american shotcrete association

# Spraying Shotcrete Overhead in Underground Applications

## INTRODUCTION

### General

In underground applications, spraying shotcrete overhead is a standard and daily operation but successful application is challenging. Shotcrete placement propels concrete at high velocity against the overhead surface and the dynamic energy compacts the concrete in place. However, because the plastic shotcrete has no immediate strength, its own weight wants to pull it down. Depending on its thickness, the weight of the shotcrete layer can be significant. The density of plastic shotcrete is in the order of 150 lb/ft$^3$ (2400 kg/m$^3$). One inch of a 1 ft$^2$ area weighs around 12 lb (5.5 kg). Each additional inch of thickness adds an additional 12 lb (5.5 kg). The weight of a single layer or multiple layers of shotcrete can be enough to pull the shotcrete down and cause local or large-scale fallouts, which may pose a significant safety hazard. In addition, improper application of overhead shotcrete and other circumstances can lead to delamination and voids in the installed shotcrete.

This position paper discusses the basic elements of the adhesion and cohesion of overhead shotcrete, proper application techniques, and a discussion about so-called "re-entry criteria" under freshly installed shotcrete. The position paper also provides recommendations for contractors and owners from ASA's perspective on not only how to properly apply shotcrete, but also on how to specify and inspect overhead shotcrete in underground projects and summarizes the topic in a conclusion.

### Adhesion and Cohesion

The phase immediately after application, when the shotcrete has not gained any significant strength prior to the initial set, is referred to as "plastic shotcrete." What is holding the plastic shotcrete in place until it gains strength? During the plastic shotcrete phase, the adhesion of the plastic material to the ground surface in combination with the cohesion of the plastic shotcrete material to itself are the forces acting against the self-weight of the plastic shotcrete. Because the chemical reaction of the cement in the mixture is still in progress and has not yet created significant strength, the plastic shotcrete sticks overhead only if the conditions for adhesion and cohesion are right.

To achieve proper adhesion to the substrate, for example, for initial tunnel linings or for shotcrete applied against an existing concrete surface, the receiving surface must be properly conditioned. If the substrate surface is too dry, water can be sucked out of the shotcrete mixture, reducing the adhesive bonding to the substrate. This can lead to a failure in adhesion. Therefore, the surface should have a so-called "saturated-surface-dry (SSD)" condition, which neither sucks water out of the mixture nor adds excess water at the bond interface.

On the other hand, if the surface is too wet, for example, due to running water or fresh washing down of the surface with water, the adhesion of the plastic overhead shotcrete is also diminished. Effectively, a thin water layer builds up between the substrate and the shotcrete and the adhesion is too small to act against the plastic shotcrete's weight and fails, creating shotcrete fallouts or delaminations and voids.

Another type of adhesion failure appears if the shotcrete is not applied directly onto a properly prepared bearing substrate, but on a thin layer of dust, debris, or overspray covering it. The thin layer prevents adhesion of the shotcrete to the substrate. It is essential that the surface be cleaned prior to receiving any fresh shotcrete.

Cohesion failure does not appear at the interface of two different materials but within the substrate or shotcrete material. There are two scenarios for a cohesion failure creating shotcrete fallouts.

Cohesion failure in the plastic shotcrete can either appear if the mixture's consistency is too wet or too dry. Slump is a generally good indicator of consistency, but it is not the only factor, especially if plasticizers and water-reducing admixtures are used to control consistency.

Cohesion failure can also appear in the substrate itself. This is a known phenomenon, for example, in soft ground tunneling for cohesionless sands, where the bonding fails within the sand due to the added weight of the shotcrete. Similar effects can also be observed in rock tunneling, for example, in highly fractured rock or fault zones. Therefore, the geotechnical conditions must be considered too when evaluating shotcrete fallouts. In addition, the geotechnical parameters are not proactively controllable. Rather, the shotcrete applicator must recognize and react to changes in geotechnical conditions as they appear.

### Interlocking

If shotcrete is sprayed overhead on an ideal macroscopically and microscopically smooth surface, the only resisting force acting against the weight of the material is provided by adhesion and cohesion. However, this assumption is unrealistic in underground projects, where the substrate is neither macroscopically nor microscopically homogeneous and horizontal. Typically, a ground surface is irregular, blocky, or porous and the shotcrete interlocks mechanically with smaller and larger niches and pores of the rock or ground surface, allowing the shotcrete material to fill and bridge over these irregularities. The use of this interlocking effect is one of the major aspects controlling the shotcrete bond when spraying in mining or tunnel applications and experienced underground nozzlemen take advantage of "reading the rock."

Interlocking also appears in a similar manner with man-made "irregularities" such as lattice girders, spider plates on rock bolts, or reinforcement. In addition, these man-made structural elements are typically anchored into the ground, allowing relatively large forces to be transferred into the ground via these anchor points and so expediting the shotcrete application process by not solely depending on adhesion and cohesion.

## PROPER APPLICATION OF SHOTCRETE OVERHEAD

### Mixture Proportion and Slump

For overhead shotcrete application, the wet shotcrete must have sufficient "stickiness" to provide the required adhesion and cohesion.

In general, mixtures with a higher fines content (for example, due to the addition of silica fume or similar materials) are advantageous for overhead applications, because the fine material increases cohesion and adhesion of the freshly applied shotcrete.

In addition, the use of accelerator improves the needed application properties, because the initial set of the shotcrete starts earlier and replaces the sole reliance on adhesion and cohesion of the plastic shotcrete to prevent fallouts. However, too much accelerator can be detrimental, because if the material sets up too quickly, it can adversely affect proper compaction of the plastic shotcrete, effectively reducing the adhesion to the substrate and cohesion of the plastic shotcrete.

The slump needs to be in the right range and should not be too high or too low. Higher slumps are necessary if the material must be pumped over longer distances. Higher slumps also are needed to help uniformly disperse the accelerator added at the nozzle and therefore enhance the effect of fast set and quick development of early-age compressive strength in the shotcrete. However, if the slump is too high, such as 10 in. (250 mm) and above, the mixture could segregate and cause problems during pumping and shooting. Therefore, the slump is typically between 6 and 8 in. (150 and 200 mm) for most underground applications when using accelerator.

High-range water-reducing admixtures, hydration control admixtures, and other admixtures are frequently used to make the mixture more pumpable and shootable to meet the operational challenges of the project. Effects of these admixtures and accelerators will depend on the mixture design, environmental conditions, and other factors. The required dosages of these admixtures and accelerators should be determined by preconstruction laboratory and field testing.

### Surface Preparation

Before the application of shotcrete, the receiving surface must be free of loose debris and dust. Loose rock should be scaled and brought to SSD conditions. If shotcrete is installed on a previously shotcreted surface, the older shotcrete also must have SSD conditions. If the surface is older, a thorough cleaning may be required to remove dust and any soot from diesel engines.

Dripping or running water needs to be channeled off and controlled before and during shotcrete placement. If groundwater runs out of joints or pores that is sealed off by shotcrete, the increasing water pressure acts from the extrados (area facing the rock or ground) on the lining in addition to the shotcrete weight and increases the risks for shotcrete fallouts. The buildup of water pressure needs to be prevented by water control measures such as drainage mats, weep pipes or holes, or similar measures.

### Thickness of Each Pass

As compared to vertically applied shotcrete, the thickness of each pass in overhead shotcrete application is much more critical. To avoid too much weight per pass, the overhead shotcrete is typically applied in thin layers of around 2 to 4 in. (50 to 100 mm) thickness per pass, depending on the mixture design and application method (wet- or dry-mix shotcrete). Thicker passes up to 6 in. (150 mm) are possible, but acceptability should be verified on a mockup for each nozzleman under site-specific conditions. After the shotcrete of the previous layer starts to set and gains initial strength, additional thin layers may be applied in subsequent passes. The total thickness installed per shift, however, should typically not exceed about 12 in. (300 mm).

To maintain sufficient cohesion between these passes, the previous layer should always have proper SSD conditions and be prepared as outlined previously. The typical rough, as-applied shotcrete surface provides additional interlocking between the layers and is therefore also advantageous. This should be taken into consideration during the spraying of subsequent layers and when planning surface finishing.

## Anchors, Lattice Girders, and Reinforcement

If spider plates are used or reinforcement is tied to anchors, building the shotcrete up around the anchor points is the first step during shotcrete installation. From there, thin shotcrete layers bridging the gaps between the anchor points should be created. After this shotcrete material has initially set and starts developing strength, additional thin layers may be applied in following passes. If the area is large enough, the additional passes may follow without interrupting the shooting process by simply varying the locations of shotcrete installation within the section, allowing freshly shot areas time to set before additional shotcrete is applied in the same area again.

If lattice girders are used, the girders should be embedded first from the bottom up, followed by closing the gap between the girders, in several passes as needed. Shooting from multiple angles and working the shotcrete like a key way from the bottom to top, always focusing on shooting into the previous layer, is essential. Lattice girders pose a challenge for proper encapsulation with shotcrete. Proper embedment of lattice girders requires the nozzleman and air lance operator to frequently move during shooting. Shooting from multiple angles and using a series of thin placements are key elements to good shotcrete encapsulation of lattice girders.

Reinforcement must be rigid. In addition, the reinforcement must be tied sufficiently to the bearing members such as the lattice girders or anchors, because these supporting members must carry the weight of the reinforcing bars plus the weight of the wet shotcrete. If the reinforcement sags or is loose, it will vibrate and cause voids around the reinforcement and potentially lead to shotcrete fallout.

## Waterproofing Membranes

Installation of overhead shotcrete on waterproofing membranes presents extra challenges and is covered in a separate ASA position paper.[1] Too much sagging or spanning of the membrane between the fixation points must be avoided. Different than form-and-pour concrete, where the liquid pressure of the poured concrete pushes and holds the membrane against the substrate, shotcrete does not provide any significant pressure against the membrane immediately after the shotcrete has been placed. If the membrane sags too much or is loose, the impact energy of the shotcrete will not push and hold the waterproofing against the substrate. If the membrane is not properly secured and loosely spans between the anchors, it may vibrate during the shooting, preventing the plastic shotcrete from adhering. This can cause fallouts, or result in defective shotcrete that may need massive grouting on the extrados of the shotcrete lining. Therefore, extensive inspection and quality control prior to the shotcrete application are required to assure the waterproofing membrane is installed and secured tightly to the substrate. This tight installation must be provided either by a sufficiently tight anchor spacing, chairs, and/or distancers from lattice girders and reinforcement actively pushing the membrane against the substrate.

In addition, waterproofing admixtures added integrally to the applied shotcrete are being used in some areas and may prevent problems associated with the use of classic waterproofing membranes. Another option is the use of spray-applied waterproofing membranes. The use of spray-applied waterproofing membranes is relatively new in North America but has been used on many underground projects around the world. A discussion of the advantages and challenges of spray-applied waterproofing membranes is, however, beyond the scope of this document.

## Overhead Shotcreting Procedures and Techniques

Due to the technical challenges and potential safety hazards, overhead shotcrete should only be applied by qualified shotcrete nozzlemen. The nozzlemen must be properly trained, experienced, and certified as ACI Certified Nozzleman for overhead application of wet- or dry-mix shotcrete. ACI Certified Nozzlemen must shoot overhead panels during the certification process and provide documentation of a minimum of 500 qualifying shotcreting hours experience prior to taking the ACI shotcrete certification exams.

However, it should be noted that the ACI overhead shotcrete nozzleman certification is the minimum requirement. The shotcrete nozzleman must also attend and pass project specific preconstruction qualification processes, which typically involve mockup shooting with the project-specific mixtures, equipment, procedures, and construction methodology. There could also be a two- or multiple-tier qualification process involving a basic level, project-specific level, and an additional level depending on the complexity of the project. The contractor and the engineers should develop a proper but rigorous project specific qualification program to qualify the shotcrete nozzlemen properly for their specific project.

To ensure proper preparation and inspection of the substrate and sufficiently close proximity of the shotcrete nozzle to the substrate, either scaffolds or manlifts are required in taller cross sections. If no surface finish is needed (for example, for a shotcrete initial lining), a manlift typically provides sufficient access and flexibility for manually applied shotcrete. A scaffold is typically needed when a more work-intense finish such as a rubber float or steel trowel or stamped or carved finish is required. A shotcrete robot or shotcrete nozzle manipulator is a typical alternative to a manlift if large volumes of shotcrete are required to be sprayed.[2] In addition, robots and manipulators also allow the nozzleman to remotely control the machine and to stay out of the potential fallout zone for the freshly applied shotcrete.

Underground applications of shotcrete often present difficult access for equipment and the steel pipe and/or rubber hoses. Special attention and planning are required to assure the safe and efficient movement of the equipment. Good air flow is required and the delivery lines should be placed out of the way in access roads.

A key element for propelling shotcrete material overhead at a sufficient impacting velocity is the air flow. Air pressure and flow losses due to wear and other uses of air must be considered. It is therefore important that sufficient air flow is received and maintained at the nozzle.

Generally, a higher amount of rebound is to be expected when applying shotcrete overhead versus vertical. However, the amount of rebound varies greatly and is dependent on numerous factors, especially the experience and skill of the nozzleman and his team.

## RE-ENTRY CRITERIA

Shotcrete fallouts from freshly applied overhead shotcrete pose a potential safety hazard. The occurrence of fallout is hard to predict, especially in underground conditions, where multiple factors can cause the fallout. Therefore, no one should stand, work, or move under freshly installed overhead shotcrete. The entire team should be trained and aware of the fallout hazard. Safety barriers or tapes should be installed.

Early-age compressive strength development is often used as an indicator of when to allow the re-entry into the previously restricted area under freshly applied shotcrete. The so-called "re-entry criteria" is based on the early strength, either tested in the field or a time period based on a previously tested early strength development graph. When a time period is used, it should be understood that the early-age strength development is also dependent on materials supply and environmental and operational conditions. Therefore, the early strength development and time to reach specific early-age strength under project conditions may vary from the conditions which prevailed during the preconstruction tests. Therefore, it is generally preferred to develop re-entry criteria based on actual early-age strength development, rather than a predetermined time period. However, it is emphasized that neither a strength- nor a time-based re-entry criterion provides a guarantee against fallouts because fallouts are influenced by a multitude of factors, as discussed previously.

The early strength development of the shotcrete should, therefore, be tested in preconstruction tests and/or mock-ups mimicking the project conditions. If factors such as shotcrete and ambient temperature, mixture design, equipment, and accelerator dosage vary, then these tests should be repeated to gather a better understanding of their influence on the early strength development.

There are testing methods available to monitor the initial set and strength development of shotcrete, but these do not test the amount of adhesion and cohesion of the plastic shotcrete. Adhesion and cohesion cannot be measured in a practical and safe manner in the field.

The initial and final set are defined as a degree of stiffening of a cementitious mixture based on empirical values to resist the penetration of a weighted test device.[3] Both the initial set and the final set are used to determine the state of the chemical reaction of the cementitious materials with the water and the accelerator, but not strength development.

Because the early-age compressive strength is typically considered to develop after the final set, the initial set and final set are used as indicators that the early age compressive strength will develop accordingly. Typical values for an early compressive strength-based re-entry criteria range between 150 to 500 psi (1 to 3.5 MPa) and are typically measured with a penetrometer or end-beam tester. However, a re-entry criteria for the general public (for example, in a rehabilitation project) should be significantly higher.

The accelerator dosage is defined as a percentage by mass of cement (not the cementitious materials, as in the water-cementitious materials ratio) in the shotcrete mixtures. Accelerator use and dosage have a very large impact on the rate of early-age strength development and with it, the re-entry criteria. The accelerator dosage is based on the amount of cement in the concrete and the amount of accelerator pumped per time unit. To maintain a constant accelerator dosage, the accelerator dosing pump must, therefore, be properly calibrated relative to the pumping rate of the concrete pump and closely controlled during shotcrete application to ensure that the planned accelerator dosage is achieved. If the concrete pumping rate is changed, the accelerator pumping rate needs to be adjusted accordingly to maintain the same accelerator dosage. Sophisticated equipment, including synchronized accelerator dosing pumps and concrete pumps, automates these adjustments and reduces the potential for over or under dosing accelerator and are therefore the best system to achieve consistently high quality while maintaining flexibility in the concrete pump rate. It should be noted that in an intermittent wet-mix pump, the flow (and pressure) of concrete can oppose the flow of accelerator (and air), resulting in layers of accelerator between pump strokes. It also means that the flow of accelerator can be higher when there is no concrete going through the air ring and nozzle.

## RECOMMENDATIONS FOR THE CONTRACTOR

The contractor is in charge of the project's safe working conditions and the quality of the placed shotcrete. It is therefore recommended that the contractor follows the guidelines provided by ACI 506 and the recommendations provided herein with regard to proper surface preparation, maximum thickness in each pass and shift, and quality control of the condition of the receiving surface.[4-6] The shotcrete application work should be conducted by ACI certified shotcrete nozzlemen, only.

Preconstruction testing and mockups are essential to test the mixture design, strength development, equipment operation, and setup, in particular the accelerator dosing pump calibration, and project conditions. If the tests show inadequate results, the process must be optimized and the tests should be repeated. The tests should be seen as a beneficial tool to avoid safety hazards and rework during execution and not simply a contractual obligation.

## RECOMMENDATIONS FOR THE OWNER

The owner and the designer should be aware of the challenges and restrictions for overhead shotcrete installation and should specify the project accordingly. It is strongly recommended that the specification follows the ACI 506 guidelines and involve personnel familiar and experienced with the application of shotcrete in the underground environment.[4-6]

Requirements recommended herein should be specified. Preconstruction testing and mockups are highly recommended and provide an efficient tool to optimize the system before applying shotcrete at the project and are money well spent.

The owner's inspection team should ensure the shotcrete operation follows the specified requirements, but should also understand the reasons behind the specified properties. Proper surface preparation, especially if the surface preparation is provided by others, is a key element.

## CONCLUSIONS

Installation of overhead shotcrete in underground applications is a challenge and requires special experience and skills to be successful. This position paper discussed the basics of overhead shotcrete installation and provides recommendations for dos and don'ts along with guidance for the development of safe re-entry criteria under shotcrete applied overhead in an underground setting.

Overhead shotcrete can be executed safely and with high quality, if the process parameters defined in this position paper are consistently and correctly executed.

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## References

1. ASA Underground Committee, "Position Statement #2, Spraying Shotcrete on Synthetic Sheet Waterproofing Membranes," American Shotcrete Association, Farmington Hills, 2019, MI, 3 pp.

2. ASA Underground Committee, "Position Statement, Robotic Shotcrete in Underground Applications," American Shotcrete Association, Farmington Hills, MI, 2019. (in development)

3. ACI CT-18, "ACI Concrete Terminology," American Concrete Institute, Farmington Hills, MI, 2018, 76 pp.

4. ACI Committee 506, "Guide to Shotcrete (ACI 506R-16)," American Concrete Institute, Farmington Hills, MI, 2016, 52 pp.

5. ACI Committee 506, "Specification for Shotcrete (ACI 506.2-13)," American Concrete Institute, Farmington Hills, MI, 2013, 12 pp.

6. ACI Committee 506, "Guide for Specifying Underground Shotcrete (ACI 506.5R-09)," American Concrete Institute, Farmington Hills, MI, 2009, 52 pp.

## Position Statements

ASA has produced position statements on the best practices for proper shotcrete placement. To date, six position statements from our Pool & Recreational Shotcrete Committee, two from our Underground Committee, and one from our Board of Direction have been issued. These statements have also been published in *Shotcrete* magazine.

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