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Chapter 14

Shotcrete

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Chapter 14

Shotcrete

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645.1400 Introduction

Shotcrete is a form of mortar or concrete placement in which the material is pneumatically projected at high velocity onto a surface. The application technique allows the shotcrete to be placed and compacted at the same time and it can be applied to vertical and overhead surfaces. A well-proportioned and properly applied shotcrete mixture will often have a higher compressive strength than conventionally placed concrete due to a lower water to cement ratio. The placement process creates a strong bond with solid materials such as rock faces and previously placed concrete.

Shotcrete is basically just a placement method for mortar or concrete and may be used in place of conventional concrete or to repair conventional concrete. Any design considerations (expansion joints, reinforcement, curing, etc.) that are needed for a conventional concrete placement are just as applicable for shotcrete. The choice to use shotcrete rather than conventional concrete is usually based on convenience and cost. Shotcrete is most cost effective when extensive reinforcement is not needed and the amount of formwork can be reduced or eliminated. It can greatly increase the speed of construction and make it easier to construct complex shapes such as tunnels, channels and shells. Shotcrete is often found as a primary construction material for swimming pools, zoo enclosures and waterparks. It is also widely used for the repair and strengthening of existing concrete structures, such as bridges and principal spillway structures.

The term shotcrete can apply to both wet-mix and dry-mix versions. The dry-mix is often referred to as guniting. NRCS Construction Specification 33, Shotcrete, (CS33) allows for either the dry- or wet-mix process unless otherwise specified by the designer. Either process can provide shotcrete that meets most design requirements.

In dry-mix shotcrete, a mixture of cement and pre-dampened aggregate is forced through a hose to a nozzle where water is added and then projected at high velocity onto the surface. This process requires an experienced nozzleman who will adjust the consistency of the mixture at the nozzle to ensure a good product with little waste. Figure 14–1 shows a typical setup for the dry-mix process.

When the wet-mix shotcrete is specified, prepared concrete (cement, aggregate, and water) is delivered to a pump where air pressure is added to project the mixture onto the surface. The shotcrete comes to the nozzle completely mixed and there is no adjustment in consistency by the nozzleman. Figure 14–2 shows the equipment necessary for a wet-mix shotcrete operation.

The purpose of this chapter is to give the construction inspector a general understanding of shotcrete materials, the shotcrete process, the requirements of CS 33 and the basic knowledge required to complete their quality assurance duties on a shotcrete operation. The ACI publication 506R-16, Guide to Shotcrete, is an excellent resource and should be in the hands of any construction inspector involved in the quality assurance of a shotcrete operation. It is a concise, well-written handbook that was updated in 2016. There is a wealth of information in this publication that will not be repeated in this chapter.

Figure 14-1 Dry-mix shotcrete process

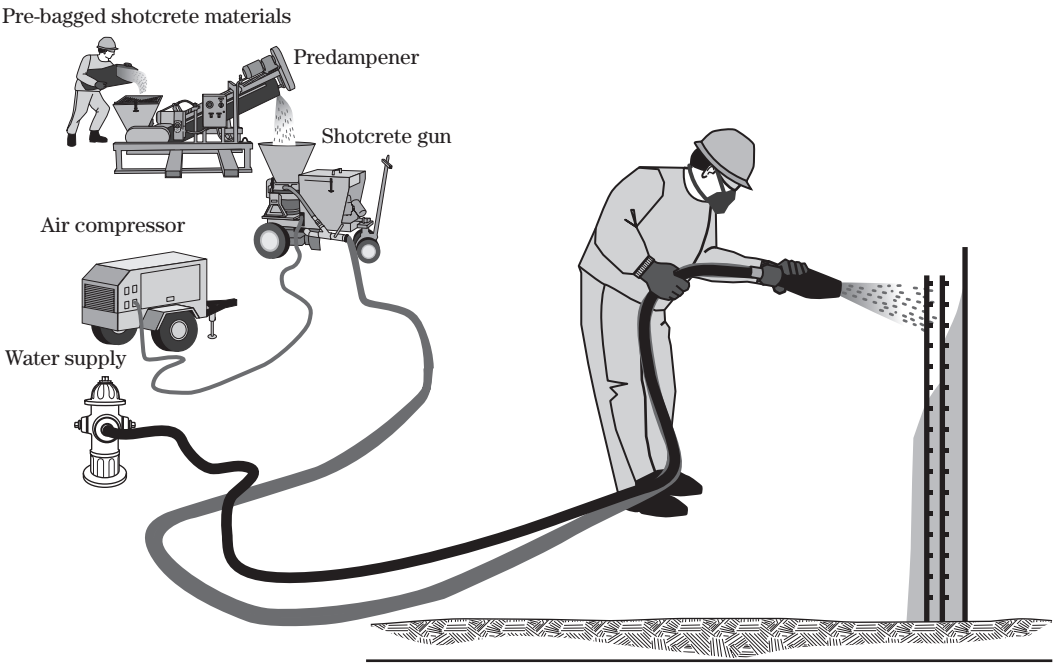
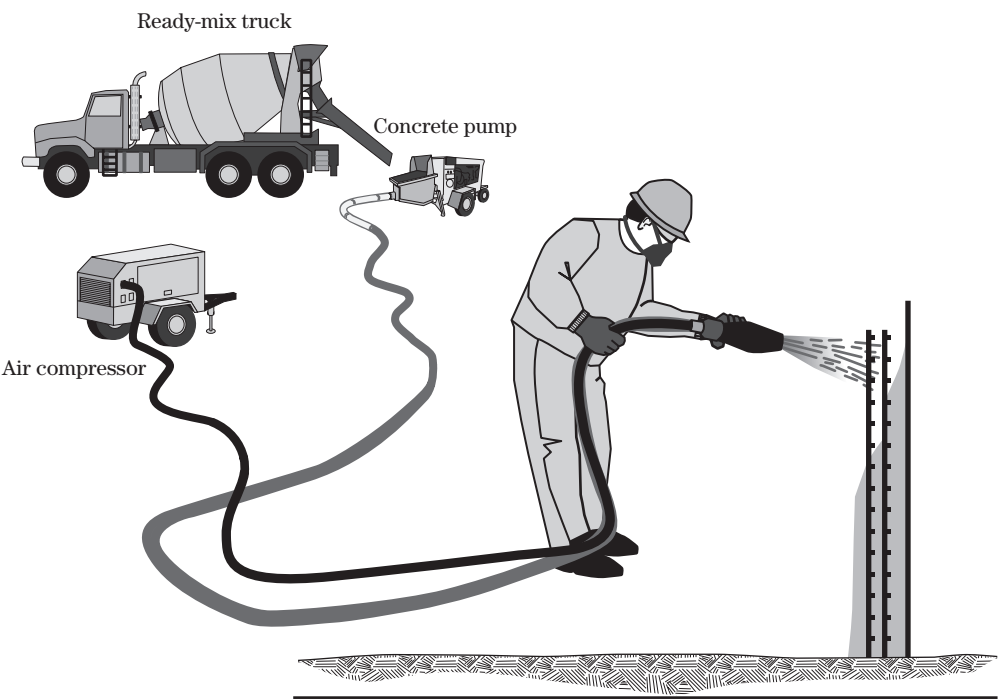


Figure 14-2 Wet-mix shotcrete process



645.1401 Installation

(a) Materials

Aggregates—The materials for shotcrete are identical to those in conventional concrete except that the aggregate gradation is necessarily smaller. Typically, a shotcrete gradation will only contain a sand aggregate. However, recent innovations in shotcrete technologies have allowed the use of larger aggregates in some mixes. CS 33 refers to two recommended gradations in ACI 506R (table 1.1). The first one is almost identical to ASTM C33 fine aggregate, while the second is slightly larger. The specification also allows the design engineer to specify other aggregate gradations if desired.

Supplementary Cementitious Materials—Supplementary cementitious materials, such as fly ash, slag cement, and silica fume, are sometimes added to shotcrete design mixes. These materials are added to increase strength, increase pumpability (wet-mix shotcrete), increase resistance to alkali-silica reactivity, decrease permeability and reduce bleeding. Each of these materials has different properties and should not be changed in the design mix without the approval of the design engineer.

Admixtures—Chemical admixtures are added to shotcrete to improve the fresh or hardened properties of the mix and can be in either powder or liquid form. In a dry-mix process, powdered materials would be added in the batching or mixing stage. Liquid admixtures would be delivered in a separate hose and added at the nozzle. In a wet-mix application, most admixtures are added during the batching and mixing with the exception of accelerators, which are added at the nozzle.

Air entraining admixtures are commonly included in a shotcrete design mix. For a dry-mix process, they can be added to the mixing water or a dry, powdered admixture can be mixed in with the other dry ingredients. They improve pumpability for wet-mix shotcrete and increase freeze-thaw resistance. Water-reducing admixtures are added to wet-mix designs to increase pumpability while maintaining the desired strength. Set retarders can be added to increase the length of

time that a shotcrete mixture will continue to be workable. Occasionally, other admixtures will be included in the design mix. The inspector should verify that the specifications allow such admixtures or they are approved by the design engineer.

Shotcrete containing all admixtures to be used should be tested prior to construction unless the admixtures have been satisfactorily used on a previous job with which the engineer or inspector are familiar or unless documentation of their performance when used with the design mix shows satisfactory results. More on admixtures can be found in NEH645.12, Concrete.

Water—Since all dry-mix applications will have the water added at the project location, it is important that the inspector verify that a clean water source is available that meets the requirements of the specification.

Reinforcement—Welded wire and bar steel reinforcement placement is virtually the same as with conventional concrete placement. The design engineer and construction inspector should make sure that a dense concentration of steel reinforcement does not exist that would inhibit shotcrete placement. It is always important to ensure that all steel reinforcement is completely encased by shotcrete.

The use of steel or synthetic fibers in shotcrete is a relatively new development and is not currently addressed in CS 33. Fiber-reinforced shotcrete is used primarily to reduce plastic shrinkage cracking in structural concrete. It also increases the toughness and impact resistance to the exterior surface which may be desirable in some applications. Additional information can be found in ACI 506.1R, Guide to Fiber-Reinforced Shotcrete.

With respect to materials, the inspector is responsible for verifying:

- Water used in mixing and curing is clean and free from injurious amounts of oil, salt, acid, alkali, organic matter, and other deleterious substances.
- Portland cement, aggregates, and admixtures meet the required specifications.
- Reinforcement is not too congested to inhibit placement and prevent the shotcrete from completely encasing the reinforcement.

(b) Shotcrete mix design

Shotcrete can be designed to be either structural or nonstructural. ACI 506R–16 considers any shotcrete with a designed compressive strength of 4,000 pounds per square inch or greater to be structural. Most NRCS applications will consider the shotcrete to be of a structural nature by providing strength, durability, or reduced permeability to the structure rather than being mainly decorative. Where it is considered to be structural, the design engineer will specify a required compressive strength as they would for conventional concrete.

(c) Nozzle operator qualifications

The success of any shotcrete placement depends highly on the skills of the nozzle operator. The best shotcrete mixture will provide a poor result if not properly placed. An experienced nozzleman will know the proper methods for preparing the surface, directing the nozzle during placement at edges and around reinforcement, and adjusting the water content of dry-mix shotcrete for proper consistency.

CS 33 requires that the contractor submit a resume for each nozzleman. They must have a minimum of 1 year experience and be ACI certified in the appropriate certification program (dry-mix or wet-mix). They must also be observed by the engineer satisfactorily shooting a test panel (figure 14–3) prior to beginning placement.

Figure 14–3 Nozzleman preparing a test panel (courtesy of Bryan Mekechuk and Bill Brown)



With respect to nozzle operator qualifications, the inspector is responsible for verifying that:

- Engineer has approved the resumé of the nozzle operator.
- Engineer observes and approves the shooting of the test sections or test panels.

(d) Equipment and mixing

The equipment needed for a shotcrete operation usually includes an air compressor, mixer, gun or pump, hoses, and nozzles.

Mixing equipment—Dry-mix mixers may be either continuous or batch. In a continuous mixer, preproportioned materials are fed into an auger designed to mix while transporting and discharging the materials into the gun. Batch mixers use a rotating drum with internal blades or a stationary drum with rotating paddles.

Guns and concrete pumps—Dry-mix materials are fed into a gun (fig. 14–4), which will pressurize the material and deliver a metered amount out through the

Figure 14–4 Workers loading premixed dry components into a shotcrete gun (Courtesy of REED Concrete Pumps & Shotcrete Equipment)



material delivery hose. Guns are either batch, double chamber, or continuous feed. Batch guns are a single chamber. One batch of material is placed into the chamber, pressurized, and metered out through the hose. Double-chamber guns are operated continuously with the material fed into the top chamber, which will then act as an airlock and allow continuous flow. A continuous-feed gun has a rotary airlock system. In wet-mix operation, a concrete pump delivers the mix to the shotcrete nozzle, where the nozzleman adds air to regulate the velocity of the material. Figure 14-5 shows a ready-mix truck discharging directly into the concrete pump.

Air compressor—Both the dry- and the wet-mix operations require a high-capacity air compressor. CS 33 does not specify the size or pressure of the air compressor but does state that it must be able to control air pressure between 50 and 80 pounds per square inch and maintain the water pressure at between 50 and 100 pounds per square inch.

Nozzles—The shotcrete discharge nozzles are a specialized product. They attach to the end of the delivery hose and allow the addition of air (wet-mix) or water (dry-mix). They can also be fitted with secondary lines to allow the addition of admixtures.

Figure 14-5 Concrete ready-mix truck discharging into concrete pump (Courtesy of REED Concrete Pumps & Shotcrete Equipment)



With respect to equipment and mixing, the inspector is responsible for verifying that:

- The dry-mix shotcrete materials are mixed into a predampened homogeneous mass before being fed through a vibratory screen into the placing equipment.
- The entire contents of the mixer are discharged before another batch is started.
- A mix that becomes difficult to pump is discarded.
- A batch is gunned within 1.5 hours of being batched (normal weather) or 45 minutes (temperature over 85 °F).
- Rebound material is not reused.
- Air-entrainment and chemical admixtures are only used in wet-mix applications.
- Wet-mix shotcrete is thoroughly mixed to produce a uniform mixture of the required consistency.

(e) Forms

One of the advantages of shotcrete is that it eliminates the need for much of the forming found in conventional concrete applications, but some forming may still be required.

Form materials are the same as with conventional concrete, with wood and steel being the most common. Forms must be constructed and braced sufficiently to prevent vibration and deflection during placement. They must also be designed such that rebound and loose aggregate can freely escape or be easily removed.

Shooting strips (guide strips) are often installed in corners, edges, and surfaces so that it is possible to ensure proper thickness. Guide wires are used for control of the surface on curving or molded surfaces. They can also be used on horizontal or sloping surfaces to control the thickness of the shotcrete.

Wooden forms should be coated with a form release agent. Since the impact of the shotcrete may dislodge some of the agent from the form, it is recommended that an agent compatible with shotcrete application be

used. CS 33 identifies form release agent as a BioPreferred® product category.

With respect to forms, the inspector is responsible for verifying that:

- Forms are structurally adequate.
- Forms are designed such that rebound of accumulated loose aggregate can freely escape or be readily removed.
- Shooting strips are used at corners, edges, and on the surface where necessary to obtain true lines and proper thickness (ACI 506R–16 defines these guide strips).
- Guide wires are properly installed where necessary to control the surface or thickness.
- Header boards are installed where indicated on the drawings.
- Form surfaces are clean and a form release agent is applied before shotcrete is placed.

(f) Preparation of surfaces

The high-velocity placement of shotcrete onto a well-prepared and conditioned surface creates a strong bond. Preparation of surfaces for shotcrete is not different from what would be expected for conventional concrete. Earthfill surfaces should be cut to grade, firmly compacted, and have enough moisture so moisture is not wicked out of the shotcrete. Rock surfaces must be cleaned by water or sand blasting so only a sound surface remains.

ACI 506R–16 states that “Shotcrete applied to a clean, roughened concrete substrate in proper moisture conditions can form a bond that is stronger than the cohesive strength of the underlying area.” A saturated surface-dry subsurface is best for bond strength. Excessively wet or dry surfaces will result in a lower bond strength. Grinding or sandblasting hardened surfaces or brooming plastic surfaces is enough to produce the roughened condition that will increase the bond strength. The bond between successive layers of shotcrete placed shortly after the first layer begins to harden slightly and is so strong that it is not considered a cold-joint as with conventionally placed concrete.

With respect to preparation of surfaces, the inspector is responsible for verifying that:

- All surfaces to receive or support shotcrete have been adequately prepared and conditioned.
- All prepared surfaces have been inspected by the engineer before application of shotcrete.
- Earth surfaces have been firmly compacted and trimmed to line and grade.
- Concrete, mortar, or rock surfaces have been thoroughly cleaned by water blasting or sand blasting to remove all dirt, laitance, weak or unbonded mortar, loose material, grease, or other deleterious substances.
- Bonding surfaces are sufficiently rough to ensure adherence.
- Offsets that would cause an abrupt and substantial change in thickness of the shotcrete have been removed.
- Surfaces are maintained in a moistened condition for 3 hours prior to application of shotcrete.
- Shotcrete is not applied to mud, dried earth, uncompacted fill, rebound material, or surfaces having free water unless specifically authorized.
- All ice, snow, and frost is removed prior to placement.
- All surfaces to be in contact with the new shotcrete are no cooler than 40 degrees Fahrenheit.

(g) Placing

Vertical—Vertical shotcrete may be placed using multiple thin layers or by bench shooting. In both methods, the nozzleman will always begin at the bottom and work up, keeping the nozzle between two and six feet from the surface. If the placement is in multiple thin layers, the nozzle must be directed normal to the surface. Successive layers should not be shot until the previous layer has set.

In bench or shelf shooting, the nozzle is directed at approximately a 45 degree angle to the vertical surface and towards the bottom. Approximately the full thickness of shotcrete is placed in one layer as the nozzleman moves up the wall.

Overhead—Most overhead shooting will be by the multiple thin layers method. The thickness of the layer will be determined by the consistency of the shotcrete. Sagging and sloughing are indications that the shotcrete is too wet to be placed at that thickness.

Horizontal—The shotcrete placement method is usually not the best option for construction of horizontal surfaces due to the excessive amount of overspray and rebound, which will land back onto the surface of the shotcrete and create a weak plane when covered by subsequently placed shotcrete. If shotcrete is used, the gun should be oriented at an angle to the surface such that rebound accumulates on the completed area where it can be removed.

When shotcrete is first applied to a hard surface, there is no layer of mortar for the coarser particles to embed, so they will rebound off of the surface. This results in a cement-rich bonding layer being established at the bonding surface. As this layer grows thicker, coarser particles will begin to be retained. This is normal and results in a strong bond with existing hard surfaces.

With respect to placing, the inspector is responsible for verifying that:

- The contractor has all equipment and material required for curing at the site and ready for use before placement begins.
- No shotcrete is placed except in the presence of the engineer or authorized representative.
- Air pressure is adjusted during placement to control the rebound and density of shotcrete.
- For dry-mix applications, the air pressure and water pressure meet the minimum specified requirements.
- Corners are filled first.
- Shotcrete is placed in a layer thickness no greater than that which will cause sagging, sloughing, or dropout.
- Sags and sloughs are cut out and replaced before previously placed shotcrete has completely set.
- Vertical applications are started at the bottom and completed at the top.

- At any time that placement is interrupted for more than 1 hour, the edge of the layer must be shaped, protected, and conditioned prior to resuming application, as required by the specifications.
- Material that rebounds and accumulates on forms, steel, and other surfaces is removed prior to placement of shotcrete.

(h) Placing in cold weather

The effect of freezing of fresh shotcrete can be severe. A general rule of thumb is that any concrete subject to freezing during the first 24 hours may never achieve the desired compressive strength. It is also likely that this shotcrete will not be as resistant to weathering and will have an increased porosity. Shotcrete's resistance to freezing is somewhat enhanced by its high cement content. This will increase the heat of hydration but this gain could be offset by the fact that shotcrete is often placed in thin layers over a large surface area.

CS 33 defines cold weather placement as any time the atmospheric temperature is expected to drop below 40 degrees Fahrenheit during placement or at any time during the curing period. Placement may not be started unless the temperature is at least 40 degrees Fahrenheit and rising and must be discontinued if the temperature falls to 40 degrees Fahrenheit and is expected to continue to fall. The specification also states that the temperature of the shotcrete at the time of placement must not be less than 50 degrees Fahrenheit.

Shotcrete can be placed during cold weather with proper planning and procedures. CS 33 requires that the temperature of the shotcrete and the surrounding air be maintained between 50 degrees Fahrenheit and 90 degrees Fahrenheit for the duration of the curing period through insulation or heated enclosures. It refers to ACI 306R, Guide to Cold Weather Concreting, for guidance on insulating, housing, and heating. It is important for the inspector to have a copy of this reference and a good maximum and minimum thermometer during placement in cold weather.

With respect to placing in cold weather, the inspector is responsible for verifying that:

- Placement is not started unless the temperature is at least 40 degrees Fahrenheit and rising.
- Placement is discontinued if the temperature falls below 40 degrees Fahrenheit and is expected to continue to fall.
- The temperature of the shotcrete is not less than 50 degrees Fahrenheit when placing.
- When the daily minimum temperature is less than 40 degrees Fahrenheit, the shotcrete must be insulated or housed and heated after placement and maintained at not less than 50 degrees Fahrenheit for the duration of the curing period.
- Methods of insulating, housing, and heating the structure comply with ACI 306.1.
- Accelerators or antifreeze compounds are not used unless specifically authorized.
- When dry heat is used to protect shotcrete, an ambient humidity of at least 40 percent is maintained unless a curing compound is applied or the shotcrete is covered tightly with an impervious material.
- Removal of insulation or artificial heating is done such that there is not a rapid temperature drop, which could cause cracking.

(i) Placing in hot weather

High ambient or materials temperatures, low relative humidity, solar radiation, and wind can greatly affect the quality of shotcrete by accelerating the moisture loss and increasing the rate of cement hydration. The temperature of wet-mix shotcrete can also increase due to being pumped long distances through a small diameter hose. Hot weather can increase water demand, which decreases compressive strength; reduce the workability and pumpability of wet-mix concrete; cause the shotcrete to set quicker, limiting the time to finish; and increase surface cracking because of moisture loss and shrinkage.

The contractor must plan in advance for ways to combat these issues during a hot weather placement. Some precautions that could be used include avoiding the heat of the day by shooting early or late, cooling the aggregates by shading or wetting, adding ice to cool the mixing water, shading or wetting the receiving sur-

face, and fogging the surface immediately after finishing to cool the shotcrete and prevent moisture loss.

CS 33 limits the maximum temperature of the shotcrete during mixing, conveying, and placement to 90 degrees Fahrenheit. ACI sets the maximum limit a little higher (95 °F) and limits the temperature of steel reinforcement to 90 degrees Fahrenheit. Placing shotcrete during hot weather conditions is not ideal but sometimes unavoidable. The inspector must verify that the contractor has a plan to take necessary precautions when conditions warrant to meet the required specifications and ensure a successful product.

With respect to placing in hot weather, the inspector is responsible for verifying that:

- The temperature of the shotcrete is maintained below 90 degrees Fahrenheit during mixing, conveying, and placing using an approved method.
- The temperature of the aggregates or mixing water do not exceed 100 degrees Fahrenheit.
- The temperature of the shotcrete does not exceed 90 degrees Fahrenheit during the curing period.
- Exposed shotcrete surface that is drying too rapidly is continuously moistened.
- Surfaces exposed to air are covered and kept continuously wet for at least the first 24 hours and for the entire curing period unless an approved curing compound is applied.

(j) Replacement or repair

The shotcrete application process can result in problems with uniformity that otherwise do not occur in conventional concrete placements. Those problems are generally segregation, honeycombing, laminations, dry patches, slugs, voids, or sand pockets. The determination as to when removal and replacement are required, and the extent necessary, should be based on the judgement of an experienced person. CS 33 requires the engineer's concurrence on the extent of removal and replacement. It also requires the presence of the engineer when any repair work is performed.

All repairs should be made with repair shotcrete meeting the same requirements as the original. Any damaged reinforcement must be replaced. The repair

areas must be trimmed to remove all of the defective shotcrete and expose enough reinforcement so that the replaced reinforcement can be effectively spliced. The edges should be trimmed to a 45 degree angle and moistened before placement of new shotcrete.

Rare uniformity problems are not a great source for concern if the defective areas are removed and repaired correctly. If problems occur more frequently, the cause of the defective work must be discovered. It may be the result of equipment failure or material problems, but it is often seen to be the result of a poor or inattentive nozzleman.

With respect to replacement or repair, the inspector is responsible for verifying that:

- The engineer concurs in the extent of removal and replacement.
- The engineer approved of the contractor's plan for making repair.
- Repair work is only completed in the presence of the engineer.
- Reinforcement damaged during removal is replaced.
- Sound shotcrete at the edges of the repair area are trimmed to expose sufficient reinforcement for competent repairs.
- Sound shotcrete at the edges of the repair area are trimmed to a slope of 45 degrees and moistened before new shotcrete is placed.
- The repair area is cured properly.

(k) Finishing

There are several finishing options available to the design engineer. CS 33 allows a natural gun finish (sometimes called a shot finish) unless further screeding or finishing are specified in the items of work. The natural finish only requires a minor amount of floating to remove the impressions left after guide strips or guide wires are removed.

If screeding is specified, CS 33 outlines a procedure to follow:

1. Place shotcrete a fraction beyond the guide strips, ground wires, or forms.
2. Allow the surface of the shotcrete to stiffen to the point it will not pull or crack under screeding or troweling.
3. Trim, slice, or scrape excess material to true line and grade and remove the placing guides.

The engineer could specify that the contractor construct a mockup panel to demonstrate the finish of the final exposed shotcrete surface. While there is no requirement for this in CS 33, it could be an added requirement in areas of high visibility or when there is another reason to have concern for the final finish.

With respect to finishing, the inspector is responsible for verifying that:

- Rebound material is promptly removed from finished surfaces before it becomes too hard to remove.
- The surface has been checked for low spots and repaired with additional shotcrete.
- The final surface is finished as per the requirements of the specification.
- When screeding is specified, it is completed as specified.

(l) Curing

With respect to curing, the inspector is responsible for verifying that:

- Shotcrete is prevented from drying for a curing period of at least 7 days after it is placed.
- Wood forms left in place during the curing period are kept wet.
- Formed surfaces are wetted immediately after form removal and kept wet until patching and repairs are completed.

- The shotcrete surface is not damaged by applying water or covering.
- Curing water is clear and free from substances that cause discoloration.
- Curing compound is mixed and applied as specified.
- Curing compound is not applied to the reinforcing steel or any surface that is to bond with subsequently placed shotcrete.
- Surfaces covered by a curing membrane that are subject to traffic are protected from damage or wear.

645.1402 Sampling and Testing

ACI recommends preconstruction testing if there are concerns about being able to completely encase reinforcement steel because of dense spacing or complex layouts. This would entail creating and shooting a typical test panel.

ACI 506.4R, Guide for the Evaluation of Shotcrete, is a comprehensive resource for destructive and nondestructive testing methods for shotcrete.

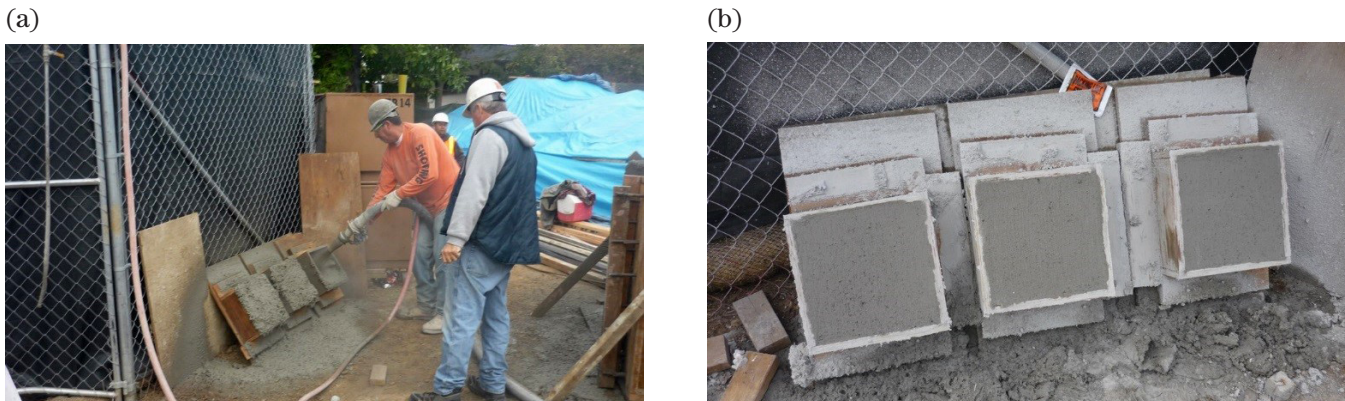
(a) Preparing test panels

ACI recognizes three different reasons to create test panels. A preconstruction test panel was previously mentioned in discussing the nozzle operator qualifications. Preconstruction test panels are also used to approve the contractor's equipment, process, and shotcrete design mix. They are usually constructed to represent the most difficult areas to shoot in terms of shape and density of reinforcement.

Mockup test panels were mentioned in the finish section of this chapter. They are prepared to demonstrate that the finish that can be achieved on exposed shotcrete surfaces.

Production test panels are prepared during construction with the purpose of documenting the compressive strength of the production shotcrete (fig. 14-6 a and b). Because of the nature of shotcrete placement, it is impossible to fill and compact a compressive strength

Figure 14-6 Construction of production test panels for compressive strength cores (*Courtesy of Bryan Mekechuk and Bill Brown*)



cylinder as you would for a conventional concrete placement. For this reason, test panels are constructed and cores taken and tested.

Test panels are prepared in a manner that attempts to replicate the field situation as closely as possible. Shotcrete test panels for applications that are vertical or overhead must be shot in the same orientation. CS 33 requires that the test panels be a minimum of 18 inches square and 6 inches thick. Cores taken must be cured in lime water at a temperature of 73.4 degrees Fahrenheit plus or minus 3 degrees within 24 hours of coring. Figures 14–7a through c show the coring of test panels for testing.

With respect to preparing test panels, the inspector is responsible for verifying that:

- Test panels are prepared in accordance with ASTM C1140.
- Panels are a minimum of 18 inches square and 6 inches thick.
- Cores are cured as required.

Figure 14–7 Coring test panels for compressive strength testing (*Courtesy of Bryan Mekechuk and Bill Brown*)



645.1403 Records and Reports

The following records and reports are related to shotcrete:

- Daily Diary—used to record the day-to-day activities of construction including concrete activities

Appendix 14C contains an example of a typical diary entry related to shotcrete construction.

645.1404 References

- American Concrete Institute. 2016. Guide to shotcrete. ACI 506R-16. Farmington Hills, MI.
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