Position Statement #3
ASA Underground Committee

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Encapsulation of Reinforcement in Tunnel Shotcrete Final Linings

Introduction

Using shotcrete for the placement of concrete for tunnel final linings is becoming more common. In the past the use of shotcrete final linings was typically limited to non-public or emergency egress areas, however, shotcrete is being used more and more in public areas. The use of shotcrete is typically an attractive alternative to form-and-pour final lining installation where formwork costs are high or technically challenging, pose a scheduling issue, or where labor rates are very high. Typical examples for successful use of shotcrete final linings are complex lining geometries, intersecting or merging tunnels, widenings, short tunnels without sufficient repeating utilization of the forms, or underground systems where formwork would block passing traffic.

However, installing final lining shotcrete has numerous challenges. Some of them are addressed in ASA's position statements about spraying shotcrete overhead [8] or on sheet waterproofing membranes. Improper application of shotcrete can create areas of lower density, resulting in higher permeability and potentially an increased rate of corrosion. If reinforcing steel bar or wire mesh reinforcement is used, proper encapsulation of the reinforcement is one of the key elements for a successful and high-quality shotcrete final lining installation.

Advances in concrete admixtures and metered alkali-free accelerator have helped reduce the issues mentioned above. Using higher slump mixes while maintaining a 0.40 w/cm ratio helps increase the material velocity as well as allowing proper injection of the accelerator. The use of silica fume and migrating corrosion inhibitors along with waterproof membranes has helped increase the density of the liner, and provides improved corrosion resistance on both sides of the shotcrete shell. Reports and guidelines developed by the American Concrete Institute's Shotcreting Committee (ACI 506) [3,4,5,6,7] provide valuable resources in this regard. Also, shotcrete is now fully recognized as a method for concrete placement in ACI 318 [2]. ACI 318 states "Shotcrete is considered to behave and has properties similar to concrete unless otherwise noted." So, it is expected that the use of shotcrete in-place of form-and-pour for tunnel final linings will increase in the future. This position statement provides guidance and recommendations for the proper encapsulation of embedded reinforcement in tunnel shotcrete final linings. Most of the guidance provided is based on the referenced documents of the ACI Technical Committee 506 that is charged with creating and maintaining consensus documents on shotcreting [3,4,5,6,7].

Encapsulation of Reinforcement

Proper encapsulation of reinforcement provides the structural integrity of the lining. The encapsulation is necessary for stress transfer between the concrete and the reinforcing bar, and the durability of the structure. Proper placement and encapsulation also prevent voids or low density areas, that could accumulate water and increase the permeability of the lining. Therefore, the encapsulation of reinforcement is very important and requires special attention.

The shotcrete nozzleman conducting the work shall be ACI-certified in the shotcrete process (wet-mix or dry-mix) and orientation that the lining requires (typically both vertical and overhead). The nozzleman should also have shotcreted on at least 2 to 3 comparable projects. Past experience is particularly important before participating on projects including complex reinforcement configurations.

The encapsulation of reinforcement in form-and-pour concrete is usually achieved by internal vibration resulting in compaction of the liquid concrete. For shotcrete, the proper consolidation and encapsulation is more challenging. The successful use of shotcrete for tunnel final linings depends on the installation process and workmanship of the nozzleman and the shotcreting crew. The reinforcement layout, and concrete mixture design used, are also key elements for a successful placement. Using proper materials, appropriate equipment, layout and placement techniques facilitates the use of shotcrete for high quality, heavily reinforced tunnel final linings.

It is essential to highlight that the shotcrete nozzleman needs to know how to correctly apply shotcrete for the entire lining section including wire mesh, reinforcing bars, lattice girders, or underlaying waterproofing layer. Each element requires different application techniques or more careful attention, which in most cases are accomplished by avoid sloughing and fall-outs. Details, such as concentrating on getting the first coat onto the waterproofing and wire mesh layer before applying a thicker layer with reinforcing bars or the backside of the lattice girders, are essential.

Shotcrete provides consolidation and densification by high-velocity impact of fresh concrete material on the receiving surface. The high-velocity impact of shotcrete onto a hardened, previously placed layer of shotcrete, that is roughened and brought to a saturated-surface dry (SSD) condition, provides a strong abrasive blast, which opens the freshly hardened surface, creating immediate exposure of the fresh cementitious material paste [3] inherently creates an excellent bond that allows multiple layers to act as if monolithically cast. In most cases when shooting a lattice girder liner two layers of shotcrete are required. The final layer usually requires more time than the initial layer. The first layer is usually water blasted to remove any loose material left by roughening the layer, and removing any dust or overspray deposited by shotcreting in adjacent areas. The water blasting also tends to open the pores of the harden concrete surface for better bond between the first and second layer.

During the shotcreting process, the high velocity flow of the concrete mixture hitting the reinforcing bars directly in the shotcreting stream may clean the outward facing surface of the reinforcing bar from a slight material build-up of fines and sand from a light overspray. However, this positive effect is highly dependent on proper airflow, material consistency and nozzling technique. In general, concrete mixture designs without larger aggregate have more potential to allow a build-up of improperly compacted material on the face of the reinforcing bar. Significant material build-up on the face of the steel bar increases the size of the spray shadow and should be avoided. Using a rapid-set accelerator may increasing the strength of the overspray, thus hindering the positive effect of the cleaning of the reinforcing bar with the material stream.

Thus, proper experience and craftsmanship of the nozzleman and shotcreting crew, as well as use of a blowpipe, are necessary key elements to achieve successful placement. The key to proper encapsulation of reinforcement is the avoidance of voids, honeycombing, or low density concrete, with special attention to areas of shadowing. The term "shadowing" refers to an area behind the reinforcement that may not be filled in or fully compacted, because the reinforcing bar interrupts the material stream (see Fig. 1). When shotcrete is properly installed, the area in the spray shadow is filled by concrete that flows around the bar, by driving fresh concrete behind and adjacent to the bars due to flowability of the mixture and compaction by the impact (Fig. 3). For proper encapsulation, the shotcrete must have sufficient plasticity and impact velocity. Though shotcrete placement generally is at a 90 degree angle to the receiving surface when encasing large bars, plates or embeds the shotcrete stream may need to be angled to place concrete behind the larger shadow zone (Fig. 2).

DESIGN

The design of structures using shotcrete placement as required by the ACI 318 Code [2] is generally not different

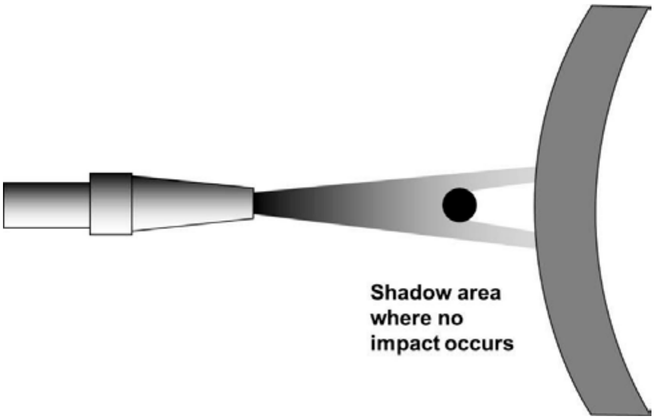

Fig. 1: Shadowing behind reinforcement [3]

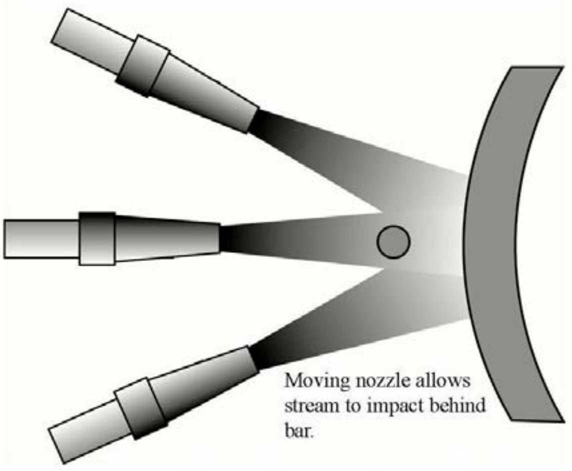

Fig. 2: Encasing large diameter bars. Nozzle slightly angled to force material behind the bar [10]

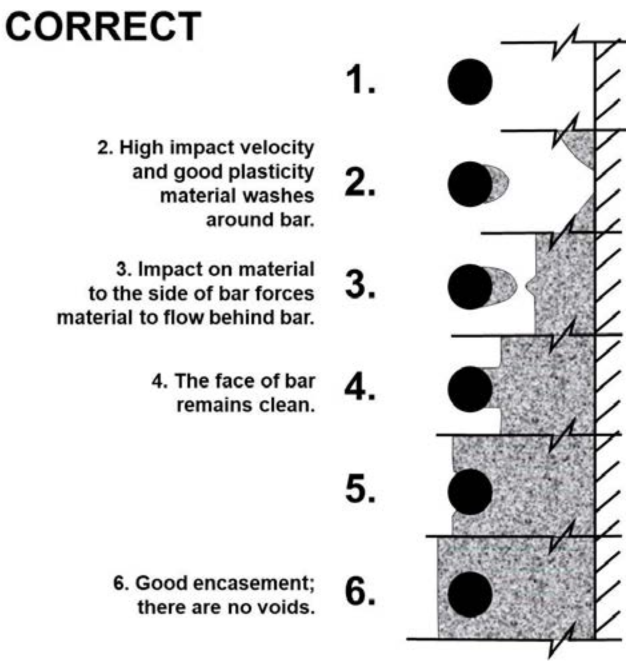

Fig. 3: Correct Encapsulation of Reinforcement [3]

from form-and-pour or other concrete installation methods. Best results are obtained when the reinforcement is designed and positioned to cause the least interference with the placement of shotcrete. The reinforcement should be designed and installed with attention to sizes, spacing, and layout to facilitate the placement of shotcrete. Sufficient clearance around reinforcement is needed to allow the shotcrete material to flow around the reinforcement while allowing the air uses to propel the concrete materials to escape. Insufficient clearance can create trapped air voids. As the reinforcing bar size increases or the spacing decreases, the nozzleman's skill becomes increasingly important to ensure complete encapsulation. Bar lap splices, couplers, number of reinforcement layers, and the depth of section can also interfere with the shotcrete stream or reduce velocity, which further complicates encasement and requires careful attention by the nozzleman [3].

ACI 318 [2] provides specific minimum spacing for reinforcement for members with "parallel non-prestressed reinforcement", which applies for tunnel linings. The clear spacing between bars shall be at least 2-1/2 in. (64 mm) for #3 (#10M) bars and 6db (db = nominal diameter of the bar) for #4 (#13M) or larger bars. If two layers of reinforcement are provided and shotcrete is shot through both layers, the clear spacing between bars in the intrados shall be at least 12db, while the clear spacing between bars in the extrados shall meet the requirement above (at least 2-1/2 in. and 6db). A tighter spacing of reinforcement is permitted if proper reinforcement encapsulation can be successfully demonstrated in pre-construction shotcrete mockup panels. The shotcrete mockups are to be representative of the most complex reinforcement configurations to be encountered. For further guidance regarding the mock-up configuration and shotcrete evaluation refer to ACI 318 [2] and ACI 506 [3,4,5,6].

The special requirements and challenges of spraying shotcrete through multiple layers of reinforcement can generally be avoided if each layer of reinforcement is encapsulated in a separate layer of shotcrete. This means the subsequent layer of reinforcement is installed after the previous layer is already fully encapsulated in shotcrete thus incrementally installing and encapsulating one layer of reinforcing bar at a time, until the full thickness of the lining is achieved.

For non-contact lap splices of reinforcement (a connection of reinforcing steel made by lapping the ends of bars not in direct contact [1]), the clear spacing provided by ACI 318 [2] shall be at least the greater of 6db and 2-1/2 in. between bars for #6 (#19M) and smaller bars. For #7 (#22M) and larger bars, the clear spacing shall be established using a shotcrete mockup panel to demonstrate that the reinforcement is properly encased [2]. ACI 506 [3,4] provides slightly different guidance; non-contact spliced should have a minimum spacing of at least three times the diameter of the largest bar (3db) at the splice, three times the largest aggregate, or 2 in. (50 mm), whichever is least.

Contact lap splices of reinforcement (means of connecting reinforcing bars in which the bars are lapped and in direct contact [1]) create a large obstruction that is more difficult to encase and should be avoided where possible [3]. However, in applications with congested reinforcement, contact lap splices can be advantageous for the installation compared to non-contact splices because they allow for wider shotcrete spray pathways between the reinforcing bars. Per ACI 318 [2] and ACI 506 [4], contact lap splices of reinforcement shall be oriented with the plane of the spliced bars perpendicular to the surface of the shotcrete (parallel to the direction of shooting) to minimize the size of the spray shadow. Also, they should be approved by the licensed design professional based on a shotcrete mockup panel to demonstrate that the reinforcement is properly encased.

Commonly used fabric gauges for welded wire fabric (WWF) are W2 or W1.4 wire [MW9.1 or MW12.8], spaced 4 in. [100 mm], or 6 in. (150 mm) in both directions [3,6]. In no case should the wires be spaced less than 2 in. apart. If WWF is used, they should be lapped at least 1.5 spaces in both directions and be securely fastened [3].

The minimum cover over reinforcement is from the same as form-and-pour concrete and should comply with the job specification and is usually based on environmental exposures and the service life of the tunnel.

Columns in tunneling are usually not shotcreted because the close spacing between ties, hoops, or spiral reinforcement makes it difficult to achieve adequate encasement of the column longitudinal reinforcement. However, shotcreting of columns is possible with an experienced nozzleman and proper materials.

Following ACI 318 [2], reinforcing bar spacing closer than 3 in. (75 mm) requires approval by the licensed design professional based on shotcrete mockup panels demonstrating that the reinforcement can be encased without voids. Special attention must be given by the designer of the temporary installation and layout of the reinforcing bar cage. Lattice girders or anchors providing support must not only carry the weight of the reinforcement but also fix its location properly during the shotcreting process as well as preventing movement and vibration. Movement and vibration can compromise the encapsulation of the reinforcement, cause sagging of freshly placed shotcrete, create voids, increase permeability to provide pathways for water ingress, and result in reduced strengths and quality.

If using anchors to support the reinforcement cage, shooting overhead work requires closer anchor spacing to minimize the reinforcement movement during placement and help support the weight of the shotcrete. Therefore, the anchor spacing, and reinforcing design require special attention by the designer and by the contractor considering the interface between the waterproofing, reinforcement, and shotcrete installation. For additional guidance on installation of shotcrete overhead and on sheet waterproofing membranes refer to the ASA Underground Position Statements on each topic [8, 9].

Shotcrete, particularly when using the dry-mix process or crushed aggregate in wet-mix, is more abrasive and can cause localized damage to epoxy-coated rebar. This may be a consideration for the designer as discontinuous epoxy-coating an a bar may negatively impact the rate of corrosion. Use of epoxy-coated bars may also reduce the bond of the fresh concrete to the bar, and make it more difficult to fully encapsulate the reinforcement. Preconstruction testing is strongly recommended before using epoxy-coated reinforcement. A preconstruction mockup panel should be shot to determine the effect of the shotcrete process on the coating [3].

REINFORCEMENT INSTALLATION

Movement and vibration of the reinforcing steel can cause a loss of adherence and sagging of the plastic shotcrete, which can create voids and compromise the concrete strength; therefore, the reinforcement must be installed properly and firmly affixed to limit movement during the placement of shotcrete. Rigid reinforcement installation is a key element for high-quality shotcrete final linings.

Compared to form-and-pour, often an additional 75% more tie wire is required to make the reinforcing intersections 100% tied. Intersecting reinforcing bars must be rigidly tied to one another and to anchors or lattice girders with 16 gauge [1.3 mm] diameter) or heavier tie wire and adequately supported to prevent vibration during shotcrete placement. Before shooting the shotcrete, cut off excess tie wire. Large knots of tie wire should be avoided to minimize the buildup of material, which may cause an obstruction and may lead to the development of voids [3,4].

If WWF is used, the mesh should be cut to the proper size and carefully bent to closely follow the contours of the areas receiving shotcrete. Like reinforcing bar, the mesh should be securely tied with 16 gauge or heavier tie wire to preset anchors, lattice girders, or reinforcing bars. Reinforcement should be free from oil, loose rust, mill scale, dust, or other surface deposits that may affect its bond to the shotcrete [3].

SHOTCRETE PLACEMENT

High impact velocity ensures that the fresh shotcrete flows around the reinforcement and ensures proper encapsulation. The key elements to provide proper impact velocity for consolidation and encasement are suitable material consistency, sufficient air flow, and proper placement techniques. Larger diameter reinforcement requires a more flowable mixture for good encasement, and the angle of the material stream may need be slightly adjusted to ensure that the area behind the reinforcement is compacted (see Fig. 2) [3].

For any given shotcrete mixture, experience shows there is an optimum impact velocity. Below the optimum impact velocity, the impact energy is too low to correctly consolidate the in-place concrete, and get adequate wrap of flowable concrete mixture to encase the reinforcing. Impact velocity can be increased by reducing the distance to the receiving surface, or increasing air flow. However, if the impact velocity due to too high an air flow, the surplus energy can increase the amount of rebound or blow the plastic material apart. The standard nozzle distance is 2 to 6 ft (0.6 to 1.8 m) for handheld nozzle placement, depending on the nozzle type, size, and air flow. For mechanically manipulated systems, typically, a higher air flow is used and produces higher material velocity compared to hand-held applications, which may allow for greater distances of the nozzle from the receiving surface.

For congested reinforcement with multiple layers of reinforcement and linings with thicker depth, the nozzleman may need to insert the nozzle tip behind the bars of the intrados layer and the use of longer tips may benefit this process. However, when working closer to receiving surfaces or reinforcement, the air volume and velocity of the shotcrete should be reduced to prevent a blowback of air that can create voids [3].

Before placement of a new layer of shotcrete and encapsulating reinforcement, rebound, overspray, cuttings from adjacent or previous placements, and other deleterious materials that inhibit the development of the bond between previous shotcrete layer and reinforcement must be removed and not be incorporated into the work [3,4].

Close observation of the face of the reinforcement during the application of shotcrete indicates the quality of encapsulation. The front face of the reinforcement shall be kept clean clearly showing the reinforcing deformations during the shotcrete placement to ensure that shotcrete builds up behind the reinforcement to get full encapsulation without creating shadows or voids.

During shotcrete placement, the shotcrete crew shall continuously remove accumulations of rebound and overspray using a compressed air blowpipe, or other suitable devices. When material builds up on the face of the reinforcement, it is an indication that material is not flowing around, and a void is potentially forming behind the reinforcement. The shotcrete placement should be stopped to allow the nozzleman to either adjust the mixture, increase impact velocity, or both. Any buildup of material on the face of the reinforcement must be cleaned off and the area behind the reinforcement opened up before continuing the operation [3].

Proper nozzle manipulation is physically demanding, requires strength, experience, and finesse of the nozzleman. The nozzle technique for placing wet-mix and dry-mix shotcrete is generally similar. Both requiring considerable attention to detail during placement. Wet-mix nozzlemen must manipulate a heavier hose, which is discharging a greater volume of material per unit of time, compared to dry-mix placement. Shotcrete application in larger tunneling cross-sections typically will use wet-mix typically uses mechanical shotcrete manipulators, also referred to as shotcrete robots.

When encapsulating multiple layers of reinforcement at vertical or overhead locations, the application should begin at the bottom, fill corners, areas around anchors, or lattice girders, and from there move upwards. The first layer should, if possible, completely encase the reinforcement adjacent to the back of the form, anchors, or lattice girders and should form "ribs" in the lining. In the following step, after the ribs have initially set, the "bays" between the ribs are filled starting from the bottom. Finishers should be careful not to disturb the freshly placed shotcrete, create cracks or tears, reduce internal cohesion, break the bond between the shotcrete and the reinforcement, or the bond to the previous shotcrete layer. If architecturally acceptable, a "gun" (natural) finish should be considered.

Admixtures

Typical slumps of the wet-mix shotcrete are between 2 and 4 in. (50 to 100 mm) at the nozzle. Admixtures such as accelerators and water reducers added to a shotcrete mixture can change the rheology of the mixture, so the 2 to 4 in. (50 to 100 mm) rule of thumb is not always applicable. For example, slumps from 6 in to 8 in. (150 to 200 mm) may be used effectively when using rapid-set alkali-free accelerator technology, A mixture with a slump less than 2 in. (50 mm) might be difficult to pump and may be too dry to easily flow around reinforcement and properly encapsulate the reinforcement. Testing should be conducted to determine what combination of admixtures and slump can be shot to achieve desired results [3].

The addition of a rapid-set accelerator admixture to the concrete mixture allows the placement of higher slumps when shooting vertical or overhead applications. However, there can be negative effects when using accelerator for shotcrete final linings. These negative effects may include too early set that compromises compaction, reduction of long-term strength, and potential change of alkalinity negatively affecting the durability of the concrete. These effects must be considered when deciding whether to use an accelerator. In general, the use of accelerator for tunnel final linings should be minimized if possible. Shooting mockups and testing the strength of the shotcrete will determine the best dosage of accelerator for vertical and overhead applications.

QUALITY ASSURANCE AND QUALITY CONTROL

Quality assurance and quality control ensure that items like concrete mixture proportions, shape, thickness, and reinforcement are constructed as designed and meet the specified properties. The quality of the placement of shotcrete and proper encapsulation of reinforcement depends not only on an experienced nozzleman but an experienced contractor and shotcrete crew. Only competent, experienced, and trained craftsmen working as a team and provided with proper equipment and materials will produce high-quality shotcrete final linings.

The contractor and nozzleman should have a demonstrated history of completed, acceptable shotcrete work, similar to that required for the project. The contractor's principals, project managers, and shotcrete field crew should have a successful background in shotcrete, as determined by references and reputation. Job specifications for structural shotcrete should require that the nozzleman is ACI-certified in the shotcrete process and orientation they will be expected to shoot on the project. The nozzlemen should also have completed at least one similar application on a project with similar size and complexity.

The nozzleman is a key person in a shotcrete operation and is responsible for applying the shotcrete. Before the shotcrete is placed, the nozzleman must ensure that all areas to receive shotcrete are clean, sound, and free of loose material, in a saturated surface dry condition, and that anchors, reinforcement, and ground wires are properly placed and spaced.

Pre-construction testing on mock-ups reflecting the reinforcement design (bar size, spacing, and amount) should be conducted. The purpose of pre-construction testing with mockup panels is to confirm that the shotcrete, in general, and placement by nozzlemen and crews who will be on the job, can properly encapsulate the project-specific reinforcement and meet all material and placement requirements. The mockup panel should always be constructed with reinforcement similar to the most heavily reinforced or critical section to be shot. ACI 506 [3,4,5,6] provides detailed information for specification, planning, and execution of pre-construction testing.

On projects with congested reinforced tunnel linings, the nozzleman must be able to demonstrate an ability to satisfactorily perform the required duties and to apply shotcrete as required by the specifications. Although a nozzleman is ACI-certified, the nozzleman may not have sufficient experience to shoot heavily reinforced sections or complex sections. The purpose of mockup panels is to satisfy the specifier that the nozzleman and shotcrete crew, with the materials and equipment to be on the project with meeting the specifiers expectations for the structural quality of the shotcrete placement. Also, mock-ups may serve as an opportunity for the nozzleman to work with the additional crew members and make sure everyone is familiar with the proper shotcrete application required for the specific project conditions.

ACI 506.6T [7] provides guidance to the specifier on visual evaluation of cores taken from mockup panels or in-situ work. It lists quantitative criteria for each category of core quality grading by a Licensed Design Professional (LDP). The cut and cored surfaces of the specimens are carefully examined and evaluated. The cores should be dense and mostly free from laminations, voids, and sand pockets for the evaluation by ACI 506.6T [7]. There are four grading categories of visual evaluation of core quality (very good, good, satisfactory, poor). Each category of quality is discussed and quantified based on two criteria. Each category is not only a function of the imperfections found, but also intimately linked to the complexity and structural demand of the reinforcement layout. Particular attention should be paid to the presence of voids and low density shotcrete behind the reinforcing bars. Factors including the size of the reinforcement, spacing, laps, layers, reinforcement location within a cross-section, and other types of placement should be considered in the evaluation.

RECOMMENDATIONS FOR THE CONTRACTOR

Often, the general contractor has a contractual requirement for coordination between the reinforcement installer and the shotcrete contractor. They may also include additional coordination with the waterproofing installer. To ensure quality and avoid deficiencies, the interface and coordination required between the different trades and proper handover requirements should be clearly defined, inspected, and documented in detail by the shotcrete contractor. This includes but is not limited to the installation and spacing of reinforcing bars, including splices and the rigidity of the installation to avoid movements and vibration.

The shotcrete nozzlemen should be ACI-certified in the shotcrete process with both vertical and overhead application, and have demonstrated experience and skill in the same type of work. Nozzlemen without underground experience will need to be specifically briefed and trained for the installation of shotcrete in reinforced shotcrete tunnel final linings. As noted above, shotcrete placement should be tested on a mock-up mimicking the project-specific reinforcement and anchor or lattice girder installation. Before the application in the tunnel, the nozzleman should be qualified for the project by shooting a mockup section with representative reinforcement. Proper shooting procedures and application sequence should be laid out in writing in the work plan and can often be tested and confirmed during the pre-construction mock-up construction.

RECOMMENDATIONS FOR THE OWNER

The owner should provide a design reflecting the specific challenges for a final lining using shotcrete, specifically focusing on reinforcing bar size, layout, splicing, and spacing. Minimum key criteria need to be specified like reinforcing bar rigidity and anchor spacing, reinforcement suspension or support, and the shotcrete material specification following the applicable ACI 506 documents [3, 4, 6]. Again, a key is properly executing pre-construction testing and the project-specific mock-ups, which should be mandatory and follow the ACI 506 guidelines [3, 4, 6].

The mock-up specimen should be saw cut or cored to clearly identify any delamination or defective shotcrete adjacent to reinforcement [7]. The owner should not allow the start of the tunnel shotcrete placement until the contractor has proven that their means, methods and procedures are capable of providing the required quality of shotcrete and proper encapsulation of reinforcement. Also, the owner should recognize that inspection of the proper installation of the reinforcement before the shotcrete installation and shotcrete placement may require the inspector to have more shotcrete specific knowledge than they may possess with conventional concrete construction. A qualified and experienced inspector is needed. Use of an ACI-Certified shotcrete inspector is preferred on these projects.

CONCLUSIONS

Installation of shotcrete tunnel final linings is a cost and time-efficient construction method, especially in areas where formwork is costly and labor-intensive. Nonetheless, the installation of shotcrete and proper encapsulation of reinforcement in underground applications is challenging. The owner and contractor should recognize the expected challenges before the start of construction. Experienced staff on either side is required for the successful execution of the project.

Acknowledgments

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