Guide Specification for Structural Shotcrete Walls

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The use of wet-mix shotcrete in lieu of conventional cast-in-place formed concrete for construction of reinforced concrete walls has a long history of successful use up and down the West Coast of the U.S. The use of wet-mix structural shotcrete has its origins in seismic retrofit of schools and commercial buildings in the Los Angeles and San Francisco areas in the 1950s, later spreading to Seattle and San Diego. When carried out by qualified shotcrete contractors, the method proved to be technically sound and economically attractive compared with conventional cast-in-place concrete and subsequently found extensive use in the construction of the permanent, deep reinforced structural walls in in-the-ground parking structures and like applications. This technology has only recently moved across the 49th parallel and a number of four to five story deep in-the-ground parking and transit structures are now starting to be constructed in Vancouver, BC, and Calgary, AB, Canada, using wet-mix structural shotcrete.

In spite of this well accepted use of wet-mix shotcrete for construction of structural shotcrete walls on the West Coast of North America, there are still a number of states in the U.S. and Provinces in Canada where the technology is almost unknown. Part of the reason for this is a lack of familiarity of structural engineers in such regions with the shotcrete process and consequently a reluctance to consider value engineering alternatives proposed by contractors to construct structural shotcrete walls. The prime purpose of this generic Guide Specification for Structural Shotcrete Walls is to provide guidance to design engineers who may be considering the use of shotcrete but don't really know where to start in preparing a suitable specification.

There are specification documents available, such as ACI 506.2R-95, Specification for Shotcrete, but this standard, while useful as a reference document, is quite cryptic and does not begin to address all the issues the design engineer needs to consider in writing a project specification for structural shotcrete walls. It is hoped that this generic specification will be helpful for design engineers not familiar with the shotcrete process. The authors take no responsibility for the use of this Guide Specification on any specific project. It is the responsibility of the design engineer to modify/add to the specification as needed to make it suitable for their specific project.

Finally, the authors would appreciate receiving feedback/comments from any persons using this Guide Specification, so that it can be improved upon, based on user experience.

1.0 General Description and Requirements

1.1 Scope

This specification is for the construction of structural shotcrete walls using the wet-mix shotcrete construction process.

1.2 Qualifications

The shotcrete Contractor's crew foreman and nozzlemen shall meet the following requirements:

1. Furnish proof that the Contractor and shotcrete crew foreman have at least 5 years of experience in reinforced shotcrete construction work on projects of similar size and character along with three references from persons who were responsible for supervision of these projects. Include name, address, and telephone number of references who will testify to a successful completion of these projects by the Contractor and shotcrete crew foreman;

2. Furnish proof that the nozzlemen are certified by the American Concrete Institute (ACI) for application of shotcrete to vertical surfaces, using the wet-mix shotcrete process, as prescribed in ACI publication CP-60 (02); and

3. Furnish proof that the nozzlemen have successfully completed three projects of similar size and character. The nozzlemen shall also pass a preconstruction mock-up test, described in Section 8.3, demonstrating their ability to satisfactorily construct the reinforced shotcrete structural elements required for this project. (Note: the requirement for construction of a mock-up may be waived if the nozzleman can provide evidence of having previously successfully shot structurally reinforced walls of similar configuration with the same equipment and shotcrete mixture).

1.3 Requirements

1.3.1 Furnish all labor, materials, and equipment for the following:

a) Demonstrate in preconstruction testing that the submitted shotcrete mixture design(s) satisfies the performance requirements of this specification;

b) Shoot a preconstruction mock-up of the reinforced shotcrete walls to demonstrate that the shotcrete materials, mixture(s), equipment, crew, and construction sequence and methods used are capable of producing a product conforming to these specifications and acceptable to the Engineer;

c) Provide quality control services as necessary to ensure compliance of the completed work with the requirements of this specification. Shoot test panels at the frequency specified for independent quality assurance testing by the Engineer;

d) Verify that the reinforcing steel bars in the walls are installed in a manner that is acceptable to the design Engineer and conducive to the shotcrete construction process;

e) Provide all hoarding, covers, or other protection devices necessary to protect all fixtures and installations in the shotcrete construction area from contamination or damage from the shotcrete construction process. In particular, protect such fixtures and installations from impact from the shotcrete nozzle stream, rebound, overspray, and shotcrete mist or dust;

f) Provide all scaffolding, platforms, lift equipment, or other devices necessary to provide the shotcrete nozzlemen and other crew and inspectors with safe and proper access to the shotcrete work;

g) Provide suitable ventilation, lighting, fans, curtains, or other devices necessary to provide the shotcrete nozzlemen and crew with good visibility and control of shotcrete mist, dust, overspray, and rebound;

h) Provide all forming, bracing, guide wires, and finishing tools necessary to enable construction of the reinforced shotcrete elements to the specified profiles, tolerance, and finish;

i) Apply shotcrete to the walls using prequalified nozzlemen and crew and approved shotcrete mixture(s);

j) Finish shotcrete to specified finish, dimensions, tolerance, and line and grade. Provide moist curing and protection as specified;

k) Provide assistance to the Engineer for quality assurance testing including access for any coring required by the Engineer. Remove and replace, at no cost to the Owner, any defective shotcrete or work that is nonconforming to the project specifications; and

l) Leave completed shotcrete work in a clean condition, free of any deposits of excess shotcrete, overspray, rebound, or other contaminants. Remove all such materials from the work area and dispose of at an approved disposal site.

1.3.2 Implement a health, safety, and environmental protection program that conforms to the requirements of the Engineer and any other authorities having jurisdiction. Such programs shall include, but not be limited to the following:

a) Ensure that all equipment, scaffolding, shoring, bracing, and other devices used on the project meet the requirements of the authorities having jurisdiction;

b) Put in place a mandatory health and safety training program for all workers, inspectors, and other persons entering the workplace; and

c) Protect all workers and other personnel from applied shotcrete and rebound during the shotcrete application process. As a minimum, all workers and personnel in active shotcreting areas shall wear appropriate respiratory protection devices as well as appropriate clothing and other personal protection equipment (hard hats, eye protection, safety boots, and reflective vests). Provide eye wash equipment at shotcrete site.

2.0 Submittals

2.1 Submit to the Engineer at least 10 working days before commencement of production of shotcrete work written documentation that provides the following:

2.1.1 The qualifications of the Contractor and work crew, including the supervisor, shotcrete nozzleman, pump operator, and shotcrete blowpipe operators, and the references for the Contractor and shotcrete crew foreman required in 1.2 (a).

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

a) Portland cement;

b) Supplementary cementing materials (silica fume and fly ash);

c) Aggregates;

d) Mixture water;

e) Chemical admixtures; and

f) Reinforcement.

2.1.3 Details of proposed shotcrete mixture(s), proportions, and means of shotcrete supply.

2.1.4 A list of the proposed shotcreting equipment, including brand name, model, and capacity of proposed pump and air compressor.

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

2.1.6 Details of proposed scaffolding, man lifts, or other temporary support system for workers and inspectors.

2.1.7 Details of proposed forming, bracing, or temporary support systems for construction of reinforced shotcrete elements.

2.1.8 Details of proposed means of preparing surface to receive shotcrete.

2.1.9 A description of proposed curing procedures and protection to be provided to shotcrete.

2.1.10 Details of proposed methods for control and disposal of waste materials, including waste shotcrete, rebound, and overspray.

3.0 Reference Documents

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

3.1.1 American Concrete Institute (ACI)
ACI 506R Guide to Shotcrete
ACI CP-60(02) Shotcrete Nozzlemen Certification
ACI 506.2 Specifications for Shotcrete

3.1.2 American Society for Testing and Materials (ASTM)
ASTM C33 Specification for Concrete Aggregates
ASTM C94 Specification for Ready-Mixed Concrete
ASTM C143 Test Method for Slump of Hydraulic-Cement Concrete
ASTM C150 Specification for Portland Cement
ASTM C231 Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
ASTM C260 Standard Specification for Air Entraining Admixtures for Concrete
ASTM C618 Specification for Coal Fly Ash
ASTM C1140 Practice for Preparing and Testing Specimens from Shotcrete Test Panels
ASTM C1141 Specification for Admixtures for Shotcrete
ASTM C1240 Specification for Silica Fume used in Concrete Mixtures
ASTM C1436 Specification for Materials for Shotcrete
ASTM C1604 Test Method for Obtaining and Testing Drilled Cores of Shotcrete

3.1.3 Canadian Standards Association (CSA) CSA A5 Portland Cement
CSA A23.5 Supplementary Cementing Materials
CSA A23.1-04 Concrete Materials and Methods of Concrete Construction
CSA A23.2-04 Methods of Test for Concrete

4.0 Definitions

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

Acceptable, Approved or Permitted: Acceptable to approved or permitted by the Engineer.

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

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

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

Engineer: The accepting authority responsible for issuing the project specifications and administering work under the contract documents on behalf of the Owner.

Guide wire (also called screed wire or shooting wire): Small gauge, high strength wire used to establish line and grade to guide work.

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

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

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

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

Shadow: Area of porous, improperly consolidated shotcrete behind reinforcing steel or other embedements.

Shotcrete: Concrete pneumatically projected at high velocity onto a receiving surface.

Sloughing (also called sagging): Subsidence of shotcrete due generally to excessive water in the mixture or placing too great a thickness or height in a single pass.

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

5.0 Materials

5.1 Cement

5.1.1 Cement shall conform to the requirements of ASTM C150 portland cement Type I, or CSA A5 portland cement Type GU.

5.2 Supplementary Cementing Materials

5.2.1 Fly ash shall conform to the requirements of ASTM C618, Type F, or CAN/CSA-A3000-03 Type F or CI.

5.2.2 Silica fume shall conform to the requirements of ASTM C1240, or CAN/CSA-A3000-03 Type SF.

5.3 Water

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

5.3.2 Similarly, all water used in pressure sprayers for removal of rebound and overspray or green-cutting and for shotcrete curing shall be of drinking water standards and free of oil and chemical or organic impurities.

5.4 Aggregates

5.4.1 Use normalweight aggregates conforming to the requirements of ASTM C33 or CSA A23.1. Aggregates shall be hard, dense, and durable and conform to limits for allowable quantities of deleterious substances as given in ASTM C33 Tables 1 and 3 or CSA-A23.1-04 Table 12.

5.4.2 Aggregates used shall not react with alkalies in the cement to an extent that results in excessive expansion of the shotcrete. The requirements of CSA A23.1-04 and CSA A23.2-27A shall be met.

5.4.3 Use nominal 3/8 in. (10 mm) maximum size coarse aggregate combined with a concrete sand to provide a blend that conforms to the following composite gradation envelope:

U.S. sieve size	Metric sieve size	Total passing each sieve % by mass
1/2 in.	14 mm	100
3/8 in.	10 mm	90-100
No. 4	5 mm	70-85
No. 8	2.5 mm	50-70
No.16	1.25 mm	35-55
No. 30	630 µm	20-35
No. 50	315 µm	8-20
No. 100	160 µm	2-10

5.4.4 The 3/8 in. to No. 8 (10 to 2.5 mm) coarse aggregate fraction shall be stockpiled and added separately from the fine aggregate (nominal No. 4 [5 mm] maximum size) during batching operations. (Note: in some jurisdictions 1/2 in. (12.7 mm) maximum size aggregate is now being used in thicker bench-gunned walls.)

5.5 Admixtures

5.5.1 Do not use any admixtures containing chlorides. Do not use any shotcrete accelerators without written authorization by the Engineer.

5.5.2 Air-entraining admixtures shall conform to the requirements of ASTM C260.

5.5.3 Chemical admixtures, such as water reducers, high-range water reducers (superplasticizers), and retarders, shall conform to the requirements of ASTM C1141.

5.6 Reinforcement

5.6.1 Use reinforcing steel of the type, size, and dimensions shown in the drawings.

6.0 Shotcrete Proportioning

6.1 Mixture Design

6.1.1 The Contractor shall be responsible for shotcrete mixture proportioning. Submit the proposed shotcrete mixture proportions to the Engineer for review and approval at least 10 working days before preconstruction trials; see Section 8.3. As a minimum, for each shotcrete mixture design, submit the following information:

a) An easily identifiable mixture designation, number, or code; and

b) Proof that the proposed mixture design is capable of meeting the specified performance requirements.

6.1.2 Performance Requirements
Proportion shotcrete to meet the following performance requirements:

Test description	Test method	Age (days)	Specified requirement
Maximum water/cementitious materials ratio		—	0.45
Air content – as shot[1,2]	ASTM C231, or CSA A23.2-4C	—	4 ± 1%
Slump at discharge into pump	ASTM C143, or CSA A23.2-5C	—	2 1/2 ± 1 in. (60 ± 20 mm)
Minimum compressive strength, psi (MPa)	ASTM C1604, or CSA A23.2-14C	7 28	2900 psi (20MPa)[3] 4350 psi (30 MPa)[3]

Note 1: To obtain an as-shot air content of 4 ± 1% will require an air content at the point of discharge into the shotcrete pump in the 7 to 10% range.

Note 2: The use of air entrainment is beneficial even in shotcrete not exposed to freezing and thawing because, as air content is lost on shooting, there is a corresponding loss of slump on impact that helps prevent sagging and sloughing.

Note 3: Some authorities require shotcrete cores extracted from test panels (or the in-place shotcrete) to only meet 85% of the specified strength, as is often done for concrete cores. If this is the requirement for the project, then this should be clearly stated in the project specification. Otherwise, the minimum specified compressive in the previous table prevails.

Note 4: The Engineer may specify higher compressive strengths if structurally required.

7.0 Supply and Equipment

7.1 Batching, Mixing, and Supply

7.1.1 Batch, mix, and supply wet-mix shotcrete by one of the following methods:

a) Central mixing with transit mixture delivery; or

b) Transit mixing and delivery.

7.1.2 Central Mixing and Supply

a) Aggregate, cement, and silica fume shall be mass batched in a central mixer in accordance with the requirements of ASTM C94 or CSA A23.1-04. Water and chemical admixtures shall be batched to the accuracy specified in ASTM C94 or CSA A23.1-04;

b) Transit mixers shall be free of excessive accumulations of hardened shotcrete or concrete in the drum or on the blades. Blades shall be free of excessive wear. Transit mixture delivery shall conform to the requirements of ASTM C94 or CSA A23.1-04; and

c) All shotcrete shall be shot within 90 minutes after addition of mixture water to the batch. Shotcrete loads shall be of such batch size that this requirement is met. This time limit may be extended, subject to approval by the

Engineer, if proper use is made of set retarding or hydration controlling admixtures to maintain workability without retempering with water.

7.1.3 Transit Mixing and Supply
The same requirements in Section 7.1.2 apply for central mixing except that all ingredients shall be added directly to the transit mixer instead of the central mixer. Transit mixers shall be charged to not more than 70% of their rated capacity, to enable efficient mixing action.

7.2 Shotcrete Placing Equipment

7.2.1 The shotcrete delivery equipment shall be capable of delivering a steady stream of uniformly mixed material to the discharge nozzle at the proper velocity and rate of discharge.

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

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

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

7.3 Auxiliary Shotcrete Equipment

7.3.1 Supply clean, dry, compressed air, capable of maintaining sufficient nozzle velocity for all parts of the work and simultaneous operation of a blowpipe.

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

7.3.3 Provide auxiliary shotcrete equipment such as material delivery hoses, blowpipes, and couplings as required to complete the work.

7.4 Reinforcing Steel

7.4.1 Reinforcing steel to be of the type, size, and dimensions detailed in the drawings.

7.4.2 Securely tie reinforcing steel bars at locations of intersecting bars with 0.06 in. (1.6 mm) or heavier gauge tie wire to minimize vibration and prevent movement of steel during shotcrete application. Avoid formation of knots of tie wire that could interfere with proper shotcrete encasement of reinforcing steel.

7.4.3 Tie reinforcing steel to avoid multiple laps or other congestion that could compromise ability of shotcrete nozzleman to properly encase reinforcing steel and embedments.

7.4.4 Submit proposed splice details to the Engineer for review and approval before installation of reinforcing steel.

7.4.5 Clearance between reinforcing bars and formwork or substrate to be as detailed in drawings, but not less than 0.79 in. (20 mm).

7.5 Alignment Control and Cover

7.5.1 Implement alignment control to establish control over line and grade and ensure that the minimum specified shotcrete thickness and cover to reinforcing steel are maintained. Verify that reinforcing bars are fixed to provide specified cover before application of any shotcrete.

7.5.2 Provide alignment control by means of devices such as shooting wires, guide strips, depth gauges, or forms. The proposed means of alignment control shall be submitted to the Engineer for review and approval before any shotcrete application.

7.5.3 When ground wires (also called guide wires or shooting wires) are used, they shall consist of a high-strength steel wire kept taut during shotcreting. Remove ground wires after completion of shotcreting and screeding operations.

7.5.4 Guide strips and forms shall be of such dimensions and installation configuration that they do not impede the ability of the nozzlemen to produce uniform, dense, properly consolidated shotcrete. In particular, installations that are conducive to the entrapment of rebound or formation of shadows and voids shall not be used.

8.0 Quality Assurance and Quality Control

8.1 Quality Assurance

The Engineer will implement a quality assurance program, paid for by the Owner, which will include:

a) Review of Contractor Submittals;

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

c) Examination and approval of areas prepared for shotcreting at start-up of the project, including installation of anchors, reinforcement, and devices to control line and grade before application of any shotcrete;

d) Provision of intermittent inspections to monitor shotcrete installation at a frequency selected by the Engineer;

e) Regular monitoring of the results of the compressive strength tests conducted by a testing agency appointed and paid for by the Owner on cores extracted from standard shotcrete test panels shot by the Contractor at a frequency specified by the Engineer;

f) Implementation of a program for in-place evaluation and acceptance, or rejection, where testing indicates shotcrete is nonconforming to the project specifications;

g) Where defective shotcrete is indicated, carrying out appropriate tests that may include core evaluation and compressive strength testing of extracted cores from the in-place shotcrete; and

h) Monitoring of a program of remedial works by the Contractor, where indicated as being necessary from the results of the quality assurance program.

8.2 Quality Control

The Contractor shall establish and maintain a quality control program for the shotcrete work to ensure compliance with the contract requirements. Such program shall include maintenance of test records for all quality control operations. Such records shall be provided to the Engineer for review on request.

8.3 Preconstruction Trials

8.3.1 Implement a preconstruction trial to enable the Engineer to evaluate the ability of the proposed materials, shotcrete mixture, equipment, and crew to produce shotcrete conforming to the project specifications. Acceptance of the preconstruction trial results by the Engineer is required before application of any shotcrete on the project.

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

8.3.3 The preconstruction trial shall use the same materials, shotcrete mixture, and equipment proposed for use on the project and approximate actual working conditions, configuration, reinforcement, and shooting positions as near as possible.

8.3.4 Nozzlemen shall prequalify by shooting mock-ups of the reinforced structural wall element. Five cores shall be taken from each mock-up for core grading from locations directed by the Engineer.

8.3.5 Cores shall be evaluated by the Engineer to check the quality of shotcrete placement. Cores shall show adequate consolidation and be free of excessive voids around reinforcing steel, shadows, sags, sloughing, or delaminations.

8.3.6 Prequalify the shotcrete mixture by shooting a plain (nonreinforced) test panel with dimensions of 18 x 18 x 4.5 in. (450 x 450 x 110 mm) deep. The test panel shall be made from wood and sealed plywood and have 45-degree sloped edges to permit rebound to escape and facilitate demoulding.

8.3.7 Cure the test panels in the field, close to the location where shot, for two (2) days before being transported in the form to the testing laboratory. Cure the test panel under wet burlap covered with plastic sheet under temperatures conditions similar to that experienced by the wall. Protect the panels from disturbance or damage.

8.3.8 Assist testing laboratory by loading test panels, in their forms, onto their trucks. Test panels and cores extracted from the test panels shall be moist cured in the laboratory at 73.4 ± 2 °F (23 ± 2 °C) until the time of compressive strength testing.

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

8.4 Construction Testing

8.4.1 Shoot one construction test panel for each 65 yd^3 (50 m^3) of shotcrete production, or for each day of shotcrete production, whichever is more frequent. Shoot the panel in the same orientation as the work being done.

8.4.2 Produce, store, handle, and cure construction test panels in the same manner prescribed for preconstruction test panels. Similarly, prepare, handle, cure, and test shotcrete in the same manner prescribed for the preconstruction test panels.

9.0 Shotcrete Application and Finishing

9.1.1 Provide suitable scaffolding, man lifts, or other devices to provide the nozzlemen, helpers, and inspectors with free unhindered access to the work area. Provide safety measures to protect the workers on such devices that comply with the requirements of the authorities having jurisdiction.

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

9.1.3 Use good shotcrete nozzling technique as detailed in ACI 506R-05. In particular:

a) Use the bench-gunning technique. Orient the nozzle at right angles to the receiving surface, except as required to fill corners, cove edges, and encase reinforcing steel;

b) Optimize the combination of air volume at the nozzle and distance of the nozzle from the receiving surface to achieve maximum consolidation of the shotcrete and full encapsulation of the reinforcing steel;

c) Adjust air volume and distance of the nozzle from the work while encasing reinforcing steel to keep the front face of the reinforcement clean during shooting operations, so that shotcrete builds up from behind to encase the reinforcement without the formation of shadows or voids;

d) Nozzleman's helper to continuously remove accumulations of rebound and overspray using blowpipe, or other suitable devices in advance of deposition of new shotcrete; and

e) Do not include rebound, hardened overspray, or stiffened shotcrete trimmings in the shotcrete work.

9.2 When applying more than one layer of shotcrete trim with a cutting rod, or brush with a stiff bristle broom to remove all loose material, overspray, laitance, or other material detrimental to bonding of the next layer of shotcrete.

9.3 Allow shotcrete layer to stiffen sufficiently before applying next layer of shotcrete. If shotcrete has set and hardened, high-pressure water blast (minimum 5000 psi [34.4 MPa]) with clean water and bring to a saturated surface-dry (SSD) condition at time of application of the next layer of shotcrete. Use air blow pipe to accelerate drying if necessary.

9.4 Use a shooting technique that provides full encapsulation of all reinforcing steel and embedments. Cut out any voids, shadows, sags, or other defects from the applied shotcrete while still plastic and reshoot. Otherwise make good any defects in the hardened shotcrete using light-duty chipping hammers (15 lb [7 kg] maximum) followed by high pressure water blasting (minimum 5000 psi [34.4 MPa]) to remove bruised shotcrete surface.

9.5 Trim shotcrete with a cutting rod or other suitable device to the specified line and grade. Finish shotcrete to a sandy texture as approved by the Engineer using suitable finishing tools. Tolerance of finished surface shall be as specified by the Engineer.

9.6 Protect all fixtures and adjacent concrete surfaces from build-up of rebound, overspray, and shotcrete trimmings. Remove all such materials from the work area on a daily basis.

9.7 Remove any excess shotcrete applied outside of the specified areas to be shot. Leave the work area in a clean condition on completion of the work, free from contamination by excess shotcrete trimmings, rebound, overspray, or slurry from shotcrete operations.

9.8 Construct construction joints to a 45-degree tapered edge. Cut plastic shotcrete with a trowel or other suitable tool to form a construction joint. Green cut with a 5000 psi (34.4 MPa) water pressure jet the next day, if necessary to remove loose material. Do not feather-edge (produce long tapered) construction joints. Square (90 degrees) joints permitted on horizontal surfaces over which concrete slabs will be placed.

10.0 Curing and Protection

10.1 Curing

10.1.1 On completion of finishing, prevent shotcrete from drying out by moist curing using fogging or wetting or maintenance of a minimum 95% relative humidity in the area surrounding the shotcrete.

10.1.2 Moist-cure shotcrete for a minimum of 7 days. Moist curing shall be accomplished using one or more of the following procedures:

a) Wrap the elements in wet burlap covered with a plastic sheet or a presaturated plastic coated nonwoven synthetic fabric; or

b) Install sprinklers, soaker hoses, or other devices that keep the shotcrete continuously wet for the specified period. Avoid the use of intermittent wetting procedures that allow shotcrete to undergo cycles of wetting and drying during the curing process.

10.2 Hot and Cold Weather Protection

10.2.1 The general requirements for hot and cold weather concreting detailed in ACI 506.2 or CSA A23.1-04 apply to the shotcrete work.

10.2.2 If the prevailing ambient conditions (relative humidity, wind speed, and air temperature) are such that the shotcrete develops plastic shrinkage and/or early drying shrinkage-cracking, terminate shotcrete application. Adopt corrective measures such as installation of wind barriers or fogging devices to protect the work before restarting shotcrete application. Do not proceed with shotcrete application if the rate of evaporation at the shotcrete surface exceeds 0.20 lb/ft^2.hr (1.0 kg/m^2.hr) as detailed in CSA A23.1-04, Appendix D.

10.2.3 Terminate shotcrete application if the ambient temperature rises above 86 °F (30 °C), unless the Contractor adopts special hot-weather shotcreting procedures that are approved by the Engineer.

10.2.4 During periods of cold weather, shotcreting may only proceed if the substrate to which the shotcrete is applied is above 41 °F (5 °C).

10.2.5 After application of the shotcrete, maintain the air temperature at the shotcrete surfaces at 50 °F (10 °C) or greater for at least four days after application of shotcrete. The means of maintaining the air temperature shall be approved by the Engineer. The use of unvented heaters that give rise to carbonation is prohibited.

11.0 Shotcrete Acceptance and Repair

11.1 Shotcrete Acceptance

11.1.1 The Engineer has the authority to accept or reject the shotcrete work. Shotcrete that does not conform to the project specifications may be rejected either during the shotcrete application process, or on the basis of tests on cores from test panels or the completed work.

11.1.2 Deficiencies observed during the shotcrete application process, such as but not limited to the following, constitute a cause for shotcrete rejection:

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

b) Incomplete consolidation of shotcrete around reinforcing steel and embedments;

c) Incorporation of shadows, excessive voids, delaminations, sags or sloughing; and

d) Failure to apply shotcrete to the required line and grade and tolerance.

11.1.3 Whenever possible, perform remedial work to correct deficiencies while shotcrete is still plastic.

11.1.4 The hardened shotcrete will be examined by the Engineer for any evidence of excessive plastic or drying shrinkage cracking, tears, feather-edging, sloughs, or other deficiencies. Sounding or suitable nondestructive testing shall be used to check for voids and delaminations. If the shotcrete does not meet the specified criteria, the work will be rejected and the Contractor shall implement a remediation program to correct the deficiency.

11.1.5 If the results of compliance tests from shotcrete test panels or assessment of the plastic or hardened shotcrete indicate nonconformance of the shotcrete to the project specifications, the Engineer will implement a program of evaluation of the in-place shotcrete. Such evaluation shall include, but not be limited to:

a) Extraction of cores from the in-place shotcrete at locations selected by the Engineer and evaluation of such cores for compliance to the project specifications;

b) Checking for delaminations using sounding or other appropriate nondestructive testing procedures; and

c) Diamond saw cutting or coring to check the adequacy of encasement of reinforcing steel and embedments.

11.1.6 Shotcrete that is proven to be nonconforming to the project specifications shall be removed and replaced by the Contractor at no cost to the Owner.

11.2 Shotcrete Repair

11.2.1 Shotcrete that is identified as being defective while still plastic shall be removed using trowels, scrapers, or other suitable mechanical devices.

11.2.2 Hardened shotcrete that is identified as being deficient shall be removed. Care shall be taken to prevent damage to reinforcing steel bars or embedments and adjacent sound shotcrete. Any embedments and adjacent sound shotcrete damaged during the shotcrete removal process shall be removed and replaced at no cost to the Owner.

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

11.2.4 The Contractor shall bear the costs for all repair and tests for nonconforming shotcrete.

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