INSPECTORS' GUIDE FOR SHOTCRETE REPAIR OF BRIDGES

TASK FORCE 37 REPORT

AASHTO-AGC-ARTBA JOINT COMMITTEE

DECEMBER 1999

Introductory Note

This manual is intended to provide guidance to inspectors of highway bridge repair, rehabilitation, and retrofit using shotcrete. However, the manual is not a substitute for training that includes classroom instruction and experience in the actual shooting of shotcrete.

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

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

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Joint Task Force 37
Shotcrete Repair of Highway Bridges

Chairman: **Gerald White**, North Carolina DOT, Raliegh, NC

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

Members: **Steven H. Gebler**, Construction Technology Laboratories, Inc, Skokie, IL

George Yoggy, Master Builders Technologies, Cleveland, OH

Frank Nelson, Oregon DOT, Salem, OR

Dan Thomas, California DOT, Sacramento, CA

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

Curt White, Coastal Gunite Construction Company, Cambridge, MD

Dr. D. R. Morgan, HBT AGRA Limited, Burnaby, B.C.

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II-2.1, II-2.2, II-2.4, II-2.5 .... George Yoggy, Master Builders
I-1.7, I-2.3, I-2.4 .... Larry Totten, Johnson Western Gunite Company
I-2.6, I-2.7, II-2.3, II-2.6 .... Steven H. Gebler, Construction Technology Laboratories
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Chapter 1. Summary of Shotcrete Basics

Introduction

The purpose of this chapter is to familiarize the inspector with the shotcrete process, the basic elements and types of shotcrete, its general applications, and construction concerns. Specific definitions are provided in the Glossary of Terms at the end of this Chapter.

Shotcreting Processes

Shotcreting is usually classified according to the process used, wet-mix or dry-mix, and the type of aggregate used, coarse or fine. For aggregate gradations for maximum sizes of 5 mm and 10 mm, see Table 1.1 of the Commentary in the *Guide Specifications for Shotcrete Repair of Highway Bridges*.

Dry-mix process

The process consists of the following steps:

(1) A cementitious binder and aggregate are thoroughly mixed.

(2) The binder-aggregate mixture is fed into a special mechanical feeder or gun called the delivery equipment.

(3) The mixture is usually introduced into the delivery hose by a metering device such as a feedwheel, rotor, or feed bowl. Some equipment uses air pressure alone (orifice feed) to deliver the material into the hose.

(4) The material is carried by compressed air through the delivery hose to a nozzle body. The nozzle body is fitted inside with a water ring, through which water is introduced under pressure. Materials are initially mixed at the nozzle.

(5) The material is jetted from the nozzle at high velocity onto the surface to be shotcreted where it is compacted by impact.

Wet-mix process

The process consists of the following steps:

(1) All of the ingredients, including mixing water, but usually excluding accelerator, are thoroughly mixed.

(2) The mortar or concrete is introduced into the chamber of the delivery equipment.

(3) The mixture is pumped into the delivery hose and moved by displacement or by compressed air to a nozzle.

(4) Air to affect a spray is injected at the nozzle to increase velocity.
(5) The mortar or concrete is jetted from the nozzle at high velocity onto the surface to be shotcreted where it is compacted by impact.

Comparison of the processes

The most significant difference between wet- and dry-mix shotcrete is in mixing of the ingredients. The mixing method determines situations where one process may result in more efficient placement than the other. Wet-mix shotcrete is premixed and pumped under pressure to the nozzle whereas dry-mix ingredients are carried to the nozzle by air pressure and mixed both in the nozzle and upon impact on the surface. Dry-mix shotcrete has been more commonly used for bridge repair since it is well suited to placement on vertical and under horizontal surfaces and in thin layers. Wet-mix shotcrete has been more commonly used in applications where reinforcement is highly congested. However, either process can produce shotcrete for common construction uses. Differences in capital and maintenance cost of equipment, operational features, suitability of available aggregate, and placement characteristics may make one or the other more attractive for a particular application. Differences in operational features and other properties that may merit consideration are given in Table 1.1.

Table 1.1 Comparison of Dry- and Wet-mix Process

Dry-mix Process	Wet-mix Process
1. Instantaneous control over mixing water and consistency of mix at the nozzle to meet variable field conditions.	1. Mixing water is controlled at the delivery equipment and can be accurately measured.
2. Start and stop placement characteristics are better with minimal waste and greater placement flexibility.	2. Better assurance that the ingredients are thoroughly mixed.
	3. Normally has lower rebound.
	4. Capable of greater production

Properties

Shotcrete is simply concrete which is placed by high pressure shooting. In general, properly applied shotcrete is a structurally sound and durable construction material and exhibits excellent bonding characteristics with other concrete, masonry, rock, steel, and many other materials. It has high strength, low absorption, good resistance to weathering and many kinds of chemical attack, and has excellent fireproofing qualities. These favorable properties are contingent on good specifications and materials, and proper surface preparation, mixing, shotcrete application, and supervision.
The physical properties of sound shotcrete are comparable or superior to those of conventional mortar or concrete having the same composition.

The water-cementitious material ratio for dry-mix shotcrete in-place normally falls within a range of 0.35 to

0.45 by weight and 0.40 to 0.50 for wet-mix shotcrete. Most published values for 28-day strength are in the range of 20 to 50 MPa (3000 to 7000 psi), although dry-mix and wet-mix shotcrete in some tests has developed strengths in excess of 70 MPa (10,000 psi) at 28 days. It is recommend that strengths higher than 40 MPa (6000 psi) at 28 days be specified only for carefully engineered and executed shotcrete work.

The drying shrinkage of shotcrete varies with the mix proportions used, but generally falls within the range of 0.06 to 0.10 percent. This is higher than most low slump conventional concrete that can be placed in heavier sections using larger aggregate and leaner mixes. Most shotcrete has a high cement factor and higher water content (compared to cast-in-place concrete) and, therefore, has a greater potential for drying shrinkage cracking which may require a closer control joint spacing or increased use of reinforcement. Shotcrete typically requires a thorough wet cure to mitigate restrained drying shrinkage cracking and to enhance strength and durability.

The freeze-thaw durability of shotcrete in laboratory tests and under field exposure has generally been good. However, problems can develop with even the best shotcrete when it is applied to a nondurable or improperly prepared substrate. It should be stressed that the properties and performance of shotcrete are largely dependent on the conditions under which it is placed. They will also be dependent on the mix and the competence and experience of the application crew.

Equipment

Proper equipment layout is essential for an efficient, economical, and successful shotcrete placement. It is important that the equipment be placed as close to the work as possible to minimize the length of material hose required. If the work is spread over a considerable area, the equipment should be centrally located to reduce the number of equipment moves required to complete the project. To avoid rehandling material, the equipment should be positioned so material suppliers have easy and direct access to the mixer, gun or pump.

Equipment Operation

It is important that each piece of equipment be inspected and cleaned, at least, on a daily basis. Equipment should be maintained in accordance with the manufacturers' recommendations. A preventive maintenance program should be established. Meetings should be held regularly to train operators on the proper use and maintenance of their equipment. Adequate backup equipment and spare parts should be readily available to minimize downtime. Good maintenance also reduces safety hazards.

Dry-Mix Equipment

There are two types of dry-mix shotcrete guns: (a) single or double chamber guns and (b) continuous feed rotary guns. Single chamber or batch guns, provide intermittent flow by placing a charge of material into the chamber, then closing and pressurizing the chamber. The material is then fed into a delivery pipe or hose. When the chamber is empty, it is depressurized and refilled, and the operation repeated. Some single chamber guns utilize a rotating feed wheel to give a positive metering action to the material flow. Single chamber guns are used for small jobs requiring an

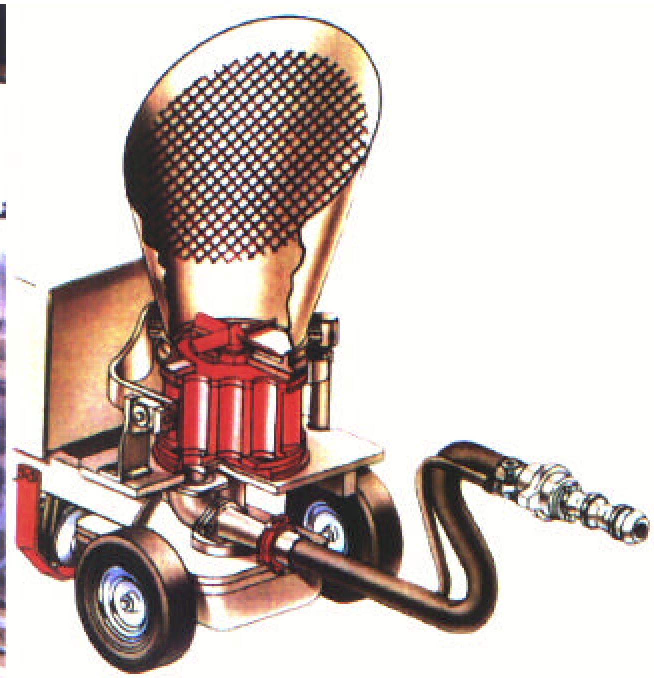

Figure I-1.1. Continuous Feed Dry-Mix Gun   Figure I-1.2. Continuous Feed Dry-Mix Gun

output of less than 0.8 m^3/hr. Double chamber guns allow for continuous operation by using the upper chamber as an airlock during the charging cycle. Most double chamber guns utilize a rotating feed wheel. Double chamber guns can produce 1.5 m^3/hr (2 y^3/hr).

Continuous feed guns provide a continuous feeding action using the rotating airlock principle. There are two types of rotary guns: the barrel and the feed bowl. The barrel type utilizes sealing plates on the top and bottom of the rotating element. Material is gravity charged from the hopper into cylinders of the rotor in one area of its rotational plane and discharged downward from these cylinders by air pressure at the opposite point in its rotation. Additional air is introduced into the outlet neck to provide proper volume and pressure for material delivery down the hose.

The feed bowl type utilizes one sealing segment on the top surface of the rotating element. Material is gravity charged from the hopper into U-shaped cavities in the rotor and discharged into the outlet neck. When the particular cavity is indexed under the sealing segment, air is injected down one leg of the U and carries material into the material hose.

Continuous feed guns are primarily used for dry-mix, but some manufacturers have adapted them for wet-mix applications. Figure 1.1 shows a continuous feed gun. Continuous feed guns can produce 0.8-1.5 m^3/hr.

Wet-Mix Equipment

Wet-mix shotcrete is placed using either a continuous feed gun as described earlier, or more commonly using a concrete pump. Concrete pumps are used to push concrete through a material

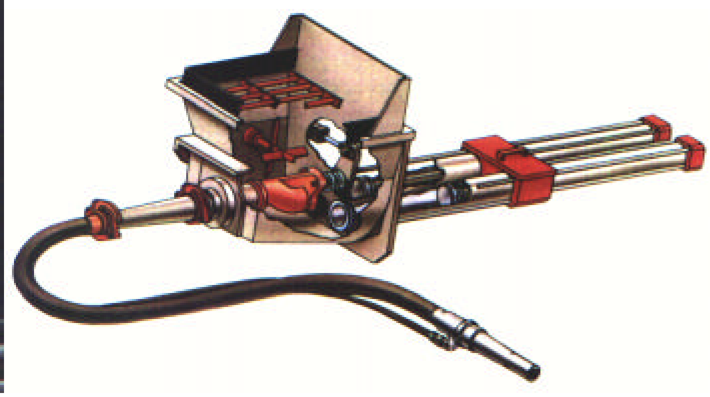

Figure I-1.3. Positive Displacement Wet-Mix Gun Figure I-1.4. Positive Displacement Wet-Mix Gun

delivery hose. Most concrete pumps are positive displacement and use pistons in action with a valve to push the concrete. A valve at the hopper permits material to flow into an empty piston cylinder while at the same time allowing the second piston to push the concrete (Figure 1.2). There are several different concrete pump manufactures each with a different style valve.

A squeeze pump (also called a peristaltic pump) is also sometimes used to place wet-mix shotcrete. The squeeze pump uses mechanical rollers to squeeze the concrete through a tube thereby pushing the concrete into the material hose.

Air Compressors

A properly operating air compressor of sufficient capacity is essential to a satisfactory shotcreting operation. The compressor should maintain a supply of clean, dry, oil-free air adequate for maintaining required nozzle velocities. Simultaneously sufficient air is needed to operate other air driven equipment. Compressed air requirements vary depending on the type of equipment, its condition, and mode of operation. It is advisable to check the gun or pump manufacturer's recommendations for required compressor capacity. Dry-mix operations typically require more air volume than a wet-mix operation.

Mixing Equipment

Wet-mix shotcrete is typically delivered to the job in transit mixers. Dry-mix process jobs usually have job-site mixers. There are two basic types of job-site mixers: batch and continuous. Batch mixers use a rotating mixing drum with blades. A continuous mixer uses a screw or auger that both mixes and conveys the mix.

Hose and Nozzles

Hoses are used to convey shotcrete, air and water. Hoses should be of the proper size, type and strength. Hose couplings should not obstruct or restrict air or shotcrete flow and must have safety restraints at all joints. The internal diameter of the material hose should be three times the size of the largest aggregate. Use only hoses specifically designed for shotcrete. Other hoses may abrade quickly and explode due to the high operating pressures. Shooting dry-mix, with dry aggregate can cause static electricity. A grounding wire should be used if this problem persists. Material hoses should be cleaned out immediately after use to prevent build up of material. Air hoses should be able to withstand at least twice the operating pressure. A typical operating air pressure of 700 kPa (100 psi) is needed for dry-mix shotcrete.

Nozzles are attached at the exit end of the material hose. Dry-mix nozzles have a removable tip and water injection ring with a valve. The nozzleman adjusts the water valve to control the amount of water that is injected into the dry-mix stream. Wet-mix nozzles are similar, except an air injection ring is used instead of a water ring. The removable tips of all nozzles are usually smaller than the material hose to increase the exit velocity of the material. Lengths and shapes of tips vary depending on what type of spray pattern the nozzleman is trying to achieve. Short tips produce a wide spray and long tips produce a narrow spray. There are many different proprietary nozzles.

Scaffolding

To properly place shotcrete the nozzleman must have safe, clear access to the work and be able to shoot perpendicular to the receiving surface. The nozzle should be between 0.6 m to 1.2 m (2 feet to 4 feet) away from the receiving surface. Access to the receiving surface should be clear of posts or braces. Scaffolding must be stable, meet OSHA standards and not interfere with the application of the shotcrete. Handrails are recommended. Nozzlemen frequently use handrails as a back brace.

Auxiliary Equipment

Air-lances/blow pipes are used by some shotcrete contractors to remove rebound, overspray and loose debris. An assistant to the nozzleman, working alongside the nozzleman, would operate the air lance to blow away rebound and debris as the nozzleman places the shotcrete. The air lance is a tool that, if used properly, can aid in reducing the accumulation of rebound and overspray especially in corners and congested reinforcement. The air lance operator must understand the purpose and importance of the lance. In many situations good nozzling techniques are used rather than placing reliance on an air lance to control rebound. Good nozzling in combination with a properly operated air lance is the best practice to control rebound.

Good visibility is critical to placing proper shotcrete. Flood lights should be used if visibility is poor. Flood lights should be protected from water and rebound.

Placement

Dry-Mix

When starting up, the gun operator introduces only compressed air into the material hose, slowly adding mix material under the direction of the nozzleman. If the material delivery pulsates, the operation should be stopped, otherwise the nozzleman will not be able to adjust the water fast enough and the in-place shotcrete will be either over-wetted or under-wetted. When shutting down, the material is shut off first, then the air is shut off when the delivery hose is free of material. When shooting begins the nozzleman adjusts the water till the shotcrete has a slight sheen with occasional dry spots.

Wet-Mix

Prior to pumping, the pump should be checked in accordance with the manufacturers' recommendations. The material hose must first be lubricated (slicked) with a mixture of water and cement or a prepackaged lubricating mixture. Since it does not have any structural value, the lubricating mixture must be wasted in accordance with local ordinances or contract requirements. When given the signal from the nozzleman, the pump operator charges the material hose. The pump operator must monitor the pump pressure, hopper, and watch the nozzleman. The pump operator must be ready to stop if the nozzleman signals. If a plug should occur, the pump operator must first relieve (on hydraulic type pumps) the pressure in the line by reversing the pump so that the pump is pulling back rather than pushing the concrete. No one should attempt to open the hose until the pump operator signals that the pressure has been relieved. If the hose is opened while the line is pressurized, the joint may burst. As with dry-mix, immediate clean up of the pump and hoses is essential. When the pump is temporarily stopped, the air supply to the nozzle should be left slightly open so that the nozzle air ring does not become blocked with paste.

Deleterious Material

Rebound is aggregate and cement paste that bounce off the receiving surface or reinforcement during the application of shotcrete because of collision with the hard surface, the reinforcement, or the aggregate particles themselves. It can accumulate on ledges and in corners and be trapped behind reinforcement if not removed with a blow-pipe during shotcreting operations. Rebound must not be incorporated in the work, as it will create weak, permeable, porous zones in the hardened shotcrete. Rebound is normally not a problem in overhead shooting and should not be a problem in relatively thin (2 to 3 in. thick) vertical applications where there is no congestion of reinforcement.

The amount of rebound varies with the position of the work, air pressure, cement content, water content, maximum size and grading of aggregate, amount of reinforcement, and thickness of layer. Most of the rebound occurs in the first layer of shotcrete applied to a hard surface. Nozzling technique can also affect rebound. If the shotcrete is not applied at right angles to the receiving surface, rebound can increase significantly. The range in percent rebound of conventional cement-aggregate shotcrete for three work surfaces is shown in the following table.

Table 1.2 Rebound from Conventional Cement-Aggregate Shotcrete

Work Surfaces	*Percent Rebound, by Mass	
	Dry-mix	Wet-mix
Floors or slabs	5-15	0-5
Sloping and vertical walls	10-30	5-15
Overhead work	25-50	10-20

*These values may be as much as 50% higher for very thin layers or when shooting through congested reinforcement.

Rebound will be less for small-aggregate mixtures and more for large-aggregate mixtures. Rebound of silica-fume shotcrete mixes may be as much as 50 percent less than other mixtures because of the highly cohesive nature of silica fume modified mixtures.

Overspray is that material which is deposited away from the receiving surface by air currents. Overspray is not densely compacted like shotcrete. Nevertheless, a fine layer of fresh overspray can be incorporated into the shotcrete during shooting, without any detrimental effects, provided it is thin (say less than 0.5 mm thick) and covered immediately. Thicker overspray, or hardened overspray, should be removed and not incorporated in the work, as it can result in porous layers in the shotcrete (these can become zones of potential delamination).

Cure

Shotcrete must be cured just like any form of concrete to develop the required strength and durability of the mix. Adequate curing is especially important for shotcrete since many applications are in thin sections and have low water-cementitious material ratios. This is particularly true for silica fume modified mixtures because they do not bleed.

Continuous water curing for at least 7 days above 5 degrees C (40 degrees F) ambient temperature is recommended. Some curing compounds have been found to be effective when drying conditions are not severe, but normally require higher application rates than normal when the surface has a rough, as-shot texture. They are not recommended when an additional layer of shotcrete or paint is to be applied, since it is unlikely that all of the residue can be removed, even with good abrasive blasting.

Applications

Shotcrete has been used successfully for heavy thick structural applications in which large reinforcement is properly encased in shotcrete. CALTRANS has placed a large amount of wet-mix shotcrete in seismic retrofit applications for bridges. Wet-mix shotcrete is being used extensively in California for strengthening buildings for seismic loads. North Carolina, Florida, Texas, Oregon,

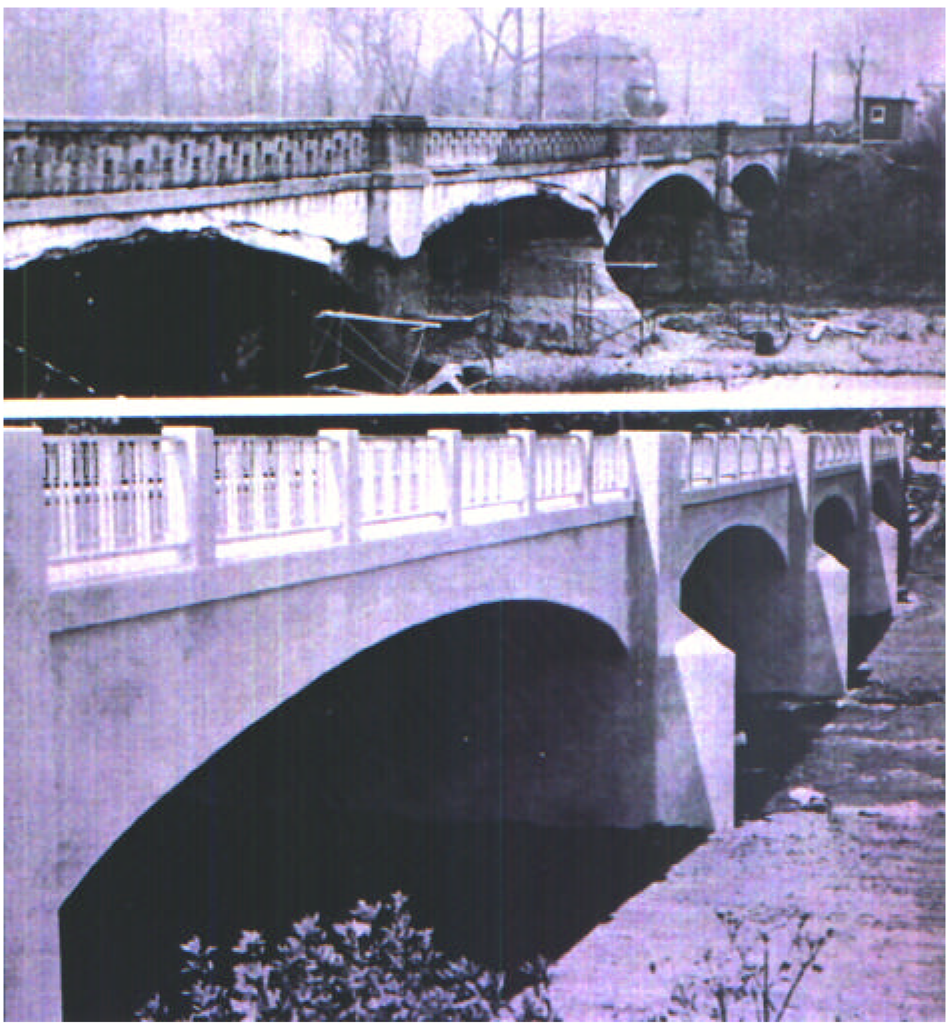

Figure I-1.5. (top left) Permanent Shotcrete Repair of an Arch Bridge

Figure I-1.6. (top right) Permanent Shotcrete Repair of Bridge Columns

Figure I-1.7. (bottom left) Before and After Photos of Permanent Repair of an Arch Bridge and Virginia are actively using dry-mix shotcrete for repair and rehabilitation of bridge substructures. A good summary of some of these applications with photos of heavily reinforced sections being encapsulated with shotcrete is contained in reference 4. Because of its ability to be placed on vertical and overhead surfaces without forming, shotcrete is particularly well suited to strengthening pier columns and cross beams, and to repair of substructures and the underside of beams and decks. Qualified, experienced nozzlemen can properly encase moderate size reinforcement up to number 25. With special attention to the layout, mix design, and shooting technique even larger bars may be properly encased.

Definition of Terms

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

Air-water jet: A high velocity jet of air and water used for scouring surfaces in preparation for next layer of shotcrete.

Alignment wire: See Ground wire.

Blowpipe: Air jet operated by nozzleman's helper in shotcrete application to assist in keeping rebound or other loose material out of the work.

Board butt joint: Shotcrete construction joint formed by sloping shot surface to a 1-in. board laid flat on receiving surface.

Brooming: Roughing and cleaning the surface of as shot material prior to application of additional layers.

Buildup: Thickness of shotcrete.

Bulking: Increase in volume of sand in a moist condition over the same quantity dry.

Conveying hose: See Delivery hose.

Cutting screed: Sharp edged tool used to trim shotcrete to finish outline. See Rod.

Cuttings: Shotcrete material that has been applied beyond the finish face and cut off in the trimming or rodding process.

Delivery equipment: Equipment which introduces shotcrete material into the delivery hose.

Delivery hose: Hose through which shotcrete materials pass on their way to nozzle; also known as material hose or conveying hose.

Dry-mix shotcrete: Shotcrete in which most of the mixing water is added at the nozzle. See Pneumatic feed.

Entrained Air: Microscopic air bubbles intentionally incorporated in mortar or concrete during mixing, usually by the use of a surface-active agent; typically between 10 and 1000 microns in diameter and spherical or nearly so.

Entrapped Air: Air voids in shotcrete which are not purposely entrained and which are significantly larger and less useful than those of entrained air, 1 mm or larger in size.

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

Finish coat: Final thin coat of shotcrete preparatory to hand finishing. See Flash coat.

Finisher/Rodman: Craftsman who trims and finishes the surface of shotcrete.

Flash coat: Thin shotcrete coat applied from a distance greater than normal for use as a final coat or for finishing; also called Flashing.

Float finish: Finish using either a wood, sponge, of rubber float.

Ground wire: Small-gage, high-strength steel wire used to establish line and grade for shotcrete work; also called alignment wire, screed wire, or shooting wire.

Gun: Dry-mix shotcrete delivery equipment.

Gun casting: Placing concrete or mortar using a special velocity reducing casting head and standard shotcrete delivery equipment.

Gun finish: Undisturbed final layer of dry-mix shotcrete as applied from nozzle, without hand finishing.

Gunite: Term sometimes used for dry-mix shotcrete.

Gunning: Act of applying shotcrete; shotcreting.

Gun operator: Craftsman on dry-mix shotcreting crew who operates delivery equipment; also known as Gunman.

Hamm tip: Flared shotcrete nozzle having a larger diameter at midpoint than either inlet or outlet; also called Premixing tip.

Hydro-mix nozzle: A special prewetting and mixing nozzle consisting of a short length of delivery hose inserted between the nozzle body and nozzle tip.

Impact velocity: Velocity of shotcrete material particles just prior to hitting the receiving surface.

Lance: An extended nozzle of various configurations consisting of a length of metal pipe with nozzle and body (or bodies) used to shoot shotcrete refractory material in areas of elevated temperature.

Material hose: See Delivery hose.

Nozzle: Attachment at end of delivery hose from which shotcrete is projected at high velocity.

Nozzle body: A device at the end of the delivery hose which has a regulating valve and contains a manifold (water or air ring) to introduce water or air to shotcrete mixture. A nozzle tip is attached to the exit end of the nozzle body.

Nozzle liner: Replaceable insert in nozzle tip, usually rubber, to prevent wear.

Nozzleman: Worker on shotcrete crew who manipulates the nozzle, controls consistency with the dry process, and controls final disposition of the material.

Overspray: Fine aggregate particles and cement that attaches to nearby surfaces during shotcreting operations.

Pass: Distribution of stream of materials over the receiving surface during shotcreting. A layer of shotcrete is built up by making several passes.

Peristatic Pump: Also, called a squeeze pump, it uses mechanical rollers to squeeze concrete through a tube thereby pushing it into the material hose.

Pneumatically applied concrete or mortar: See Shotcrete.

Pneumatic feed: Shotcrete delivery equipment in which material is conveyed by pressurized air.

Positive displacement: Wet-mix shotcrete delivery equipment in which the material is pumped through the delivery hose in a solid mass by a pump or other non-pneumatic means. Air is introduced into the material flow at the nozzle.

Predampening: In the dry-mix process the addition of water to the aggregate or pre-bagged materials prior to mixing to bring its free moisture content to a specified range, usually 3-6 percent.

Prewetting: In the dry-mix process the addition of a portion of mixing water to shotcrete materials in the delivery hose at some distance prior to the nozzle, typically in a hydro-mix nozzle.

Puddling: Placement of shotcrete wherein air pressure is decreased and water content is increased, usually an undesirable method of shotcreting.

Pump: Wet-mix delivery equipment.

Pump operator: Craftsman on wet-mix shotcreting crew who operates delivery equipment.

Rebound: Mainly large aggregate with some sand and cement that bounces or ricochets off the receiving surface and falls on to lower surfaces.

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

Rolling: Result of applying shotcrete at angles less than 90 degrees to the receiving surface resulting in an uneven, wavy, textured surface at the outer edge of the spray pattern.

Sagging: See Sloughing.

Sand pocket: A porous zone in the shotcrete containing fine aggregate which is deficient in cement.

Scratch coat: Shotcrete layers that are placed prior to the finish coat and are scratched to provide a textured surface suitable for bonding of the surface coat.

Screed wire: See Ground wire.

Shadow: The area behind an obstacle that is not impacted by the shotcrete stream. In hardened shotcrete, shadow refers to any porous area behind an obstacle such as reinforcement.

Shooting: Act of applying shotcrete; see Gunning.

Shotcrete: A method used to shoot concrete at a sufficient velocity to achieve proper in-place compaction.

Sloughing: Subsidence of shotcrete, due generally to excessive water in mixture; also called Sagging.

Slugging: Pulsating or intermittent flow of shotcrete material.

Squeeze Pump: Also called a peristatic pump, it uses mechanical rollers to squeeze concrete through a tube thereby pushing it into the material hose.

Water ring: A perforated manifold in the nozzle body of dry-mix shotcrete equipment through which water is added to the materials.

Wet-mix shotcrete: Shotcrete in which the ingredients including water, are mixed before Introducing them into the delivery hose. Accelerator, if used, is normally added at the nozzle.

Chapter 2. Contract Documents

Performance Specifications

There are two general approaches to specifications, the performance method and the prescription method. The performance specification states the required quality of the shotcrete, and the applicators must decide how it can be achieved. Typically these properties are specified:

1. Cement type,
2. Aggregate gradation,
3. Compressive strength at a specified age,
4. Slump, if wet mix,
5. Air content, if wet mix,
6. Permeability,
7. Specific performance requiring use of admixtures, and
8. Specific performance of fiber reinforced shotcrete.

It is common in most structural repair applications to specify at least the first three properties. It is strongly recommended that mixture proportions be determined during a preconstruction test program as required in the *Guide Specifications for Shotcrete Repair of Highway Bridges*.

The prescription specification should be used for special job requirements or to limit the work to a particular type of shotcrete. Typically the following are specified:

1. Cement type and content,
2. Aggregate gradation, mass, or volume,
3. Admixtures and dosage,
4. Slump, if wet mix,

5. Air content, if wet mix, and

6. Fibers and dosage, if required.

This type of specification is frequently simplified by specifying cement-aggregate proportions such as 1:4 for dry-mix or 7 ½:1 for wet-mix. It is recommended that a performance specification be used whenever possible. It is also recommended that the installer be consulted on the types of cement, aggregate, and shotcrete equipment available and the shotcrete properties that can be practically achieved with locally available materials.

Inspector Qualifications

Shotcrete is concrete which is placed, compacted, and often finished very differently than conventional concrete. A shotcrete inspector should have a very thorough understanding of concrete principles, but should also have a thorough understanding of shotcrete based on training and experience inspecting shotcrete projects. State highway agencies should preferably develop inspector training programs. These can be standing courses or training can be included as a part of a contract for shotcrete work. A one-day course covering shotcrete fundamentals and hands on nozzling is considered to be the minimum introduction. A three-day course with both classroom and practical training in the field is the desirable length to enable satisfactory performance on the job. There are several such courses available in the U.S.

A training course for shotcrete inspector’s has been developed by CALTRANS and several shotcrete equipment suppliers. Videos have also been prepared to accompany these training programs.

The American Concrete Institute (ACI) has a guide to Certification of Shotcrete Nozzlemen that can also be used as a basis for inspector certification. However, the certification program is not administered by ACI and must be done by a highway agency, contractor, consultant, or supplier. Certain consulting engineering companies and universities also offer such certification programs. Specifications that require ACI certification should be specific to identify an acceptable organization to conduct the certification, since ACI does not currently have a program. ACI only publishes the guide which others should use to conduct the certification process.

Contractor Qualifications

Before any production work begins, the contractor must be qualified under a 2-step process. First, the contractor must show that the crew foreman and nozzlemen are experienced in applying shotcrete in applications similar to that planned. This is accomplished when the contractor supplies written proof that the shotcrete crew foreman has at least 5 years experience in shotcrete repair work along with 5 references. The contractor must also provide written proof that the nozzleman has successfully completed 3 projects along with 3 references regarding similar applications (e.g.: similar reinforcement congestion, section thickness, shooting orientation, etc). The written proof must be sufficiently detailed to allow the owner to determine if the nozzleman has the required experience. Generic lists of projects are generally unacceptable, as specified in

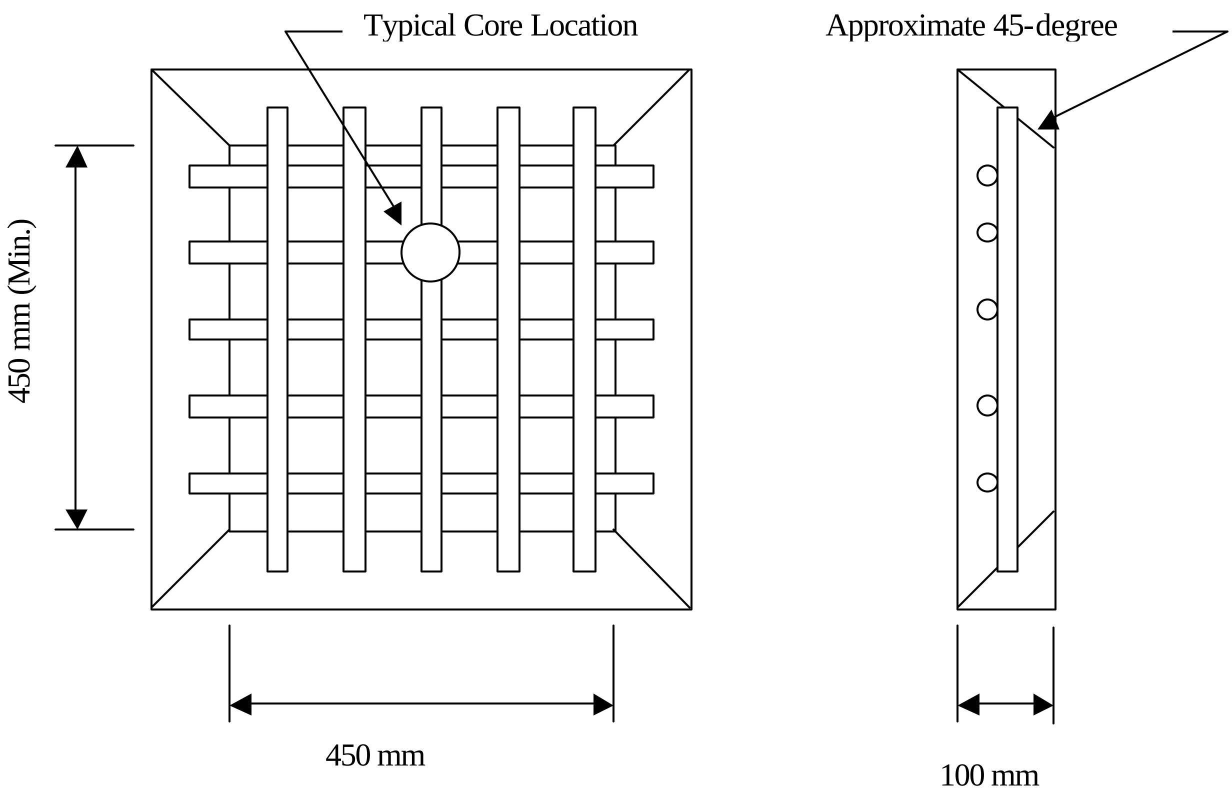

Figure 2.1 Pre-Construction Test Panel

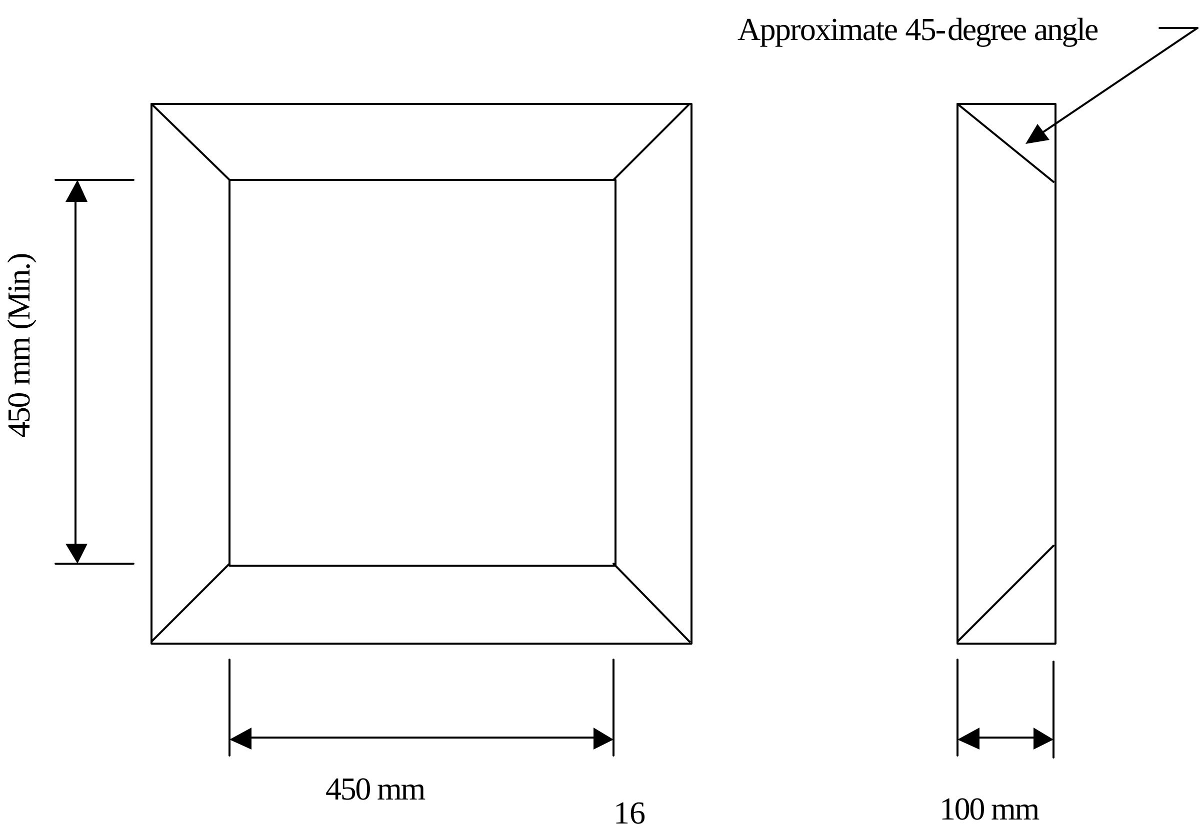

Figure 2.2 Mix Design Test Panel and Construction Test Panel

the contract documents, without identifying the percentage of time that the employee performed the nozzleman duties. Equivalent proof may be acceptable as determined by the Engineer. These qualification provisions may be waived if the State has a prequalification procedure based on performance. The blowpipe operator is also crucial to the quality of the finished product, however, there are no certification requirements. Finishers familiar with shotcrete are essential for both proper strike off and surface finishing, where required or allowed. This is especially true when shotcrete finishing to a ground wire is required.

The second step of the qualification process includes proof of actual shotcrete application in preconstruction test panels. Two types of panels are required, one to qualify the mix design (unless prequalified by past satisfactory experience) and the other type to qualify the nozzlemen and their helpers. (See Figures 2.1 and 2.2) If the panel is large enough to get the cores for both prequalification of the mix and the nozzlemen, only one set of panels may be needed. For the nozzlemen qualification the contractor must set up and shoot a preconstruction test panel with reinforcement and any other obstructions identical to the most heavily reinforced section to be shot in the project. This test panel setup should approximate actual field conditions as close as possible. (See Figures I-2.3 and I-2.4) Cores are taken from an area of intersecting reinforcement to perform core grading and assure appropriate nozzleman technique to achieve good encapsulation. (See Figure I-2.1.)

Figure I-2.3. Shotcrete Application in Mock-Up For Heavily Reinforced Thick Structural Section

Figure I-2.4. Using the Blowpipe to Keep Rebound and Overspray Out of the Mock-Up

Nozzleman Technique

Properly encasing reinforcement with shotcrete is critical for long term performance and durability. Steel bars in the shotcrete mix stream cast a “shadow” behind the steel that is not directly impacted by the shotcrete stream. The size of the shadow will increase as the distance from the receiving surface increases and as the size of the steel increases. The shadow area is not properly compacted if the material stream does not impact it, and voids can develop. To fill in the shadow area behind the bars, the shotcrete must have both good plasticity and sufficient impact velocity so that the material will flow easily around the bar and be spread into the shadow area from compaction. A mix that is too stiff or is not hitting with sufficient impact velocity will build up on the face of the bars creating a larger obstacle and a void will form behind the bars. High impact velocity can to some degree overcome a stiff mix and force material to flow around the steel. Moving the nozzle closer to the work can increase impact velocity. Typically, 0.6 to 1.2 m (2 to 4 feet) is the proper distance. Adding more air at the nozzle can also increase impact velocity. To properly encase steel the shotcrete mix (wet-mix) should have a minimum 50 to 75 mm (2 to 3 inches) slump. The proper plasticity is the key to good encasement. A higher plasticity mix (75 to 100 mm slump (3 to 4 inches)) requires less impact velocity to force the material to flow around to the backside of an obstacle. It is the nozzleman's job to ensure both the plasticity and impact velocity of the shotcrete are sufficient and that the mix does not sag. When the combination of plasticity and velocity is right, the face of the steel will glisten and remain clean. Deformations on the reinforcing bars will be clearly visible. A ridge, building up at the back of the bar, will develop, rather than developing a valley behind the bar.

Encasing bars larger than #5's requires a higher slump. Reducing or eliminating the shadow can be achieved by directing the shotcrete placement at a slight angle from both sides of the bar to force the material behind the bar. The slump generally must be at least 75 mm. The volume of material should be reduced and the nozzle stream directed so material can hit the area directly behind the reinforcement (thereby reducing the shadow area). In some cases the velocity must be reduced and the nozzle brought closer to the work.

Figure I-2.5. Typical Nozzleman Technique

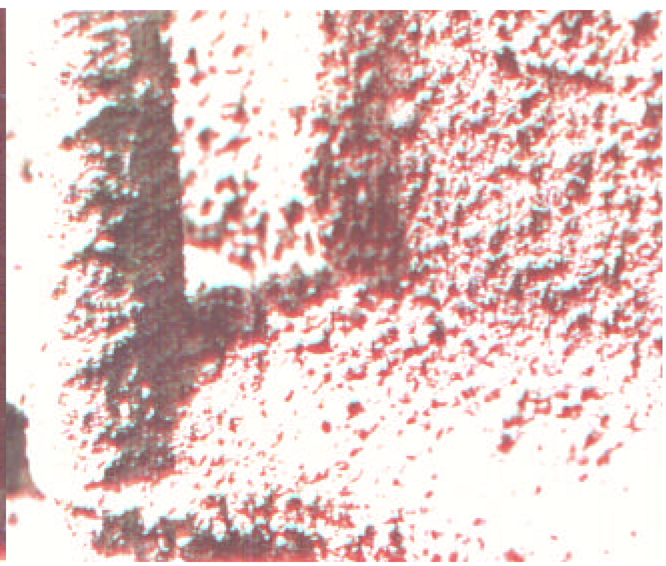

Figure I-2.6. Close-Up of Proper Plasticity Shotcrete for Complete Reinforcement Encasement

Figure I-2.7. Proper Reinforcement Clearance to Substrate

Nozzlemen Qualifications

An essential part of nozzlemen qualifications is the determination of their ability to place dense, homogeneous material. This is done by coring and may also be done by visually inspecting the interior of both the preconstruction and production test panels. From both panels, there must be sufficient length of unreinforced core available for compressive strength testing. The 75 mm diameter cores preferably require a 150 mm long section of unreinforced core although shorter cores may be tested provided core strength correction factors are applied. (See ASTM test method C42.) Even though cores are taken, a preconstruction panel should be saw cut open to examine steel encapsulation and check for any defects, such as sand pockets, entrapped rebound, etc. This panel may be the same one used for approval of the architectural finish, as specified in the contract documents.

Shotcrete Prequalification

The prequalification process is not just for the nozzleman but includes prequalification of the shotcrete mix, the equipment, and the rest of the application crew. A panel or portion of a panel should also be constructed without reinforcement using a mix reviewed by the Engineer to verify it meets specifications. The normal review process for shotcrete mixes is distinct from the prequalification test. The prequalification test panels can be used to verify that the mix will meet a required compressive strength, but the mix should be reviewed for gradation, aggregates, admixtures, etc., prior to the prequalification test, similar to any other concrete mix to be used in structural work.

If the completed work will require a specified finish, the prequalification test panel should be finished by the finish crew and appraised for conformance to the requirements. If the contractor proposes to achieve a finish by application of a separate finish coat (approximately 13 mm (1/2 inch) thick), then the test panel should not be accepted until the finish coat is applied and approved. The finish coat is applied after the previous layer of shotcrete has set up sufficiently. Any curing method proposed by the contractor should be demonstrated on the test panel. If the finished surface requires a radius, the ability to reproduce this radius should be proven during the fabrication of the preconstruction test panel. The method for production of construction joints should also be demonstrated in the preconstruction test panel.

Prequalification should include compressive strength tests. Shotcrete in bridge repair work often has a minimum required f'_c of 28 MPa at 7 days and 35 MPa at 28 days per the *Guide Specifications for Shotcrete Repair of Highway Bridges* or a different strength requirement may be established for a specific project.

The *Guide Specifications for Shotcrete Repair of Highway Bridges* recommends making one non-reinforced production test panel 450 x 450 x 100 mm each day of shooting. The purpose of this test is to assure that the shotcrete mixture meets the specified compressive strength, boiled absorption, and permeable voids when properly shot. The panel is made with the same mix as the preconstruction trial and the production shotcrete. The non-reinforced panel is tested in accordance with ASTM C42. The production test panels are sized to allow sufficient test cores to be obtained. All panels should be labeled as soon as possible after shooting with the date and nozzleman's name.

If a project has more than one cross section to be shot and these sections have significantly different characteristics it is expected that a preconstruction test panel will be made for the cross section which is most challenging or has the most congested reinforcement. The applicable differences include shotcrete thickness, mix design, field application conditions, or reinforcement.

If the work intended is large enough, it is recommended that more than one nozzleman be qualified. For projects where shotcrete application will be continuous for more than 4 hours, having more than one prequalified nozzleman will allow work to continue when the first nozzleman becomes tired or is unable to work. Examination of the saw-cut sections of the panel should show no differences in quality of work.

In summary, the prequalification test consists of 4 goals.

1. Prove the workability of the concrete mix.

2. Prove the mix will meet compressive strength requirements.

3. Prove the ability of the nozzleman and the blow pipe operator, if used, to place dense, homogeneous concrete, and to completely encase the reinforcement under the field conditions to be encountered.

4. Prove that the required surface finish can be achieved.

The following table summarizes the three main elements of shotcrete qualification described in this section.

Table I-2.1 Shotcrete Project Qualification Requirements

Qualification Requirement	Submittals	Preconstruction Test Panel
Mix Design	Mix Design	Non-Reinforced
Crew Foreman	Resume	N/A
Nozzlemen	Resume	Reinforced

On some large very complex projects a mock up of the actual work may be required as part of the nozzleman qualifications process. The details of the mock up should match the actual work and the mock up construction should be done as close as possible to the actual work site and conditions. The main purpose of the mock up is to allow refinements to the shotcrete construction procedures to be made before beginning work on the actual structure.

Chapter 3. Know Your Design

Introduction

Shotcrete is concrete, so it is important to have good understanding of concrete fundamentals.

Concrete is a mixture of two major components: aggregates and paste. The paste, made of cementitious material and water, binds the aggregates into a rock-like mass as the paste hardens. The hardening is a chemical process called hydration, not a drying process, and it can take place under water as well as when exposed to air. Concrete does not harden or cure by drying, because the cementitious material needs moisture to hydrate and harden. When the concrete dries fully, it no longer gains strength.

The paste part of the concrete also contains air, called entrapped air, usually less than 2 percent by volume. Entrapped air voids are usually scattered, comparable in size to the larger grains of sand. Often the paste also contains very small spherical air voids, referred to as entrained air, intentionally introduced into the mix by means of an air-entraining admixture to improve certain properties in both the fresh and hardened concrete.

Shotcrete Mix Design

Below are the important factors that control how concrete develops and gains strength.

1. Temperature and humidity

This includes the temperature of the concrete as mixed and the humidity and ambient air temperature as it sets. Warm concrete hardens faster than cool concrete, but will not get as strong as concrete exposed to cooler temperatures (lower ultimate or final strength). When humidity is low and temperature is high, or the wind is strong, cracks may appear on the concrete surface before it hardens. These cracks are commonly called plastic shrinkage cracks. (This can also happen in cool weather when the relative humidity is low.)

2. Water content in relation to the amount of cementitious material in the mix

Too much water causes concrete to be weaker and to shrink more.

3. Type and fineness of cement

The specifier usually selects one of the five standard types of Portland cement. Although the choice of cement is usually beyond the contractor's control, it often affects work at the site because it can influence workability, setting time, and finishability of the concrete.

4. Accelerating and retarding admixtures

These admixtures change the setting and hardening time of the mix. When properly selected for a particular site and weather conditions, they often make it easier for the nozzleman to do a good job.

Portland Cement

Portland cements are hydraulic cements, which means they set and harden by reacting chemically with water, and they are able to do so under water. During the reaction, which is called hydration, they give off heat as they form a stone-like mass that binds the aggregate particles together. Most of the concrete hydration and strength gain take place in the first month.

Aggregate

The sand, gravel, crushed stone, and similar materials that are mixed with cementitious material and water to make concrete are called aggregates. Fine aggregates are the particles smaller than 5 mm (1/4 inch). If the particles are larger than 5 mm (1/4 inch), the aggregate is called coarse aggregates. Aggregate makes up 60 to 75 percent of the absolute volume of the concrete. Some shotcrete applications use only fine aggregates (along with cement, admixtures, and water).

Water

Adding water to make the shotcrete mix as wet as possible to reduce the labor of placing (but not necessarily the overall labor requirement) should not be allowed. Adding water results in a lower strength and higher permeability of the shotcrete, increases the possibility of sloughing, and may result in shotcrete outside compliance with specifications.

Engineers and specifiers use a term called water-cementitious material ratio to show how much water should go into the mix. This is simply a fraction or proportion arrived at by dividing the mass of water in a batch of concrete by the mass of cementitious material. A cubic meter of shotcrete containing 180 kg of water and 400 kg of cement would have a water-cementitious material ratio of:

w/c=   180 kg water / 400 kg cement =0.45

In the United States this water-cementitious material ratio is sometimes stated as gallons of water per bag of cement. To change from the numerical ratio to gallons per bag, multiply by 11.28. The ratio 0.45 then becomes:

0.45 x 11.28 = 5 U.S. gallons per bag

In proper shotcrete, each aggregate particle is completely coated with paste. Also, all of the spaces between aggregate particles are filled with paste. So if the aggregates are of satisfactory quality, the quality of the shotcrete depends mostly on the quality of the paste. In turn the quality of the paste depends on the water-cementitious material ratio of the paste. For shotcrete mixes that are workable (can be placed with a reasonable amount of effort), those with low water-cementitious material ratios (small amount of water in the paste) are stronger and more durable than those with high water-cementitious material ratios.

Most shotcrete mixes have water-cementitious material ratios between about 0.35 and 0.5. Water-cementitious material ratios lower than 0.4, along with pozzolan or admixtures, are used in low permeability and very high strength shotcrete. And the mix may still achieve the required properties when flyash is used as a substitute for Portland cement.

Avoiding the use of excess water will make stronger, more durable shotcrete. There are other reasons to resist adding water. Shotcrete shrinks as it dries, and this can lead to unsightly cracking. The more water used the greater the shrinkage. Excess water in the shotcrete also increases bleeding, which is the appearance of water on the fresh shotcrete surface as cement grains and aggregate particles start to settle. Increased bleed water may delay finishing.

Mixture Proportions

Unlike the evaluation of conventional concrete mixtures, shotcrete testing is difficult to perform in a laboratory environment. The equipment and application 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.

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 may require significant lead-time, often in excess of 45 days, to attain the required 28-day strength results, or the process could be shortened if the strength is achieved sooner. More extensive testing will add more time to the process. This is not a laboratory exercise but a field production of test panels with actual equipment, personnel, and materials. Test panels should be fabricated as described in paragraph 8.3: Preconstruction Trials of the *Guide Specifications for Shotcrete Repair of Highway Bridges*.

Historical data

Although not covered in the *Guide Specifications for Shotcrete Repair of Highway Bridges*, many States have a procedure for acceptance of concrete mixes based on historical performance. These procedures may be adopted for approval of mixes used for shotcrete as well. Often, test data from materials and mixture proportions that will meet the requirements for the current project are available from previous projects. If past documentation and performance is acceptable, no further preconstruction testing may be necessary. Submittal of the historical mixture proportions and performance data should 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.

Fibers

Steel fiber-reinforced shotcrete

It is critical that fibers be uniformly distributed throughout the mixture. Proper batching procedures and equipment can prevent 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. Consult the fiber supplier regarding the proper sequence of addition of fibers in the batching cycle. Adding the fibers first, before other ingredients, can result in severe balling. Some dry-mix shotcrete projects use prebagged material, including premixed 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 feed systems. Careful calibration of the system is mandatory to achieve proper proportions. Typically when fibers are required, a toughness or flexural strength specification will be included in the project documents.

Steel fiber reinforcement

Steel fibers have been used in shotcrete to increase its ductility, toughness, impact resistance, and reduce crack propagation. Typical steel fiber lengths for shotcrete range from 20 to 40 mm and are used in the amount of 0.5 to 1.0 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 improved load carrying capacity after the member has cracked.

Steel fiber source

Steel fibers are manufactured in several ways. Wire fibers are produced from drawn wire that has been subsequently cut or chopped and deformed. Flat steel fibers are cut or slit from sheets 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.

Synthetic-fiber reinforcement

Collated fibrillated-polypropylene (CFP) and other monofilament synthetic fibers are used in shotcrete. Typical fiber lengths of 20 to 40 mm have been the most common in use. The common application has been 1 to 2 kg/m^3. The primary benefit is to control thermal and plastic shrinkage cracking. Synthetic fiber doses of up to 18 kg/m^3 with monofiliment fibers and special mix designs have been used successfully yielding shotcrete toughness performance approaching that of some steel fiber shotcretes (Morgan et al. 1998). Rebound is generally reduced when polypropylene is used.

Applicable technology

ACI 506.1R, "State-of-the-Art Report on Fiber Reinforced Shotcrete" (ACI 1991e), is being revised and will provide comprehensive information covering the full range of fiber shotcrete technology.

Reinforcement

Even though it takes special care by the nozzleman to ensure proper encapsulation of reinforcement by shotcrete, reinforcement should not be left out of most shotcrete since it is required for tensile and shear strength, crack control, and durability. It is common to provide welded wire mesh in shotcrete, even when conventional reinforcing bars are used. The mesh is usually galvanized with square openings of 50 to 100 mm with wire sizes W2.1 to W0.9. The mesh provides crack control and helps tie the shotcrete to the receiving surface as long as it is properly anchored. Whether mesh or conventional bars are used, the reinforcement must be securely tied and held in the proper configuration. It must be able to withstand the pressure of the shotcrete stream without moving or vibrating excessively.

Conventional bars are used when required for strength of structural sections. Number 15M and smaller size bars can be encapsulated with normal care. Larger bars have been successfully used, but the work should be inspected carefully to assure good nozzleman techniques are being used.

Fibers can provide crack control and add strength, depending on the amount and type of fibers used. When used, anchorage is still required. Fibers have been successfully used in combination with conventional bars and with mesh.

Anchorage

The inspector must be aware that variations in the thickness of applied shotcrete may be significant if they become deeper than envisioned in the project design. Thicker repair sections normally require tiebacks to fully designed anchors. Standard design practice should require "mechanical tie-back" and reinforcement of any shotcrete repairs more than about 40 mm deep. This is because the long-term performance of a shotcrete repair is totally dependent on:

a. No delamination occurring at the shotcrete/concrete bond interface, and
b. No continuing deterioration occurring in the substrate concrete

The provision of mesh or other forms of reinforcement provides thermal and shrinkage crack control in the shotcrete. The use of anchors provides restraint against curling induced delaminations and also provides a safety factor against pieces of delaminated shotcrete becoming dislodged and falling (thermal, shrinkage and vibration induced stresses can precipitate dislodgement). See Photo P10.

Construction Sequencing

Construction sequencing is always a key factor in planning for a successful project. But there are some unique aspects of shotcrete work that the inspector should verify has been taken into account by the contractor, which can impact the owner, overall safety, and traffic. Structural shotcrete work in general proceeds from the bottom up. Installation of a finish coat generally proceeds from the top down. Access for structural work will often require a different setup than for finish work. Protection from overspray should be addressed from three aspects, the work itself (both finished work and prepared surfaces for upcoming work), the workers, and traffic. In addition to overspray, the work should be protected from traffic vibrations, if possible. The number of layers required to achieve full planned thickness of shotcrete and any finish coats should be considered in the timing of traffic stages, and other phases of the project. Cure time can have a significant impact on production rate and should planned into the schedule early in the project.

Figure I-3.1. Positive Anchorage of Reinforcement to Substrate

Chapter 4. Corrosion Protection Considerations

Introduction

Long-term performance of shotcrete repairs depends on the ability of the finished material to withstand corrosive attack from the environment. Corrosion protection is an integral and extremely important aspect of shotcrete repair and of inspection procedures.

The common methods of corrosion protection are complete cleaning and proper preparation of the surface, proper cover, adequate anchorage, low permeability shotcrete mix, surface sealers, or a combination of these. Each measure results in keeping the new or existing steel from the corrosive environment and maintaining the passive property of cementitious shotcrete mixes as long as possible. Corrosion protection measures are normally carefully considered in the design stage and should not be changed during construction without engineering approval.

Corrosion Resistance of Mixes

Adding silica fume to shotcrete results in dramatic reductions in chloride diffusion rate. NCHRP Project 18-3 found that with silica fume content of 6-8 percent chloride diffusion will be reduced by a factor of three or more. Further addition of silica fume provides little additional benefit. Good experience has been achieved using steel fiber reinforced, silica fume shotcrete with water cementitious material ratios below 0.4 in direct marine applications for periods up to 15 years, so far.

Sealers and coatings have similar effectiveness as they do on concrete. Penetration is normally limited to the top 1 mm and any abrasive action on the surface will limit the effectiveness of the sealer to a very short time. Most coatings require reapplication within a few years to maintain their effectiveness.

Chapter 1. Field Quality Control of Materials

Introduction

The four basic elements of quality shotcrete are experienced, qualified crew members, control of materials, care and inspection during shooting, and testing of production test panels. The last two require a full time on site inspector who understands shotcrete materials and shooting procedures. After production begins the inspector's role is to observe preparation of the test panel, observe the shooting, and dig out small sections of shotcrete occasionally to verify complete encasement and proper compaction.

Materials Control on the Project

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.

Aggregate 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 whenever there is a change in appearance or performance of the material.

Aggregate Grading

The grading of each aggregate group should be verified by testing according to 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.

Aggregate Moisture Content

The moisture content of each aggregate group of wet-mix shotcrete must be known to calculate the amount of free water to be added to each batch of shotcrete and to adjust the mass of aggregate batched. The moisture contents should be established prior to the start of each shift and whenever a change is made in stockpile sources.

Admixtures and Curing Compound

Manufacturers' certificates of compliance for any admixture or curing compound should be furnished at a specified interval and whenever there is a change in the appearance or performance.

Field Handling and Inspection of Shotcrete Materials

Shotcrete is very sensitive to the amount of water in the mix and the water-cementitious material ratio. The inspector should verify that the contractor is using adequate storage protection to keep shotcrete materials at a uniform moisture. This is true for both wet-mix and dry-mix, but is especially true for dry-mix materials because it is very difficult for the nozzleman to maintain shotcrete consistency when the aggregates or prebagged materials are not kept at a uniform moisture content.

Reinforcing Bars and Welded Wire Fabric

To encase pre-placed steel such as reinforcing bars or mesh, the shotcrete has to either flow around or be directed behind the steel. The larger the bar the more difficult it is to adequately encase with shotcrete. With careful attention large bars can be adequately encased. Parallel bars should be spaced at least two bars diameters apart. Contact splices should be avoided since a contact splice doubles the size of the obstruction. At all times, reinforcement should be secure and not vibrate during shooting. Vibration of reinforcement will create cavities around the steel. Reinforcement should be clean and free of set overspray and rebound. Reinforcement must be placed so there is adequate coverage and clearance as required by the contract drawings. (See Photo P9) Reinforcement bar sizes and spacing should be checked prior to encasement.

Where welded wire mesh fabric is used, it should be placed as shown on drawings. Where sheets of mesh overlap, the mesh squares should be staggered to minimize obstructions. At corners where three or more sheets overlap, cut out excess layers. Proper support of fabric is important. Loose fabric will move when shot.

Steel Fibers

Both steel and nonmetallic fibers can be used in dry-mix or wet-mix shotcrete. They improve the tensile strength, increase toughness (if sufficient quantity is used), improve crack control (if sufficient quantity is used), and improve impact resistance of the shotcrete. There are many different manufacturers of fibers. Always follow the manufacturer’s recommended instructions. In particular, the nozzleman must pay attention to an even distribution of the fibers. Don’t allow the fibers to ball-up. If a lot of the fibers are lost as rebound, the shotcrete won’t be as tough as designed. For dry-mix, shooting too dry will significantly increase the rebound and loss of fibers. As overall shotcrete rebound increases, fibers loss increases. Safety goggles are particularly important when shooting steel fibers. Steel fibers can be dangerous and cause injury.

Synthetic Fibers

As with the steel fibers, when working with synthetic fibers follow the manufacturer’s instructions. Once again, look for even distribution.

Production Testing

Like any other product that goes into the work, shotcrete is tested to assure the quality of the finished product. Testing is done on test panels made before any production work begins and on test panels made periodically during the production work. Tests of the completed in-place shotcrete product is normally only required when a production test panel fails one of the required tests. This testing is intended to prove the quality of the workmanship and the finished product by testing the procedures and nozzleman's abilities before and during the project. Normal testing of the in-place work is by visual and non-destructive methods such as sounding, and by carving or digging out a section of freshly applied shotcrete when defects are suspected, the nozzleman's technique is suspected, or to perform a routine verification of proper nozzling.

Figure II-1.1. Production Test Panels using Dry-Mix Shotcrete

Figure II-1.2. Production Test Panels using Wet-Mix Shotcrete

Compressive strength values of test panel cores or, when necessary, of cores from the completed work, can provide an indication of uniformity of workmanship. Normally you can expect shotcrete to have higher compressive strength values than conventionally placed concrete due to lower water-cementitious material ratios and higher cementitious material content. When compressive strength values vary excessively, it is an indicator that the workmanship was not consistent. This warrants a closer look at the quality of a production core. Varying values of f'_c alone, with no other indicators, would not be a cause for concern, provided the specified f'_c has been reached.

Quality Control (QC) specifications will require the contractor to provide testing of the production test panel cores. If testing of in-place production shotcrete is necessary based on failure of the test panel cores, the payment will be as specified in the specifications, usually depending on the outcome of the test.

Nozzleman Qualification

Specifications typically require either a minimum experience or certification of Nozzlemen. The standard for Nozzlemen certification is ACI 506.3R. However, that document only represents a procedure for doing the certification. The American Concrete Institute (ACI) does not actually conduct the certification tests or issue certificates for nozzlemen. Specifications that require ACI Nozzlemen certification should indicate which agency or organization is acceptable to the owner to perform the certification process. It may be done by the specifying agency, the contractor, an independent laboratory, or private organization. The intent of ACI 506.3R is that some training and hands on application will accompany the certification process. In order to receive the certification, a written test and workmanship demonstration should be required.

In lieu of certification a minimum amount of experience may be specified. Typically, specifying agencies will require documentation of the experience and the names, addresses, and phone numbers of qualified references for checking the quality of previous work.

Chapter 2. Construction Monitoring

Introduction

Shotcrete is an inspector intense operation. Shotcrete is relatively new to bridge work in some states and some agencies do not have years of experience to fall back on for advice. Shotcrete inspectors should take an active part in the shotcreting process, and they should insist on a quality product. When in doubt, dig (or carve) it out. Inspection by digging out suspected areas can keep the crew alert. However, excessive digging out can disrupt the production, so it should be done judiciously. Dug-out areas can be easily reshot by the shotcrete crew without any significant delay to the work. This is one of the advantages of shotcrete, instantaneous inspection of the freshly placed material as long as it does not hinder the progress or quality. Inspectors should be cautious about unnecessarily digging out areas of completed work that are not suspect, especially if no flaws were found previously.

Construction Testing

Production cores are taken from the production test panels. If those cores fail any of the required tests, cores should be taken from the completed work after the cure period is complete. The purpose of the production core is to provide test samples for compressive strength, boiled absorption, and permeable voids testing. Three cores are required for each test to determine the mean value.

When cores are required from the completed work, cores should be taken at locations that test the quality of shotcrete in the most difficult sections to place. The inspector should use the provisions of ACI 506.4R as a guide. The major area of concern is behind reinforcement, especially at the intersection of reinforcing bars and in acute corners. Production cores should be taken randomly within the following guidelines:

- Production cores from completed work are to be laid out close enough to the reinforcement intersections to show any shadowing behind the bars.
- Obviously there will be occasions when the reinforcement will be cut or nicked.
- Cored holes should be patched without repairing cut or nicked reinforcement.
- Avoid cutting through critical structural reinforcement. Only take cores at locations approved by the Engineer.

Surface Preparation

Any shotcrete repair is only durable if there is adequate substrate preparation. The surface to which shotcrete is to be applied must be inspected to insure that satisfactory conditions exist prior to application. Shotcrete bonds well to properly prepared surfaces without the use of bonding agents. The surface must remain clean (free of set overspray and rebound) immediately before and during shotcrete application. The best substrate preparation is one that is sound, free of a damaged or "bruised" surface layer, and rough. One measure of roughness that has been used is surface roughness profile (SRP). One possible requirement for the SRP is as follows:

A) Three peak-to-valley measurements of 5 mm exist in 150 mm of measured length, or

B) Five peak-to-valley measurements of 4 mm exist in 150 mm of measured length.

C) Some states have investigated the use of ASTM E965 with a 2 mm macro texture specification and found it to provide satisfactory adhesion to concrete substrate.

D) Some agencies are now specifying International Concrete Repair Institute (ICRI) profiles, e.g. C.P.9.

SRP's should be checked on a systematic basis by the quality control inspector throughout the project using a simple profile gauge (movable tooth comb-like tool).

Extensive testing has demonstrated that the highest bond strengths (and most durable bond) is achieved with surfaces which are prepared by:

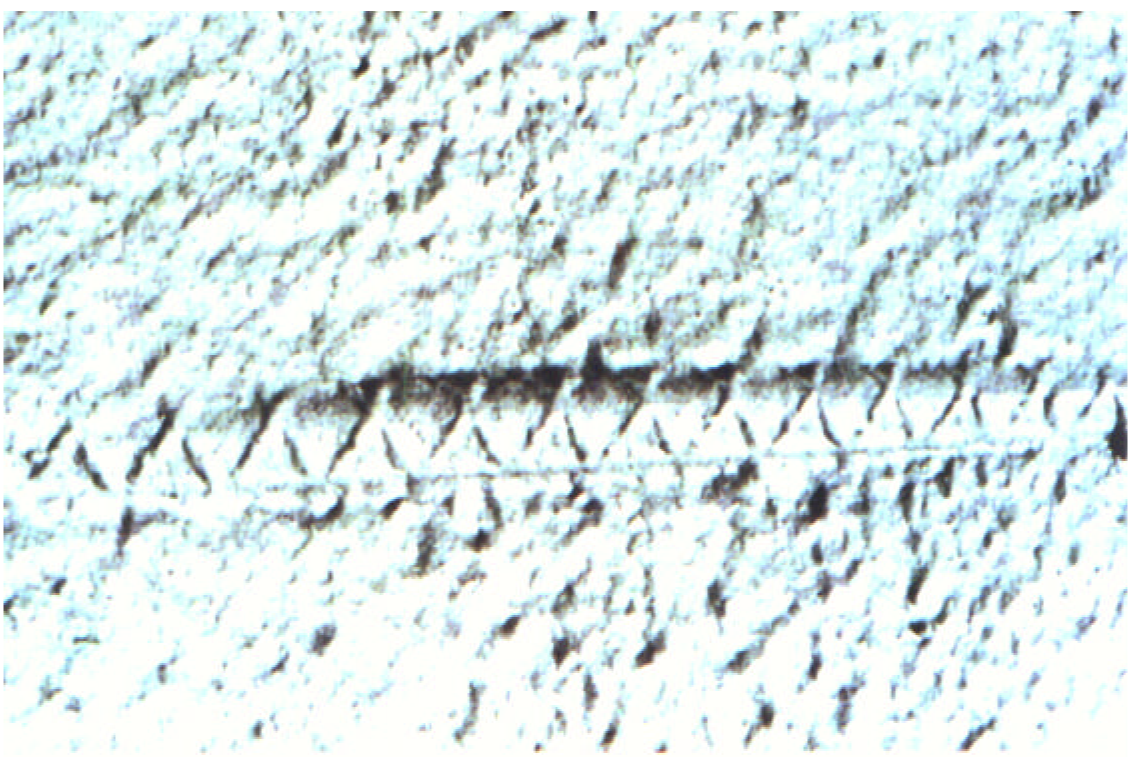

Figure II-2.1. Good Texture from Proper Surface Preparation

Figure II-2.2. Good Intermediate Surface Texture from Scoring

1. High pressure (minimum 30 MPa) water blasting,
2. Chipping (with light duty chipping hammers) followed by grit blasting or high pressure water blasting to remove the "bruised" surface layers, or
3. Grit blasting only.

Chipping alone, or abrasive blasting alone, with a non-grit medium (without development of an adequate SRP) result in either lower bond strengths, or a reduction in bond over time. Abrupt changes in thickness should be avoided. In the case of an area repair of concrete (patch), the edge of the repair should not be feathered. The edge of the repair should be either saw cut to a minimum of 13 mm, or chipped nearly perpendicular to the finished surface.

It is recommended that the concrete substrate be saturated with potable water for at least 24 hours prior to shotcrete application. Immediately prior to shotcrete application the substrate concrete should be brought to a saturated surface dry (SSD) condition. If the surface is too wet (has free-standing surface water) this can be detrimental to good bond, by creating a high water-cementitious material ratio at the shotcrete/concrete bond interface. Excess free surface water can be removed by blasting with oil free compressed air or waiting in a natural drying environment. If the substrate concrete surface has dried back excessively, it can be readily brought to an SSD state by fogging and misting with an air/water pressure sprayer. It has been found that maximum bond is achieved when the substrate is in a SSD condition. Excess free surface water can be particularly damaging to good bond.

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. Complete bonding of the shotcrete layer to the underlying stratum is essential for proper performance and longevity.

Ambient Conditions

Shotcrete, like concrete, dries and shrinks or contracts in all directions as it hydrates and must be protected and cured. Fresh shotcrete must also be protected from hot and cold weather. Shotcrete can generally be safely placed when the temperature is 40 degrees F (5 degrees C) and rising. Placement should be stopped when the temperature is 40 degrees F (5 degrees C) and falling. Accelerators may be used when allowed by the specifications, but they can reduce the long-term strength and durability of the shotcrete exposed to freeze-thaw cycles. When placing shotcrete in cold temperatures, the mix temperature should be kept above 50 degrees F (10 degrees C) to assure hydration will take place. When the substrate temperature is below 50 degrees F (10 degrees C), the shotcrete hydration may be slowed. Thin sections of shotcrete are especially sensitive to low temperatures. Shotcrete must be protected from freezing with blankets or heated enclosures until it gains a strength of at least 5 MPA, or it will be damaged and only achieve a small percentage of its design strength.

Generally, shotcrete mixes have a high cementitious content that produces a lot of heat. Precautions must be taken in working with shotcrete in hot weather. Generally shooting should be suspended when the temperature reaches 38 degrees C (100 degrees F). The nozzleman must pace the work to allow finishers to keep up or add more finishers to the operation. Shade and fogging are effectively used both before shooting to cool the substrate and after shooting to minimize cracking due to plastic drying shrinkage and thermal stress. Excessive heat and lack of adequate curing will result in cracking and reduction of potential strength.

Wind can result in a reduction in shotcrete strength when it causes a separation of the cementitious material from the aggregate as dry-mix shotcrete exits the nozzle. Barriers should be erected to minimize the effect of wind and minimize moisture loss during shooting and curing. Shotcrete operations should be suspended if adequate protection cannot be provided. Wind can also cause premature surface drying resulting in plastic shrinkage cracking.

To minimize plastic shrinkage cracking the following measures can be taken:

1. Dampen the substrate prior to shooting, but do not have running water on the substrate surface at the time of shotcreting.
2. Erect sunshades in hot weather to keep the sun from overheating the shotcrete surface.
3. Erect windbreaks to protect the shotcrete surface.
4. Plan ahead to avoid delays so that shotcrete can be deposited as soon as possible after it is mixed. Prolonged mixing and agitation will raise the shotcrete temperature especially if in direct sunlight.
5. Lower the temperature of the wet-mix shotcrete in hot weather by adding ice as part of the mix water and sprinkling the aggregate piles with water.
6. Work at night.
7. Use a surface retardant and/or finishing aid.

8. Start curing immediately after finishing the shotcrete. Use fog sprays or covers such as damp burlap covered with plastic, plastic coated fabric, or water-saturated curing blankets (ASTM C171).

Shotcrete Application

Shotcrete can be applied on overhead, vertical, or horizontal surfaces. It can be applied to earth, wood, concrete, or shotcrete surfaces. Shooting techniques vary depending on the shotcrete system (wet or dry-mix), location, thickness, type of surface and whether or not steel reinforcement must be encased.

As the shotcrete exits the nozzle, the mix stream fans out. The material in the center of the stream travels the shortest distance and hits the receiving surface with the highest impact velocity. At first the aggregate ricochets off the receiving surface until sufficient paste builds up to provide a bed into which the aggregate can stick. The impact of the shotcrete stream compacts the shotcrete. The indirect stream, that part of the stream that fans out, hits the receiving surface slower and at an angle. Some of the indirect stream ricochets away creating overspray and rebound. Overspray attaches to nearby ledges and reinforcement. Overspray is comprised of fine and coarse aggregate with a small amount of cement. Rebound is predominately aggregate that ricochets off the receiving surface and falls onto lower surfaces. Rebound and overspray have just enough cement to be sticky. There is not enough cement paste in either rebound or overspray to fill the voids between the aggregate particles. Consequently, both rebound and overspray are porous and weak. Rebound must not be incorporated into the work. A fine layer of fresh overspray can be incorporated into the shotcrete during shooting, without any detrimental effects, provided it is thin (say less than 0.5 mm thick) and covered immediately. Overspray is controlled by shooting first into corners, shooting perpendicular to the receiving surface, and cleaning any area that accumulates overspray prior to shooting that area. Rebound can be controlled by shooting perpendicular to the receiving surface and by using an blowpipe to clean away the rebound.

The nozzle should be held about waist to shoulder height. To balance the thrust of the shotcrete nozzle stream the nozzleman typically braces himself by placing one leg to the rear. A common stance is for the nozzleman to straddle the hose, i.e. stand with his legs on either side of the hose. Other shooting positions may be required for unusual access locations. The nozzle is held so that the shotcrete is placed perpendicular to the receiving surface to maximize impact velocity. Shooting at an angle greater or less than 90 degrees to the receiving surface increases both rebound and overspray and reduces the area adequately compacted by the shotcrete stream.

During the application it is important that the blowpipe operator keep up with the nozzleman. If the blowpipe air hose becomes snagged or for some reason air stops flowing, or if the blowpipe operator cannot keep up with the nozzleman, the nozzleman should stop until the problem is solved and the operation can continue properly. The blowpipe operator is responsible for blowing all of the loose aggregates (aggregate that hasn't become embedded into the mass) from in front of the nozzleman. This eliminates trapped aggregate pockets and non-homogeneous shotcrete. The blowpipe can also be used to blow any grout buildup off of the reinforcement that might set before encasement. The blowpipe needs to be maneuverable and will typically be shorter and smaller in diameter than the blowpipes used to clear debris from forms prior to a placement.

Following the nozzleman and the blowpipe operator will be a finisher/rodman with a rake. This rake is a short piece of 10 mm (3/8 inch) reinforcement or rod stock with a short (say 100 - 150 mm) 90 degree bend at the end. This tool is used to rake a sloping face (sloping from the back to the front). If the raked surface will become a shotcrete construction joint, the exposed layer of material should still be sufficiently plastic to allow the next lift to consolidate itself into the sloping face, or the exposed layer should be left in a clean and roughened condition.

After raking, the finishers/rodmen follow with long strike off cutting screeds (sometimes called rods) or finishing trowels. These are used to cut the wet material back to the ground wire or forms and control the finished dimensions. At locations where a thin wire will not hold the shape desired (a curve for instance), a 6 mm (1/4 inch) diameter spring steel rod (usually referred to as a pencil rod) is often used.

Sloped, vertical, and overhead surfaces should be watched to ensure there is no sloughing after the finisher/rodman passes. If the mix is too wet or is built-up too quickly it can slough. Typically the shotcrete will slough back to the reinforcement mat. The sloughed material must be cleaned out and reshot. Areas of sloughing should be referenced and later sounded with a hammer to ensure there is no delamination of the reinforcement cover in the hardened shotcrete. The foreman should be advised to correct any placement problems before proceeding. Corrective actions could be to place

Figure II-2.3. Using the Blowpipe to Keep Rebound and Overspray Out of the Work smaller lifts, delay the timing between subsequent lifts, use a stiffer shotcrete mix, etc. Sloughing of vertical surfaces can occur with any application but is more likely to occur on walls less than 20 m (50 feet) long when the lower lift does not set up sufficiently before the nozzleman returns and placement begins on the next lift.

One of the advantages of shotcrete is that the inspector has the ability to carve out areas of suspected or anticipated problems for an instant look. On any surface large enough to require the application crew to move, this should be done without hindering the progress of the work and can be quickly repaired on the next pass. Carve outs should be timely while the shotcrete is still fresh so that the rake out can be easily and quickly repaired. On smaller surfaces any rake out may slow the operation but the inspector needs to verify that the application is dense and homogeneous. An understanding about the procedure for rake outs should be discussed in advance with the foreman.

On projects with a double mat of reinforcement this may require placing the nozzle through the front mat of reinforcement and shooting from the sides of large bars to properly place shotcrete behind the bars. Where the reinforcement is congested or the placement is very thick, special placement procedures may be required.

Initially, the percentage of rebound is large but becomes less after a cushion of fresh shotcrete has been built up. While rebound contains some cementitious paste, it consists mostly of the coarser aggregate particles. Consequently, the cementitious material content of the in-place shotcrete is higher because of aggregate loss from rebound. This increases the strength of the shotcrete, but also increases the tendency toward shrinkage and subsequent shrinkage cracking. Rebound must not be worked back into the construction by the nozzleman. If it does not fall clear of the work, it must be removed. Trapped rebound, if not removed, creates sandy, porous areas and laminations in the cross section which are a great detriment to shotcrete quality. Rebound should not be salvaged and included in later batches because of the danger of contamination. Also, the cementitious material content, state of hydration, and the grading of the aggregate in rebound are all variable and unpredictable.

Shotcrete operations pose the threat of injury from high velocity particles of rock, cementitious material, and dust striking eyes and other exposed areas of the body. Rebound particles constitute the same type of hazard as the materials in the shotcrete stream, but to a lesser degree since impact on the surface usually reduces their velocities. Suitable headgear must be worn in the vicinity of the nozzling operation. The nozzleman is less likely to be injured than a workman who stands close to the nozzle but at an angle to the material stream. Use of protective clothing and safety equipment will help prevent serious injury from rebound.

Evaluation of Shotcrete and Mix Performance

Shotcrete is a method of shooting concrete at sufficient velocity to ensure proper compaction. Good shotcrete is similar to high quality concrete with a water-cementitious material ratio between 0.35 to 0.45. Shotcrete quality is a function of its mix proportions and compaction that occurs during placement. Proper compaction is needed to achieve good quality shotcrete.

Dry-Mix Shotcrete: Dry-mix shotcrete is the process in which most of the mixing water is added at the nozzle. A typical mixture without coarse aggregate is approximately 1 part cement to 4 parts of sand by mass

(1:4 mix). Although mix designs are usually based on mass proportions, some equipment measures both aggregate and cement by volume. The aggregate free-moisture should be around 3 to 5 percent. If there is too much water in the aggregate, the dry cementitious material/aggregate mixture will clump and plug either at the gun or in the hose. If there is too little moisture the shotcrete will be dusty and porous. Because there is always some moisture in the aggregate the mixture should be shot within 45 minutes after mixing (Temperature may alter this time). It is important that the aggregate and cementitious materials are thoroughly mixed. In some cases, prebagged materials are used. If so, mixing is not required. The dry-mix process is typically dusty since most of the water is not added until the mixture reaches the nozzle. Predampening of the mixture will reduce dust, improve mixing and reduce static electricity at the nozzle. Predampening is especially important with prebagged materials since they are drier. Prebagged mixes are used for special mixes such as refractory, silica fume and accelerated set shotcrete or for special durability when tight quality control is required by specification or there is a special concern about proportions. Prebagged mixes have a higher uniformity of materials. Dry-mix compressive strengths vary depending on the mixture, but typically range between 40 and 70 MPa.

To get the right amount of water in the mix the nozzleman adds water by adjusting the water valve on the nozzle until the surface has a slight sheen. If the nozzleman does not provide enough water the surface will be dry and sandy. Rebound will increase dramatically. If the nozzleman adds too much water the material will become runny or sag and not stay in place. A properly trained nozzleman can easily see if the mix is right.

Wet-Mix Shotcrete: Wet-mix shotcrete is the process in which the ingredients, including water, are mixed before introduction into the delivery hose. Typically shotcrete is delivered in a ready-mix concrete truck and the mix has been designed for the particular application. Accelerator, if used, is normally added at the nozzle. A good wet-mix mixture has three qualities. A wet-mix mixture must have aggregate (stone and sand) that is well-graded (uniformly different size particles), sufficient paste for pumping, and sufficient plasticity to encase reinforcement.

Proper aggregate gradations minimize bleeding and enhance pumpability. If the aggregate is gap graded (aggregate that is largely one size), the finer sand particles will bypass the larger aggregate and water will separate from the mix creating bleed water. When bleed water is squeezed from the mix, the aggregate jams creating a plug in the line. A mix that is over sanded (too much sand, sand that is too fine, or not enough coarse aggregate) may be subject to frequent plugs and will result in lower strengths and lower durability.

The other important characteristic of a good wet-mix shotcrete is sufficient paste (cementitious material and water). The paste must coat all the aggregate and provide a lubricating film to “slick” the hose lining as the shotcrete slides through the hose. Smaller lines need more lubricating paste to coat the line. Small aggregates have greater surface area than larger aggregates and so need more paste. Shotcrete mixes typically use small aggregate. Shotcrete mixes require more paste than typical concrete mixes to coat the increased surface area and slick the pump line for wet-mix shotcrete.

To properly encase reinforcement the wet-mix must have sufficient plasticity/consistency (slump) so the material will easily flow around reinforcement. If the shotcrete mixture that arrives in a ready-mix truck is too stiff, water or chemical admixtures may be added, provided the specified water-cementitious material ratio is not exceeded and specifications allow the addition of water after initial mixing. If water cannot be added and the mix is too stiff, the mix must be redesigned. Adding water increases the water-cementitious material ratio and that reduces the strength. Added water also increases shrinkage and cracking. Generally four liters of excess water added to a cubic meter will reduce the strength of the concrete approximately 1.4 MPa. If water is added, only enough water should be added to keep the mix plastic so it will pump easily and flow around reinforcement. For different sizes and types of aggregates, there is a specific amount of water that allows a mix to be pumped and still be stiff enough to adhere to a vertical surface or stack. A well graded wet-mix with sufficient paste to pump easily produces compressive strengths between about 30 and 50 MPa at 28 days.

A slump test is used as a measure of wet-mix shotcrete consistency/workability, which relate to the plasticity of a mix. All tests must be performed in strict accordance with ASTM procedures in order for the test to be meaningful and repeatable. Nozzlemen should be familiar with the slump test. Proper slump/plasticity of the wet-mix mixture is important during application. A high slump may result in sagging and sloughing. A low slump may result in a mix that will not pump or flow readily around reinforcement. Typically a mix with a slump of 50 to 75 mm works best. Lower slumps require higher impact velocity to force material around obstacles. Slumps under 40 mm will usually not result in properly encased reinforcement. Low slump shotcrete is used to build out thick non-reinforced sections. Mixes with a slump greater than 100 mm will not stick to a vertical wall or stack and will sag under reinforcement. Uniformity of slump (i.e., having the same slump load after load) is also important.

Wet-mix shotcrete exposed to freezing and thawing should have at least 8 percent entrained air in the mix before being discharged into the concrete pump. Air is entrained shotcrete by adding an air-entraining agent to the wet-mix shotcrete before pumping. An air-entraining agent is an additive that creates tiny (microscopic size) air bubbles in concrete. The bubbles are beneficial in several ways; they make the shotcrete more resistant to freezing and thawing damage and they improve its pumpability. About half the entrained air is lost in the shooting process. The shotcrete process however, entraps some air so a typical air entrained shotcrete mix, after placement, will have about 4 percent entrained and entrapped air.

Wet mix should be typically used within 90 minutes of the first water addition (job specifications govern the exact time). Temperature also affects the usable time. Because of the typically higher cementitious material contents for shotcrete, hot weather may dictate shorter useable time. Adding water to maintain slump should not be permitted. Slump can be reinstated with suitable chemical admixtures, e.g. superplasticizers or hydration controlling admixtures, if permitted.

Surface Finishing

Shotcrete can be finished to a pleasing appearance similar to cast-in-place concrete. It is important that the finish method proposed be demonstrated during the construction of the preconstruction test panel. The natural gun finish is preferred from the standpoint of both structural soundness and durability. Further finishing may disturb the section, harming the bond between the shotcrete and reinforcement or between the shotcrete and the underlying material, and creating cracks in the shotcrete. Less finishing is better. A wood or sponge float finish is preferred to a steel trowel finish. However, the natural gun finish is unacceptable for most visible portions of structures because of the roughness of its appearance. Where greater smoothness or better appearance is required, special finishes, as specified, must be applied. These include (in order of desirable affect on durability) gun finish, rodded finish, flash shotcrete finish, wood float finish, sponge float finish, and steel trowel finish (lightly brushed). Finer finishes are generally more costly and may affect the surface durability.

On large surface areas it may be economical to first apply the design structural thickness with shotcrete and apply a scratch finish, i.e., a rough texture that will provide acceptable bond for a finish coat. The finish coat is then applied later to the cured, prepared surface. Typically this finish coat will be about 13 mm thick. The use of a non-fiber reinforced finish coat is common when fibers are used in the repair shotcrete.

Curing

Proper curing of shotcrete is extremely important to ensure proper hydration, matrix and bond strength development, and to prevent cracking, curling, and delamination due to drying shrinkage. The rate of bond strength development is significantly slower than compressive or tensile strength development. The moist curing procedures of ACI Standard 308 (paragraph A-1. ACI (1991c)) should be followed. Thin sections sometimes used in shotcrete construction are particularly susceptible to drying shrinkage and curling. Surfaces should be kept continuously moist for at least 7 days. After this time interval, the shotcrete will normally have gained sufficient tensile strength to resist the shrinkage strains that cause cracking and curling, and the permeability near its exposed surface is low enough to minimize loss of water from the interior of the section. Membrane curing is only permissible when drying conditions are not severe, where no additional shotcrete or paint is to be applied, and where it is aesthetically acceptable. Coverage rates of membrane curing compounds on rough shotcrete surfaces should be twice that used on conventional concrete surfaces.

Silica-fume shotcrete must always be continuously moist cured to prevent plastic shrinkage cracking and assure proper strength gain and surface durability. NCHRP Project 18-3 found that when concrete is cured for 7 days under continuous moist conditions, there is no statistically significant effect of silica fume on the tendency of the concrete to exhibit early-age cracking. The use of fogging nozzles can be very helpful in maintaining a moist condition on all new surfaces. Sprinklers and soaker hoses can also provide adequate curing so long as it can be assured that all the surface area is maintained in a moist condition. The use of water-saturated burlap, covered with plastic sheets or plastic coated water-saturated geotextile fabrics can also be appropriate for certain structures. The use of fibers in shotcrete has no significant effect on the effectiveness or requirements of curing.

Figure II-2.4. Gun Finish Surface as Shot

Figure II-2.5. Gun Finish Surface Close-Up

Figure II-2.6. Wood Float Finish on Bridge Curb

Figure II-2.7. Completed Steel Trowel Finish Using Steel Wire for Alignment

Bond Testing

Shotcrete properly applied with sufficient compaction on well-prepared substrate usually develops bond strength greater than 1.0 MPa. Bond strength tests for dry-mix and wet-mix shotcrete with various types of substrate preparation indicate that the surface preparation has more influence on bond than the mix composition. Best results have been obtained with hydro milling, gritblasting only, or chipping with light jackhammers followed by gritblasting. A saturated surface dry substrate at the time of shotcrete application also increases the bond strength. Excessively dry or wet surfaces at the time of shotcrete application reduce bond strength. See the table below.

Table 2.1 Representative Shotcrete Bond Strength in MPa*

Shotcrete Type	Hydro Mill	Gritblast	Grinding	Jackhammer	Jackhammer + Gritblast
Dry-mix	1.57	2.03	0.18	1.28	1.68
Dry-mix w/ silica fume & fibers	1.97	2.31	0.83	1.07	1.91
Wet-mix (Average)	1.59				

*Reference 5

Chapter 3. Contract Documentation

Measurement and Payment

The Guide Specifications recommend payment for shotcrete by the cubic meter of in-place material. If the grid spacing is not specified in the contract documents, the inspector and contractor should agree on the measurement method and depth measurements after the removal is completed and before shotcrete is placed. Paying for in-place material avoids the necessity of keeping track of waste material and material supplied. The measurement of the quantity is time consuming, but will avoid many potential disagreements about the quantity of materials supplied and wasted. The selection of the grid spacing for measurement will depend on the uniformity of the removal. This method of measurement requires that the inspector also monitor the removal of deteriorated concrete to ensure excessive amounts are not unnecessarily removed.

Chapter 4. Contractor Relationships

Introduction

Shotcrete work is highly specialized. The quality of the finished product depends on the ability and performance of the crew, as well as the quality of the materials used. The owner's inspector is an integral part of the team and should be involved directly with the work throughout the preparation, placement, and evaluation of the shotcrete. Establishing and maintaining a good working relationship with the contractor is of primary importance. It is the responsibility of the contractor to determine the construction methods. The inspector should determine the acceptability and effectiveness of these methods with respect to their conformance to the contract requirements.

Experience has shown that shotcrete work, like many other types of construction, is best accomplished when the contractor and the inspector perform as a team and maintain a strong relationship in which each mutually respects and openly acknowledges the experience and opinions of the other. This does not imply that the inspectors should overlook their responsibilities to enforce the specifications. The inspector's first priority is to ensure the project is constructed in accordance with the requirements of the contract. However, the manner in which the inspector achieves this goal is the key to establishing and maintaining a good relationship with the contractor. In general the inspector should be confident, based on a thorough knowledge of the project, and be assertive without being overbearing. The inspector should provide prompt responses to any questions and never intentionally delay the contractor's work.

Personal Safety

During shotcrete application there is a lot of cementitious dust and mist in the air. Because this dust is moist, it may become stuck on the mucous membranes of the nose and mouth and expelled by spitting or blowing one's nose. There is little concern that this dust or mist will enter the lungs. A respirator or a nuisance dust mask will provide the necessary respiratory protection. Ear plugs, safety glasses, and hard hats should also be used to protect personnel from noise and flying aggregates. Inside box girder cells, between T-beams, and in some other locations the inspector may not be able to see past the nozzleman and the blowpipe operator without hindering the shotcrete application process. At such locations, sounding of the completed work with a hammer, and inspection and testing of the production cores will provide proof of workmanship.

Partnering

Partnering is a long-term commitment between two or more organizations for the purpose of achieving specific business objectives by maximizing the effectiveness of each participant's resources. This requires changing traditional relationships to a shared culture without regard to organizational boundaries. The relationship is based upon trust, dedicated to common goals, and an understanding of each other's individual expectations and values. Expected benefits include improved efficiency and cost effectiveness, increased opportunity for innovation, and the continuous improvement of quality products and services. (Reference 7) Partnering should be considered on shotcrete projects because of the importance of close cooperation between the contractor and inspector that is necessary to achieve high performance shotcrete.

Full Time Inspection

Shotcrete requires consistent attention to detail to achieve a dense homogeneous product. Even though the finished and cured shotcrete can be sounded to evaluate its quality, it is not easy to find problems such as incomplete encapsulation of reinforcement and entrapment of rebound or overspray in finished shotcrete. Shotcrete should be inspected continuously and any suspected areas should be checked as the work progresses by digging out the area as described in Chapter II, Part 2, Construction Monitoring. The contractor is expected to provide access on scaffolding or moveable access equipment that will accommodate the inspector, as well as the nozzleman and blow-pipe operator. A good working relationship between the inspector and the contractor is necessary to provide proper full time inspection while not unduly interrupting the progress of the work.

Chapter 5. Problem Solving on Construction

Introduction

The objective of any construction project is the delivery of a quality product to the owner. There are many paths to this end, all of which will require interaction and active problem solving between the inspector and contractor. As the owner's representative, the inspector must require that the final product meet the contract requirements. The inspector should allow the contractor to use ingenuity and experience and ingenuity in reaching that goal as long as quality is maintained.

Removal of Deteriorated Concrete

The best analogy for a bridge repair contractor is dentistry. While the dentist removes tooth decay and replaces it with sound material (filling) the bridge repair contractor removes deteriorated or spalled concrete and replaces it with shotcrete. With a dentist, if all of the decayed tooth is not removed, deterioration continues and the filling will fail. So with a bridge structure repair, if all deteriorated concrete is not removed, the repair will fail.

Most concrete removal from structural members of a bridge will be done using lightweight chipping hammers. These tools are powerful enough to remove bad concrete but too lightweight to remove sound concrete with any efficiency. From that standpoint they are almost self-policing from over-chipping since workers will wear themselves and their tool out before they chip much sound concrete.

When removing spalled concrete from around corroded reinforcement, care must be taken to follow the steel until the corrosion ceases. Care must also be taken not to vibrate the steel so that the bond is broken between it and the sound concrete. Make sure that a minimum of one bar diameter of concrete is removed behind the steel so that full encapsulation by the shotcrete will occur. As a general rule the full bar should be exposed if a face is corroded. There are exceptions, however, where concrete has spalled exposing one corroded face but a tight bond exists on the remainder of the bar. In this instance, full excavation of the bar may do more harm than good. As usual, a knowledgeable inspector can make this call for the good of the project.

Scaffolding and Containment

All jurisdictions should now be requiring that scaffolding meet OSHA fall-protection requirements. Once that is done there are many ways to provide access to the work. On a grade separation bridge scaffolding and debris containment will in all likelihood be very simple. Bridges over water will vary in complexity of access systems depending on height, structural member to be worked, navigation restrictions and other factors peculiar to that structure. Scaffolding for shotcrete work must take into account additional load capacity for hoses, debris, and the blow pipe operator, if applicable.

Consideration of locations for shotcrete equipment staging areas should be given in design to limit the distance from the equipment to the placement area. Work areas must be large enough for the inspector to have ready access to observe the shotcreting process. When scaffolding is impractical, and workers are using a man lift, the bucket or platform should be large enough to accommodate the inspector as well as the crew.

For the most part, concrete removed is rubble and not a threat to navigation or the environment. In those instances where it must be contained, a separate system will probably be required to receive the chippings. Where it is practical to catch removed concrete on the personnel scaffolding, provisions must be made for the additional loading. When a full water cure is required, the scaffolding may be required to support a delivery and containment system.

The scaffolding or other access methods must accommodate the contractors sequence of operations. Normally a series of operations must be done over a period of time, which includes preparation, placement, finishing, and curing. The scaffolding or access method must allow access throughout the work sequence including access for the inspector for possible sounding for delaminations and taking cores of the finished work up to 28 days after completion, if required.

Provisions must also be made to shield the traveling public from gritblasting, shotcrete nozzle blast, and rebound. This is generally done with tarps suspended from the bridge structure. In very sensitive areas where overspray may be a problem, more complete containment may be required, and should be specified clearly in the specifications.

Bond

So long as the receiving surface is kept clean and damp, bonding between that surface and the new shotcrete is generally not a problem. Of course, good shooting practices as described elsewhere are a necessity. The bond plane is composed of neat cement blasted onto the parent concrete by the shotcrete process. Once sufficient buildup of neat cement has occurred, the surface then starts to receive aggregate. This procedure happens automatically and is a prime component of the superior results available for repair work using the shotcrete process.

If bond failures are found, cores must be taken to determine if failure is occurring in the existing concrete, at the interface, or in the shotcrete. This will help determine if additional effort is needed in deteriorated concrete removal, surface preparation, or shotcrete procedures.

Delamination and Cracking

Concrete cracks and also delaminates. Shotcrete is concrete so it, too, is susceptible to that possibility. Proper surface preparation, control of hydration water, and curing procedures will greatly reduce delamination and cracking in the shotcrete repair. Many times inadequate curing will allow the surface to quickly dry and leave a cracked alligator finish. While not significant structurally, the appearance is very unsightly and leaves the impression of poor workmanship. Improper curing can lead to delamination, which is the structural failure of the repair. Where possible, the work should be isolated from traffic vibrations. However, in bridge repair this is often not possible. The possible affects of vibrations can be minimized by slowing the traffic and by placing shotcrete in thinner layers.

The following are design-related causes of cracking, curling, and delamination:

1. Allowing the use of curing compounds instead of proper moist curing.
2. Insufficient length of time for pre-saturation of the substrate concrete prior to shotcrete application.
3. Lack of shrinkage/thermal reinforcement and anchors in the shotcrete repairs.
4. Lack of contraction joints.

The following are construction-related causes of cracking, curing, and delamination:

1. Inadequate substrate preparation, including deficient surface roughness or profile and failure to remove the "bruised" surface layer.
2. Inadequate substrate moisture condition at the time of shotcrete application.
3. Incorporating rebound and dried overspray into the shotcrete.
4. Use of poor quality aggregates and poor control of site batching (inconsistent proportioning).
5. Poor quality application and finishing.
6. Improper or inadequate curing.

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Preconstruction Inspection Checklist

Prequalification

____ Wet-mix shotcrete mix design approval is similar to any structural concrete mix.

____ Each nozzleman requires three successfully completed similar projects.

____ Test panels should be constructed with reinforcement similar to the most heavily reinforced section to be shot.

____ Test panel conditions must simulate field conditions as accurately as possible, e.g. if actual application will be done from the knees, nozzleman should shoot the test panel from a kneeling position.

____ The Contractor has two options to prove f'_c:
1) shoot a nonreinforced panel and test cores or
2) take cores from the reinforced panel. If option 2) is selected, the Contractor must also saw cut the test panel to inspect for sand pockets, voids, reinforcement encasement, and homogeneous concrete.

____ Verify that f'_c , the core grading, and the other performance requirements meet or exceed contract requirements.

Daily Inspection Checklist

Production

____ Verify that the proper mix is delivered for wet-mix shotcrete by checking the delivery ticket of the first truck and periodically throughout the days work.

____ Watch to be sure the nozzleman and the blowpipe operator are working together and that the nozzleman isn't getting ahead of the blowpipe operator.

____ The finishers/rodmen should rake away any loose material that the blow pipe was unable to remove and keep the surface at approximately a 45 angle.

____ Watch vertical surfaces to ensure there is no slough off of mix that is too wet. Any wet mix that does slough off should be removed to firm material and reshot. Note the location of any areas that do slough off and are repaired so that they can be carefully sounded later.

____ Nozzleman should make the full effort required to ensure complete encasement of the reinforcement. Where the reinforcement is congested or the placement is very thick, special placement procedures may be required.

____ Obtain in advance any personal safety equipment required. For example: earplugs, safety glasses, nuisance dust face mask, safety belt, etc.

____ When in doubt, carve it out. Occasionally, carve out areas of congested reinforcement to verify that placement is fully encasing the reinforcement. Show the Contractor you are concerned with quality of the finished product.