Institute 1991d.**
American Concrete Institute. 1991d. "Guide to Certification of Shotcrete Nozzlemen," ACI Report No. 506.3-82, *ACI Manual of Concrete Practice,* Part 5, Detroit, MI.

[4]**American Society for Testing and Materials 1978.**
American Society for Testing and Materials. 1978. "Significance of Tests and Properties of Concrete and Concrete-Making Materials," ASTM STP 169B, Philadelphia, PA.

[4]**American Society for Testing and Materials 1992.**
American Society for Testing and Materials. 1992. "Standard Specification for Epoxy-Resin-Basin Bonding Systems for Concrete," Designation C-881-90, *1992 Annual Book of ASTM Standards,* Philadelphia, PA; also published as CRD-C 595, *Handbook for Concrete and Cement* (with quarterly supplements), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

[2]**Brekke, Einstein, and Mason 1976.**
Brekke, T. L., Einstein, H. H., and Mason, R. E. 1976 (Jun). "State-of-the-Art Review of Shotcrete," Contract Report S-76-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

[3]**Crom 1966.**
Crom, T. R. 1966. "Dry-Mix Shotcrete Practice," *Shotcreting,* SP-14, pp. 15–32, American Concrete Institute, Detroit, MI.

[3]**Crom 1981.**
Crom, T. R. 1981 (Jan). "Dry-Mix Shotcrete Nozzling," *Concrete International: Design and Construction,* Vol. 3, No. 1, pp. 80–93, American Concrete Institute, Detroit, MI.

[3]**Fredricks, Saunders, and Broadfoot 1966.**
Fredricks, J. C., Saunders, N. R., and Broadfoot, J. T. 1966. "Recent Developments in Positive Displacement Shotcrete Equipment," *Shotcreting,* SP-14, pp. 75–83, American Concrete Institute, Detroit, MI.

[3]**Gopalaratnam, Shah, Batson, Criswell, Ramakrisknan, and Wecharatana 1991.**
Gopalaratnam, V. S., Shah, S. P., Batson, G. B., Criswell, M. E., Ramakrishnan, V., and Wecharatana, M. 1991 (Jul–Aug). "Fracture Toughness of Fiber Reinforced Concrete," *ACI Materials Journal,* pp. 339–353, American Concrete Institute, Detroit, MI.

[3]**Hoffmeyer 1966.**
Hoffmeyer, T. A. 1966. "Wet-Mix Shotcrete Practice," *Shotcreting,* SP-14, pp. 59–74, American Concrete Institute, Detroit, MI.

Holland 1987.
Holland, T. C. 1987 (Mar). "Working with Silica Fume Concrete," *Concrete Construction,* Vol. 32, No. 3, Addison, IL.

[5]**Krantz 1984.**
Krantz, Gary W. 1984. "Selected Pneumatic Gunites for Use in Underground Mining: A Comparative Engineering Analysis," Bureau of Mines Information Circular/1984, 64 pp., United States Department of Interior, Washington, DC.

[4]**Luther 1989.**
Luther, Mark D. 1989. "Microsilica (Silica Fume) Concrete Durability in Severe Environments," Proceedings of the Structural Congress 1989, American Society of Civil Engineers, New York, NY, pp. 95–105.

[5]**Mahar, Parker, and Wuellner 1975.**
Mahar, J. W., Parker, H. W., and Wuellner, W. W.

1975 (Aug). "Shotcrete Practice in Underground Construction," Report No. FRA-OR&D 75–90, U.S. Department of Transportation, Washington, DC.

[2]**McDonald 1991.**
McDonald, James E. 1991 (Mar). "Properties of Silica Fume Concrete," Technical Report REMR-CS-32, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

[3]**Morgan 1988.**
Morgan, D. R. 1988 (Jan). "Dry-Mix Silica Fume Shotcrete in Western Canada," *Concrete International: Design and Construction*, Vol. 10, No. 1, pp. 24–32, American Concrete Institute, Detroit, MI.

[5]**Morgan, McAskill, Richardson, and Zellers 1989.**
Morgan, D. R., McAskill, N., Richardson, B. W., and Zellers, R. C. 1989. "A Comparative Evaluation of Plain, Polypropylene Fiber, Steel Fiber and Wire Mesh Reinforced Shotcretes," Transportation Research Record, No. 1226, Concrete and Concrete Construction, Transportation Research Board, National Research Council, Washington DC, pp. 78–87.

Prestressed Concrete Institute 1981.
Prestressed Concrete Institute. 1981 (Jan-Feb). "Recommended Practice for Glass Fiber Reinforced Concrete Panels," *Journal of Prestressed Concrete Institute*, Vol. 26, No. 1, pp. 25–93.

[3]**Reading 1981.**
Reading, T. J. 1981 (Jan). "Durability of Shotcrete," *Concrete International: Design and Construction*, Vol. 3, No. 1, pp. 27–33, American Concrete Institute, Detroit, MI.

[3]**Rutenbeck 1974.**
Rutenbeck, Todd. 1974. "New Developments in In-Place Testing of Shotcrete," *Use of Shotcrete for Underground Structural Support*, SP-45, pp. 246–262, American Concrete Institute, Detroit, MI.

[6]**Ryan 1973.**
Ryan, T. F. 1973. *Gunite — A Handbook for Engineers*, Cement and Concrete Association, London, England.

[2]**Tynes and McCleese 1974.**
Tynes, W. O., and McCleese, W. F. 1974 (July). "Investigation of Shotcrete," Technical Report C-74-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

[5]Reference available from National Technical Information Service, Springfield, VA 22151.

[6]Reference available from 11 Grosvenor Crescent, London, SWIX, 7EE, England.

APPENDIX B

GLOSSARY OF TERMS

Accelerator.
A substance which, when added to concrete, mortar, or grout, increases the rate of hydration of a hydraulic cement; shortens the time of setting; or increases the rate of hardening or strength development, or both.

Admixture.
A material other than water, aggregate, hydraulic cement, or fiber reinforcement used as an ingredient of concrete or mortar and added to the concrete immediately before or during its mixing.

Air Ring.
Perforated manifold in the nozzle of wet-mix shotcrete equipment through which high-pressure air is introduced into the material flow.

Aspect Ratio.
A term used to describe the geometry of an individual fiber; it is the ratio of the length of a fiber to the equivalent diameter; the equivalent diameter is that circular area that is equal in area to the cross-sectional area of the fiber.

Bench Gunning.
When building up thick sections of vertical work, shotcrete is applied against the advancing top surface of the shotcrete rather than directly against the vertical surface, the top surface of the shotcrete is maintained at a 45-degree slope. (Also known as shelf gunning.)

Blowpipe.
Air jet operated by the nozzleman's helper in shotcrete gunning to keep rebound or other loose material out of the work.

Build Up.
Gunning of shotcrete in successive layers to form a thicker mass.

Bulking.
Increase in the bulk volume of a quantity of sand in a moist condition over the volume of the same quantity dry or completely inundated.

Cutting Screed.
Sharp-edged tool used to trim shotcrete to a finished outline.

Delivery Hose.
Hose through which shotcrete passes; also known as a material or conveying hose.

Dry-Mix Shotcrete.
Pneumatically conveyed shotcrete in which most of the mixing water is added at the nozzle. (See also Pneumatic Feed.)

Feed Wheel.
Material distributor or regulator in certain types of shotcrete equipment.

Finish Coat.
Final thin coat of shotcrete applied preparatory to hand finishing.

Flash Coat.
A light coat of shotcrete used to cover minor blemishes on a concrete surface applied from a distance greater than normal.

Ground Wire.
Small-gauge high-strength steel wire used to establish line and grade as in shotcrete work; also called alignment wire or screed wire.

Gun.
(1) Shotcrete material delivery equipment used to receive materials and deliver them to the nozzle; the equipment often consists of double chambers under pressure (equipment with a single-pressure chamber is used to some extent).
(2) A pressure cylinder used to pneumatically propel freshly mixed concrete.

Gun Finish.
Undisturbed final layer of shotcrete as applied from the nozzle, without hand finishing.

Gunite (former trademark).
A method of applying dry-mix shotcrete; term sometimes used for dry-mix shotcrete.

Gunman.
Workman on a shotcreting crew who operates the delivery equipment.

Gunning.
The act of applying shotcrete; ejection of material from the nozzle and impingement on the surface to be gunned. (Sometimes called shooting.)

Gunning Pattern.
Conical outline of the material discharge stream in shotcrete operation.

Hamm Tip.
A flared shotcrete nozzle having a larger diameter at midpoint than either inlet or outlet; also called a premixing tip.

Nozzle.
A metal or rubber tip attached to the discharge end of a heavy, thick-wall rubber hose from which a continuous stream of shotcrete is ejected onto the placement.

Nozzle Velocity.
The rate at which shotcrete is ejected from the nozzle, usually stated in feet per second or meters per second.

Nozzleman.
The operator who manipulates the nozzle and controls placement of the shotcrete; in the case of dry-mix shotcrete, the nozzleman also controls the water content of the shotcrete.

Pneumatic Feed.
Shotcrete delivery equipment in which material is conveyed by a pressurized air stream.

Positive Displacement Concrete Pump.
Wet-mix shotcrete delivery equipment in which the material is pushed through the material hose in a solid mass by a piston, auger, or other displacement type equipment.

Rebound.
Aggregate and cement or wet shotcrete which bounces away from a surface against which shotcrete is being projected.

Sand Lenses.
A general term for areas in the shotcrete that are either voids or pockets of aggregate that have segregated from the cement, sand lenses are oriented in planes parallel to the layering of the shotcrete, analogous to rock pockets or honeycomb in conventional concrete.

Sand Pocket.
A zone in concrete or mortar containing sand without cement.

Shelf Gunning.
When building up thick sections of vertical work, shotcrete is applied against the advancing top surface of the shotcrete rather than directly against the vertical surface; the top surface of the shotcrete is maintained at a 45 degree slope. (Same as bench gunning.)

Shooting.
(See gunning.)

Shotcrete.
Mortar or concrete pneumatically projected at high velocity onto a surface; also known as air-blown mortar pneumatically applied mortar or concrete, sprayed mortar, or gunned concrete. (See also Dry-Mix Shotcrete, Pneumatic Feed, Positive Displacement Concrete Pump and Wet-Mix Shotcrete.)

Sloughing.
Subsidence of shotcrete, plaster, or the like, due generally to excessive water in the mixture; also called sagging.

Water Ring.
A device in the nozzle body of dry-mix shotcrete equipment through which water is added to the materials.

Wet-Mix Shotcrete.
Shotcrete wherein all ingredients, including mixing water, are mixed before introduction into the delivery hose; it may be pneumatically conveyed or moved by displacement. (See also Pneumatic Feed and Positive Displacement Concrete Pump.)

APPENDIX C

SHOTCRETE APPLICATIONS CORPS OF ENGINEERS PROJECTS

TABLE C-1. Shotcrete Applications, U.S. Army Corps of Engineers Projects

Application (1)	Type of shotcrete (2)	Project (3)	Location (4)	District (5)
Tunnel lining	Dry-mix	Little Goose Dam	Snake River, WA	Walla Walla
Tunnel lining	Dry-mix with silica fume	Lower Monumental Dam	Snake River, WA	Walla Walla
Spillway ogee	Wet-mix	Willow Creek Dam	Heppner, OR	Walla Walla
Canal lining	Wet-mix and wet-mix with steel fibers	Mill Creek Lake	Walla Walla, WA	Walla Walla
Navigation lock coating	Wet-mix with glass fibers and polymer	Lower Monumental Dam	Snake River, WA	Walla Walla
Navigation lock rehabilitation	Wet-mix	Emsworth, Dashields Monogahela Lock No. 3	Pittsburgh, PA	Pittsburgh
Tunnel lining	Wet-mix with steel fibers	Harlan Diversion Project	Harlan, KY	Nashville
Rock slope prot	Dry-mix with accelerator	New Melones Dam	Stanislaus River, CA	Sacramento
Tunnel lining	Dry-mix with accelerator	New Melones Dam	Stanislaus River, CA	Sacramento
Rock slope prot	Dry-mix	Little Dell Dam	Del Creek, UT	Sacramento
Tunnel lining	Dry-mix	Little Dell Dam	Del Creek, UT	Sacramento
Sloped channel Repair/overlay	Wet-mix	Los Angeles River Channel	Los Angeles River, CA	Los Angeles

APPENDIX D

MIXTURE PROPORTIONING SAMPLE SUBMITTAL

HARCON INCORPORATED
P.O.BOX 2661
POCATELLO, ID. 83206-2661

SHOTCRETE MIX DESIGN (BY VOLUME) Mix # 1

Project # DACW 68-91-C-0002

LOWER MONUMENTAL PERMANENT JUVENILE FISH BYPASS FACILITIES

Shotcrete Producer: Connell Sand & Gravel, Inc., Connell, Wa.
Shotcrete Uses: Gallery Lining

W/C ratio <= 0.40, Entrained air = NA
Cement from: South Dakota Cement

C.A.= 3/8" x #4 w/ ASTM C 33 combined gradation per 3B-6.3
Bulk S.G.: SSD = 2.81 Absorption = 2.2%
Source = Connell Sand & Gravel

F.A.= Concrete Sand w/ ASTM C 33 combined gradation per 3B-6.3
Source = Connell Sand & Gravel
Bulk S.G.: SSD = 2.706 Absorption = 3.2% F.M. = 3.01

COMPUTATION of 1 CY TRIAL MIX Revised 5/22/91

Ingredients		Batch Weights		S.G. SSD	Volume
WATER @ W/C =	0.36	256		1.000	4.095
CEMENT T I-II LA		705		3.150	3.587
C.A. (3/8"x#4)		640	0.21	2.590	3.960
F.A.		2450	0.79	2.625	14.957
SILICA FUME		56	0.08	2.200	0.408
VOLUME					27.006

Additives: None

Water Source: Same as for structural concrete

APPROVED
Subject to conformity with plans and specifications. Approval does not constitute acceptance of responsibility of assembling and furnishing
CONSTRUCTION DIV.
W. DIST.
Sig: Date: 19 JUL 1991

91-02---3B-2.1----1

TILBURY CEMENT COMPANY

DATE-06-04-91
Connell Sand & Gravel

Sieve Size	Percent Passing	Specification
3/8"	100	100
#4	98	95-100
8	77	80-100
16	70	50-85
30	42	25-60
50	15	10-30
100	5	2-10
200	2	
F M	2.83	

Screen Size	Percent Passing	ASTM Specification
3/8"	100	85-100
#4	13	10-30
#8	4	0-10
#16	0	0-5

Screen Size	80% Sand 20% 3/8" Percent Passing	Specification
1/2"	100	100
3/8"	100	90-100
#4	81	75-85
8	62	50-75
16	55	35-55
30	34	20-35
50	12	8-20
100	4	2-10

TESTED BY

INTERMOUNTAIN MATERIALS TESTING, INC.
7446 Lemhi St., Boise, Idaho 83709 (208) 376-8203
1718 West A St., Pasco, Washington 99301 (509) 547-1121

Materials Engineering and Testing • Construction Inspection • Project Consultation

REPORT TO: Fausett Mine Services
P.O. Box 968
Osbourn, ID 83849

DATE: 6-26-91
FILE NUMBER: 91-53
SHEET: 6 of 6
INVOICE: T910279

PROJECT: Lower Monumental Dam

Sample Identification

On May 29, 1991, your personnel delivered to our laboratory shot crete cores. It was reported that the test panels were shot on May 22, 1991, by your operator, Cunningham. The panels were reportedly shot at horizontal position, using mix #1 (7.5 bag mix with 8% silica fume).

At your request, we performed compressive strength tests in accordance with ASTM C42. The test results are as follows.

Test Results

Lab Number	Date Tested	Age	Length / Diameter	Compressive Strength PSI
911871	6-17-91	26	6.25 / 2.75	5920
911872	6-17-91	26	6.125 / 2.75	5860
911873	6-19-91	28	3.875 / 2.75	6130
911874	6-19-91	28	4.625 / 2.75	6120

Reviewed by Lew A. Beck

INTERMOUNTAIN MATERIALS TESTING, INC.
7446 Lemhi St., Boise, Idaho 83709 (208) 376-8203
1718 West A St., Pasco, Washington 99301 (509) 547-1121

Materials Engineering and Testing • Construction Inspection • Project Consultation

REPORT TO: Fausett Mine Services
P.O. Box 968
Osbourn, ID 83849

DATE: 6-26-91
FILE NUMBER: 91-53
SHEET: 4 of 6
INVOICE: T910279

PROJECT: Lower Monumental Dam

Sample Identification

On May 29, 1991, your personnel delivered to our laboratory shot crete cores. It was reported that the test panels were shot on May 22, 1991, by your operator, Easley. The panels were reportedly shot at horizontal position, using mix #1 (7.5 bag mix with 8% silica fume).

At your request, we performed compressive strength tests in accordance with ASTM C42. The test results are as follows.

Test Results

Lab Number	Date Tested	Age	Length / Diameter	Compressive Strength PSI
911854	6-17-91	26	4.375 / 2.75	5910
911855	6-17-91	26	4.625 / 2.75	5860
911856	6-19-91	28	4.00 / 2.75	6480
911857	6-19-91	28	4.50 / 2.75	6700

Reviewed by Lew A. Beck

INTERMOUNTAIN MATERIALS TESTING, INC.
7446 Lemhi St., Boise, Idaho 83709 (208) 376-8203
1718 West A St., Pasco, Washington 99301 (509) 547-1121

Materials Engineering and Testing • Construction Inspection • Project Consultation

REPORT TO: Fausett Mine Services
P.O. Box 968
Osbourn, ID 83849

DATE: 6-26-91
FILE NUMBER: 91-53
SHEET: 2 of 6
INVOICE: T910279

PROJECT: Lower Monumental Dam

Sample Identification

On May 29, 1991, your personnel delivered to our laboratory shot crete cores. It was reported that the test panels were shot on May 22, 1991, by your operator, Rainville. The panels were reportedly shot at horizontal position, using mix H1 (7.5 bag mix with 8% silica fume).

At your request, we performed compressive strength tests in accordance with ASTM C42. The test results are as follows.

Test Results

Lab Number	Date Tested	Age	Length / Diameter	Compressive Strength PSI
911833	6-05-91	14	4.88 / 2.75	4100
911834	6-05-91	14	4.88 / 2.75	4130
911838	6-19-91	28	5.50 / 2.75	6770
911839	6-19-91	28	4.875 / 2.75	6180

Reviewed by Lew A. Beck

SOUTH DAKOTA CEMENT

AMERICAN OWNED & OPERATED

Phone (605) 342-4752
FAX (605) 342-4742

To: Connell Sand & Gravel Inc.
P.O. Box 156
Connell, Wy. 99326

Re: DACW68-91-C-0002
Franklin Co. Lower Monumental
Permanent Juvenile Fish
Bypass Facility

CERTIFICATION OF COMPLIANCE:

This is to certify that all Dakota Type I-II LA Portland Cement shipped to you meets or exceeds the quality standards set forth by the American Society for Testing and Materials (ASTM C - 150 - 89).

Questions concerning these specifications may be directed to this office at the above number.

Court Patterson
Signature
Quality Control Manager

30 January, 1991
Date

HARCOM INCORPORATED
P.O. BOX 460
KAHLOTUS, WA. 99335-0488

LOWER MONUMENTAL PERMANENT JUVENILE FISH BYPASS FACILITY
FRANKLIN COUNTY WASHINGTON
Contract No. DACW 68-91-C-0002

☑ Reviewed
☐ Reviewed As Noted Resubmit ☐
☐ Rejected, Resubmittal Required
☑ Approved

Signature
Date 1/31/91
Item No. 1
Transmittal No. 312-02

RECEIVED
CONSTRUCTION DIV.
WALLA WALLA DIST.
Sig:
Date: 26 FEB 1991

3A 6.1.1

91-02---3A-002----1

Post-it™ brand fax transmittal memo 7671 | # of pages ▸ 1

To	From D. Baker
Co. Cornell Dubilier	Co. S.A. Armstrong
Dept.	Phone # (509) 547-1535
Fax # (509) 547-1532	Fax # (509) 547-1532

CERTIFICATE OF COMPLIANCE
DACOTAH CEMENT
RAPID CITY, SOUTH DAKOTA

DATE.....1-21-91
ORDER #.....MC-921
CONSIGNED TO:.....TILBURY CEMENT

DESTINATION.....PASCO, WA

CAR #	LBS.	CAR #	LBS.
BN 441440	195700		
BN 441234	197000		

TYPE: I-II LA
BIN # 39 LAB# 51915

CHEMICAL	A.S.T.M. C-150-89 SPECIFICATION LIMIT TYPE I	TYPE II	DACOTAH CEMENT ANALYSIS
Silicon dioxide, min, % (SiO2)		20.00	22.67
Aluminum oxide, max, % (Al2O3)		6.00	4.44
Ferric oxide, max, % (Fe2O3)		6.00	3.32
Magnesium oxide, max, % (MgO)	6.00	6.00	3.12
Sulfur trioxide, max, % (SO3)			2.15
When (C3A) is 8% or less	3.00	3.00	
Loss on ignition, max, %	3.00	3.00	0.83
Insoluble residue, max, %	0.75	0.75	0.32
Tricalcium aluminate, max, % (C3A)	[illegible]	[illegible]	6.36
Alkalies, max, % (*) (as Na eq.)	0.60	0.60	0.5[illegible]
PHYSICAL			
Blaine Fineness, (M2/Kg), min	280	280	385
Autoclave expansion, max, %	0.80	0.80	-0.02
Gillmore initial set time, min.	1:00	1:00	2:30
Gillmore final set time, max.	10:00	10:00	4:30
Vicat setting time, min, not less than	145	145	2:10
max, not more than	6:15	6:15	
3 Day Compressive Strength, p.s.i.	1800	1500	3185
7 Day Compressive Strength, p.s.i.	2800	2500	4753
28 Day Compressive Strength, p.s.i.	4000	4000	6820
Air content of mortar, volume, max. %	12.0	12.0	8.7
False set final penetration, min, (*)	50	50	

RECEIVED
CONSTRUCTION DIV.
WALLA WALLA DIST.
WALLA WALLA
FEB 1991

(*) Optional Requirements
This will certify that the above described shipment of DACOTAH cement meets current ASTM C150-89 and AASHTO M85 specifications. All testing complies with the requirements by A.S.T.M. for Portland Cement. WE ARE NOT RESPONSIBLE FOR ANY ADDITIVES NOT STATED IN THE CERTIFICATE OF COMPLIANCE.

DATE OF REPORT....01/22/91 CHEMIST.. Court Patterson

C3S..... 48.16
C4AF..... 10.11

91-02---3A-002----2

Master Builders Technologies

Master Builders, Inc.
23700 Chagrin Boulevard
Cleveland, Ohio 44122-5454
Phone 216/831-6500
Telex 980-305

June 12, 1991

Certificate of Quality
Master Builders Raw Silica Fume Mineral Admixture (West Coast Source)

Re: Corps. of Engineers Projects

TO WHOM IT MAY CONCERN:

State of Chio
County of Lake . } ss.

Before me, a Notary Public, in and for the aforesaid State and County, personally appeared Brian E. Caine, who being duly sworn, deposes and says:

That he is Manager, Chemistry Laboratory for Master Builders, Inc., Cleveland, Ohio; and

That Raw Silica Fume Mineral Admixture (West Coast Source) is Master Builders dry uncompacted silica fume mineral admixture for improving the properties of hardened concrete, especially strength and impermeability; and

That Raw Silica Fume Mineral Admixture (West Coast Source) meets the following Master Builders quality assurance acceptance criteria:

Silicon dioxide (SiO_2), min, %	85.0
Available alkalies, as Na_2O, max, %	1.5
Moisture content, max, %	3.0
Loss on ignition, max, %	6.0
Amount retained on U.S. No. 325 Sieve, max, %	10.0*
Pozzolanic Activity**	Not Tested
Uniformity of Density***	Not Tested

* Recent production runs have shown retained amounts of less than 5%.

** Silica Fume containing more than 85% SiO_2 is certainly pozzolanic. Pozzolanic activity was developed to test the effectiveness of fly ash and has no meaning with silica fume.

*** Master Builders does not use density as a measure of uniformity. This silica fume is from a furnace in which only one metal product is made. This test has more meaning for fly ash than silica fume.

Subscribed and sworn to before me
this 12th day of June, 1991

Brian E. Caine

Brian E. Caine
Manager, Chemistry Laboratory
Admixture Research & Development

Robert C. Miller

Robert C. Miller, Notary Public
State of Ohio
My Commission Expires February 7, 1996
(Recorded in Lake County)

Doc. 5325

INDEX

Accelerated shotcrete 6
Accelerated testing 26
Accelerators 5, 6, 9, 11, 39, 49
Acrylic latex 6
Admixtures 8-9, 49; accelerators 5, 6, 9, 11, 39, 49; air-entraining 4-5, 7, 9, 11, 39, 41; ASTM standards 45, 46; bonding compounds 9; certificate of compliance 39, 41, 43; dispensers 18-19, 31; dry-mix shotcrete 4, 5, 8, 11, 18-19; polymers 6, 9, 12; testing 8, 45, 46; water-reducing 7-9, 19, 39, 41; water-retarding 9; wet-mix shotcrete 5, 9, 11, 19
Aggregate, 8; ASTM standard 45; grading 8, 40; premoisturizer 20, 31; rebound 11, 35; testing 39-41
Air compressor 19
Air content 41, 45
Air ring 49
Air-entraining admixtures 4-5, 7, 9, 11, 39, 41
Alignment control 30
Anchors 30
Application techniques 4-5, 15-22, 31-35
As-gunned finish 36, 49
Aspect ratio 49
ASTM standards 45-46

Bar reinforcement 9-10, 29-30, 33-34
Batching 30-31; ASTM standard 45; equipment 17-18, 30; fiber-reinforced shotcrete 20; silica-fume shotcrete 20, 31; test data sample submittal 54
Beams 41, 45
Bench gunning 35, 49
Blowpipe 22, 34, 49
Bond strength 4, 5, 12, 36
Bonding 3, 4; delamination 40-42
Bonding agents 9
Bridge repair 3
Building repair 3
Bulking 49
Butt joints 35

Calcium chloride 9
Canal linings 29, 35, 51
Cement 7; proportioning 11-12; test data sample submittal 54, 55, 60; testing 39, 40
Certificate of compliance 39-41, 43
Certification; nozzleman 23, 26, 39, 43
CFP fiber *see* Collated fibrillated polypropylene fiber
Chemical admixtures *see* Admixtures
Chlorides 9, 11
Collated fibrillated polypropylene (CFP) fiber 6, 10
Columns, shotcrete placement 29
Compressive strength 12; curing 36; dry-mix shotcrete 5, 11; test data sample submittal 56-58; testing 40, 41
Compressor 19, 20
Concrete surfaces; shotcrete placement 29
Construction joints 35
Continuous-feed gun 15, 16, 18-20
Contraction joints 35
Core strength 24
Cores 24, 41, 45; repair of holes 37
Corners; application techniques 31-33
Crew *see* Personnel
Cube strength 24
Curing 36-37, 39, 41
Curing water 8
Cutting screed 36, 49

Dams 3, 51
Defects; preproduction testing 40; sand pockets 27, 37, 50; surface defects, repair 37; visual inspection 27; voids 27, 33, 34, 37
Delamination 40-42
Delivery hose 49
Density 13
Depth gauge 30
Depth probe 30
Dispensers; admixture 18-19, 31
Domes 4
Double-chamber gun 15, 16
Drum mixer 18, 30
Dry shrinkage 36
Dry-mix shotcrete 4-5, 15-17, 49; accelerators 5, 6, 9, 11; admixtures 4, 5, 8, 11, 18-19; aggregate 8; air compressor 19, 20; air-entraining admixture 5, 11; application 4, 15-16; batching and mixing 30-31; bond strength 5; compressive strength 5, 11; freeze and thaw resistance 4, 5, 9, 12; guns 15-16; nozzle 20, 21; nozzleman 43; placement time limitations 35; plant layout 15, 17; pozzolan 7; premoisturizer 20; proportioning 11; quality assurance 43; rebound 4, 5; references 46, 47; silica fume 8; strength 5, 11; water supply 19-20; water-reducing admixture 8
Durability 47

Earth surfaces; shotcrete placement 29
Encasing; reinforcing steel 33-34
Engineering Considerations and Instructions for Field Personnel 43
Entrained air 11, 12
Epoxy resins 6
Equipment 15-20; batching 17-18, 30; maintenance costs 5; preconstruction testing 23; specifications 39
Erosion repair; spillways 3-4, 51
Excavations 4

Feed wheel 49

Fiber-reinforced shotcrete 5-6, 10; batching and mixing 20; certificate of compliance 39, 41, 43; glass-fiber-reinforced 5-6, 10, 12; placement 30; polypropylene-fiber-reinforced 6, 10, 12; proportioning 12; references 10, 46, 47; steel-fiber-reinforced 5-6, 10, 12; synthetic-fiber-reinforced 6, 10, 12; testing 24, 26; toughness 13, 24, 26
Finish coat 49
Finishing 36
Flash coat 8, 36, 49
Flash set 9
Flexural strength 12, 40; ASTM standard 45; evaluation 24, 41, 45
Floors 4
Fly ash 7, 45
Fog nozzles 36
Formed surfaces; shotcrete placement 29
Forms 29
Freeze resistance 4, 5, 9, 12

GFRS *see* Glass-fiber-reinforced shotcrete
Glass fibers 10, 12
Glass-fiber-reinforced shotcrete 5-6, 10; proportioning 12; references 47
Grading; aggregate 8, 40
Ground wire 49
Gun finish 49
Gunite 1, 49
Gunman 49
Gunning 31-35, 49; bench gunning 35, 49; corners 31-33; joints 35; pattern 32-33, 49; shelf gunning 35, 50
Guns 11, 49; continuous-feed gun 15, 16, 18-20; double-chamber guns 15, 16; pneumatic-feed guns 15, 17-19, 50; positive displacement guns 15, 18, 19, 46, 50

Hamm tip 50
Harlan Diversion Project (Kentucky) 51

In-place thickness 41
Interior corners; gunning 31, 32

Jobsite mixing 18, 30
Joints 35

Latex admixture 6, 9
Little Dell Dam (Utah) 51
Little Goose Dam (Washington) 51
Load capacity 13
Load deflection testing 13, 26
Los Angeles River Channel (California) 51
Lower Monumental Dam (Washington) 51

Manufacterer's certificate 39-41, 43
Marine structures 3, 6, 51
Masonry surfaces; shotcrete placement 29
Membrane curing 36
Mill Creek Lake (Washington) 51
Mixing 30-31; ASTM standard 45; drum mixer 18, 30; equipment 17-18, 30
Mixing water 8
Moisture content 30-31, 40-41
Moisture trap 19
Monongahela Locks (Pennsylvania) 51

Natural gun finish 36, 49
Navigation locks 3, 51
New Melones Dam (California) 51
NMSE *see* Nominal maximum size aggregate
Nominal maximum size aggregate (NMSA) 11
Nondestructive testing 41
Nozzle angle 31
Nozzle distance 31-32
Nozzle motion 32-33
Nozzle velocity 50
Nozzleman 20-22, 50; certification 23, 26, 39, 43; safety 22, 36; test panels 23-24
Nozzles 20, 21, 50
Nozzling 31-35

Overspray 33, 35

Penetration resistance 45
Permeability 13
Personnel 20-22; certification 23, 26, 39, 43; safety 22, 36; test panels 23-24
Pilasters; shotcrete placement 29
Placement 29-37
Plant layout; dry-mix shotcrete 15, 17; wet-mix shotcrete 15, 18, 19
Pneumatic-feed gun 15, 17-19, 50
Polymer-modified shotcrete 6, 9, 12
Polymer-portland-cement shotcrete 6
Polypropylene fiber 6, 10, 12, 47
Pools 4
Portland cement 5-7, 45
Positive displacement gun 15, 18, 19, 46, 50
Pozzolan 7, 45
Premoisturizer 20, 31
Preproduction phase; submittals 39-40, 43; testing 23-27, 39-40
Production phase 40-42
Proportioning 11-12; dry-mix shotcrete 11; evaluation 23; fiber-reinforced shotcrete 12; quality assurance 43; test data 39, 41; test sample submittal 53-61; trial batching 10; wet-mix shotcrete 11
Protection; during curing 36, 39, 41; during shotcrete application 35; slope and surface protection 4
Pullout strength 45
Pulse velocity 45

Quality assurance 43-44, 53-61

Quality control 39-42

Rain; shotcrete application 35
Ready-mixed concrete 17, 45
Rebound 11, 31, 35-36, 50; aggregate size 11, 35; air entrainment 9; ASTM standard 45; blowpipe 22, 34, 49; dry-mix shotcrete 4, 5; percentage 36; polypropylene-fiber reinforcement 10; removal 36; safety 36; silica-fume shotcrete 31, 35; testing 41, 45; wet-mix shotcrete 4, 5
Reinforcement *see* Glass-fiber-reinforced shotcrete; Steel-fiber-reinforced shotcrete; Synthetic fiber-reinforced shotcrete
Reinforcing 30-31; bar reinforcement 29-30, 33; gunning 31; steel, encasing 33-34
Remote-controlled nozzles 20
River channels 51
Rock surfaces 29, 51
Rubber float 36

Safety 22, 36
Sagging 8, 31, 50
Sand pockets (sand lenses) 27, 37, 50
Sawing 24
Scaffolding 29
Shelf gunning 35, 50
Shooting see Gunning
Shotcrete 50; accelerated shotcrete 6; application techniques 4-5, 15-22, 31-35; applications 3-4, 6, 51; ASTM standards 45-46; batching and mixing equipment 17-18, 30-31; curing 36-37, 39, 41; defects 27, 33, 34, 37, 40, 50; equipment 5, 15-20, 23, 39; glass-fiber reinforced 5-6, 10, 12, 47; nozzleman 20-24, 26, 36, 39, 43, 50; placement 29-37; polymer-modified 6, 9, 12; polypropylene-fiber-reinforced 6, 10, 12; preconstruction testing 23-27, 39-40; production phase testing 40-42; properties 12-13, 40; proportioning 10-12, 23, 39, 41; quality assurance 43-44, 53-61; quality control 39-42; references 46-47; silica-fume shotcrete 6, 12, 20, 31, 35, 36-37, 46, 47, 61; steel-fiber reinforced 5, 10, 12, 20, 29-30; synthetic-fiber reinforced 6, 10, 12; testing 10-11, 23-27, 39-46; *see also* Dry-mix shotcrete; Wet-mix shotcrete
Shrinkage 12, 35-37
Silica-fume shotcrete 6; batching and mixing 20, 31; curing 36-37; proportioning 12; rebound 31, 35; references 46, 47; shrinkage 12; test data sample submittal 61
Slope protection 4, 35, 51
Sloughing 8, 31, 50
Slump 11
Snow; shotcrete application 35
Specimen testing 24, 40
Spillways 3-4, 51
Spray-up 5, 6
Square joints 35
Steel; bars 9; fiber 5, 10, 12; prestressed 9; reinforcement 9-10, 29-31, 33-34; wire fabric 9-10, 30, 47
Steel-fiber-reinforced shotcrete 5, 10; batching and mixing 20; proportioning 12; references 47; repairing 29-30
Strength 5, 12, 40; accelerators 9; ASTM standard 45; dry-mix shotcrete 5, 11; polymer-modified shotcrete 6; pozzolan 7; rebound 31; test data sample submittal 56-58; testing 24, 26, 40, 41, 43, 45; wet-mix shotcrete 5
Styrene-butadiene polymer 6
Surface defects; repair 37
Surface preparation 29-30, 41
Surface protection *see* Protection
Surface tolerances 42
Synthetic-fiber-reinforced shotcrete 6, 10, 12

Tanks 4
Temperature; shotcrete application 35, 39, 41
Tensile strength 36
Test panels 10-11, 23-35, 39-41, 43; equipment 23-25; production phase 40, 41; quality assurance 43
Testing; accelerated 26; admixtures 8, 45, 46; aggregate 39-41; ASTM standards 45-46; cement 39, 40; compressive strength 40, 41; fiber-reinforced shotcrete 24, 26; nondestructive 41; preconstruction 23-27, 39-40; preproduction submittals 39-40; production phase 41-42; quality assurance 43-44, 53-61; rebound 41, 45; references 46-47; sample data submittal 53-61; specimen testing 24, 40; test panels 10-11, 23-35, 39-41, 43; trial batching 10, 23; visual examination 24, 26, 27, 42, 44
Thaw resistance 5, 12
Thickness 41
Time limitations 5, 35
Total chloride ion 11
Toughness 13, 40; ASTM standard 45; evaluation 24, 26; polypropylene-fiber reinforcement 10
Toughness index 13, 26
Trial batching 10, 23
Trowel; finishing 36
Tunnels 4, 6, 35, 51

Underground uses 4, 46, 47

Visual examination 24, 26, 27, 42, 44
Voids 27, 33, 34, 37

Walls 4

Washout 6
Water 8, 19-20
Water ring 50
Water-cement ratio; dry-mix shotcrete 12, 22
Water-reducing admixtures 9; certificate of compliance 39, 41; dry-mix shotcrete 8; high-range water-reducing admixture 8, 19; silica fume additions 7, 8
Water-retarding admixtures 9
Waterstops 35
Weather; curing 39, 41; frost and thaw resistance 4, 5, 9, 12; shotcrete application 35
Welded wire fabric 9-10
Wet-mix shotcrete 4-5, 50; accelerators 5, 6, 9; admixtures 5, 9, 11, 19; air content 41; air-entraining admixture 4, 5, 7, 9; batching and mixing 31; bond strength 5; equipment 15, 17-18; frost resistance 4, 5, 9, 12; guns 15, 17, 18; nozzle 20, 21; placement time limitations 35; plant layout 15, 18, 19; pozzolan 7; proportioning 11; rebound 4, 5; references 46; silica fume 8; strength 5
Willow Creek Dam (Oregon) 51
Wind; shotcrete application 35
Wire fabric 9-10, 30, 47
Wood float 37
Workability 11

Zirconium glass 5, 10