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Position Statement #4
ASA Underground Committee

Mechanical Application of Shotcrete in Underground Construction

INTRODUCTION

The manual hand application of shotcrete began over 100 years ago and continues today in a wide range of applications and projects. To provide a proper distance of the shotcrete nozzle tip to the underground surface wall, surface receiving shotcrete or 'substrate,' the hand application of shotcrete in larger diameter underground structures required the nozzlemen to operate from a man-lift or similar equipment. Working from elevated platforms and the close proximity of the nozzleman to the substrate added safety challenges to projects. Thus, as more underground projects started to use the wet-mix shotcrete process, spraying shotcrete with mechanical arms began to address these safety concerns.

Compared to manual shotcrete application, mechanized shotcreting equipment improves job safety and reduces nozzleman fatigue, especially when wet-mix shotcrete is used. Mechanized shotcrete applications allow more flexibility, increased reach, and more efficient mobility of the operation, which are important factors in planning and executing underground shotcrete projects. The self-contained mobile shotcrete application machines can also enhance safety in challenging areas. After the shotcrete operation is completed at one location, the self-contained equipment can be quickly redeployed to the next work area.

This position paper provides an overview of the basic design and operation of mechanical equipment for underground shotcrete applications, often referred to in the industry as a "mobile shotcrete sprayer," "shotcrete robot" or "shotcrete manipulator." This position paper uses the terms "mechanized shotcreting," "shotcrete nozzle manipulator," or "shotcrete boom manipulator" when describing the process and equipment. This is intended to distinguish this equipment from equipment used in manual shotcreting and to emphasize this equipment is controlled by operators and is not fully automated. It is important to recognize that the often used terms "robotic sprayer" or "robot" are inaccurate and can be misleading. Semi and fully automated mechanized systems have been under development for many years; however, it will likely take many more years before reliable fully automated systems become available and gain acceptance in the industry.[1]

COMPARISON OF MANUAL AND MECHANICAL SHOTCRETING

Dry-mix shotcrete (gunite) is commonly applied by manual spraying techniques. Because the shotcrete materials are delivered by pressured air, the weight of the shotcrete delivery line and nozzle is lighter compared to wet-mix shotcrete equivalents. In wet-mix shotcrete, the entire shotcrete delivery line is filled with wet concrete. This makes the portion of the line leading to the nozzle much heavier compared to the equipment used in dry-mix shotcrete application.

Therefore, mechanical spraying equipment is more commonly used in wet-mix shotcrete applications. This is particularly true if working near or under unsupported ground where thick shotcrete linings are needed or working in large tunnel cross-sections.

Manual application of shotcrete implies that the nozzleman is manually handling, operating, and moving the nozzle during shotcrete spraying. The manual application of dry-mix shotcrete is typically preferred in applications or projects:

1. with small daily or total shotcrete placement volumes,

2. requiring generally lower output rates compared to wet-mix shotcrete (e.g., concrete repair or rehabilitation projects),

Fig. 1: Shotcrete application by hand.

Fig. 2: Shotcrete application by mechanized equipment via radio remote.

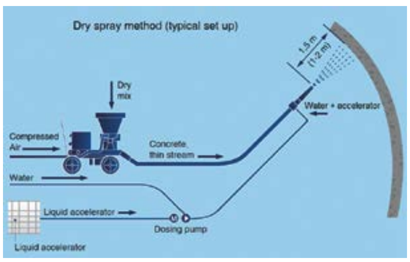

Fig. 3: Typical schematic diagram of dry-mix shotcrete equipment material flow.

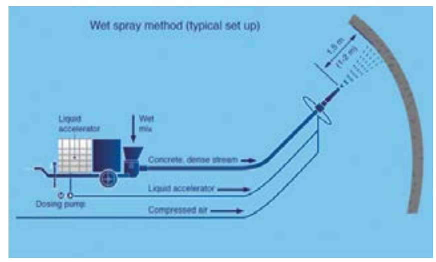

Fig. 4: Typical schematic diagram of wet-mix shotcrete equipment material flow.

Fig. 5: Typical tunnel electric-hydraulic sprayer.

3. where the smaller and lighter nozzle and hoses can be moved more easily by hand,
4. where the dry-mix shotcrete materials can be easily conveyed by compressed air from the shotcrete gun to the nozzle, and
5. where fast-reacting materials, that must remain dry until contact with water at the nozzle, are used.

To clearly distinguish it from manual application, mechanized shotcreting should be defined as "a shotcrete application using a hydraulic or electrically powered shotcrete boom manipulator." With wet-mix, the nozzle is typically rotated around the concrete flow centerline during the shotcrete application to enable proper distribution of the shotcrete and accelerator.

During the mechanical application of shotcrete, the nozzleman does not manually handle and move the nozzle for the shotcrete application. Instead, the operation of the boom manipulator is done by remote control (either wireless or cable). The mechanical application of wet-mix shotcrete is typically preferred in applications or projects:

1. where the required shotcrete placement volume is frequently large,
2. which require higher output rates (e.g., for ground support or tunnel linings),
3. where nozzle and hoses are larger and heavier and cannot be safely moved by hand, and
4. application reach would require scaffolding or a man-lift.

Mechanized shotcreting is the preferred method of applying wet-mix shotcrete in large underground projects. This is especially true when shooting overhead due to the exposure of the operator to rebound and 'fallouts' of fresh layers of hardening concrete that breaks off from the substrate.[2] For example, mechanized shotcreting is utilized in projects requiring higher output, such as initial and final support liners in new tunnels and underground cavern construction. Hose diameters are typically in the range of 2.0 to 2.5 in. (50 to 62 mm) inside diameter (ID) at the nozzle body. The delivery line weight of fresh wet-mix shotcrete being pumped through the line is several times heavier than the delivery line weight of pneumatically conveyed dry-mix shotcrete materials. Additionally, the wet-mix nozzle body is typically heavier compared to a dry-mix nozzle. Therefore, hand-application of wet-mix shotcrete can fatigue the nozzleman more quickly, leading to safety issues. The added weight can also cause operational challenges that may be detrimental to the quality of placed shotcrete.

Finally, it needs to be pointed out that dry-mix shotcrete application with shotcrete boom manipulator can be done but it is not common.

SAFETY

Elevated work locations can create a major risk in underground construction. Application of overhead shotcrete in larger diameter tunnels by hand is only possible from a man-carrying platform (man-lift) to provide optimum distance between the nozzle and substrate. However, the nozzleman's operation oftentimes is conducted at an elevation of 5 ft to 20 ft (1.5 to 6 m) above the 'invert' or tunnel ground level.

Typically, mechanized operation of the shotcreting nozzle allows the nozzleman to operate from the invert and does not require the nozzle operator to work from a man-lift. In most cases, mechanized equipment eliminates the potential hazards of elevated work for the nozzleman.

A major safety concern of underground applications is working under unsupported ground. Therefore, application

Fig. 6: Typical setup showing concrete hauler (left) feeding concrete pump of mechanized sprayer (right).

of shotcrete by hand is often not allowed due to potential fallout of substrate (rock, soil) or the hardening shotcrete. In such instances mechanized shotcrete booms are utilized, which allows, the nozzleman to operate from an area of supported ground and a safe distance from potential hazard.

Also, exposure to dust and rebound in the working area is a concern of manually applying shotcrete as the nozzleman operates directly behind the nozzle, near to the shotcrete being applied to the substrate. In mechanical spraying, the nozzleman can operate the system from an area farther away from the application site, where there is better air quality.

Mechanical shotcrete equipment is operated by hydraulic pressure, which is more powerful and potentially more dangerous, if not properly managed, than hand-applied pneumatic power. However, with remote control units the operator is farther away from the pressurized concrete and hydraulic hoses.

In summary, mechanical spraying shotcrete typically eliminates the hazards of elevated work, working near pressurized hoses, shotcrete rebound or fallout, and exposure to dust.

PRODUCTIVITY

The mechanized nozzle operation process, which utilizes a concrete pump with larger hose diameters, enhances the spraying performance of wet-mix shotcreting. This process typically allows 2 to 4 times more shotcrete placement than the dry-mix manual shotcreting process. The logistics of delivering wet-mix shotcrete to the heading can be simpler than those of a typical manual dry-mix process. And the remote controlled operation utilized for mechanized equipment is physically less demanding on the operator than nozzle operation by hand, thus, the performance of the operator is enhanced.

NOZZLE POSITIONING, COMPACTION, REBOUND AND VISIBILITY

The excavated substrate, for example in a drill-and-blast rock tunnel, can be a surface of varying angles, asperities, and fissures. Maintaining the proper distance and angle of the nozzle tip from the substrate allows the cement paste to fill these natural cracks and thus enhance the bond between the shotcrete and the substrate.

The remote-controlled operation of a mechanized boom allows for an easily manipulation of the nozzle. The optimum distance between the nozzle tip and the substrate surface of 4 to 5 ft (1.2 to 1.5 m) can be maintained as well as the optimum perpendicular angle to the substrate surface. Also, the continual rotation of the nozzle allows for a more uniform shotcrete thickness. Maintaining the proper distance and angle to substrate improves shotcrete compaction which increases shotcrete strength.

Dust and rebound in dry-mix shotcreting manual operation can impact the visibility of the nozzleman operating manually behind the nozzle. However, as previously mentioned, the visibility of the nozzleman operating during wet-mix mechanical shotcrete system is typically much better, as the nozzleman is not near the nozzle.

QUALITY CONTROL

Testing of mix-designs in pre-project trials, mockups, and certification of operators is typically a mandatory requirement and very important for the success of any underground shotcrete project. For mechanical shotcreting, all shotcrete placement should meet the recommendations of ACI 506[3].

Quality can be met by using shotcrete that is properly batched, pumped and applied by trained personnel. When using a rapid-set accelerator a proper calibration of the accelerator pump or dosing system in conjunction with early strength testing is essential to providing quality shotcrete placement.

MECHANIZED SHOTCRETE EQUIPMENT

1. SPRAYERS -

A typical underground mechanized shotcrete nozzle manipulator system has the following components:

- diesel or electric engine carrier (usually rubber-tired);
- electric power pack;

- concrete pump and line;
- accelerator pump (typically controlled by a computer-driven monitoring and control system synchronizing the concrete pump strokes with the accelerator pump dosage);
- shotcrete boom and nozzle manipulator;
- cable or radio remote control;
- on board air compressor; and
- shotcrete accelerator tank.

There are several manufacturers that specialize in developing and building mechanized shotcrete equipment, with different designs and sizes to match varying tunneling and mining excavation profiles and needs.

Some of these manufacturers offer compact diesel-hydraulic or electric-hydraulic powered, track-mounted and mechanical nozzle manipulators that can work with trailer mounted or skid mounted concrete pumps.

CARRIER & POWERPACK

Carriers, with the mechanical shotcrete equipment mounted on it, can be either rubber-tired or track-mounted units. They are typically powered by diesel engines. Battery-electric carriers are also available. The concrete pump, boom, and all other functions are typically operated with electric-hydraulic power packs in tunnels and by diesel-hydraulic power in mines.

ON-BOARD COMPRESSOR

In mine applications compressed air is generally available from the mine's main compressors; therefore, the sprayers used in these environments are often diesel-hydraulic where the operators hook the machine to the compressed air lines at each work site. The drawback of using a mine's compressed air is that there can be fluctuations in the air volume or air pressure depending on other mining activities (such as drilling) taking place. Another potential issue is accumulated condensed water in the compressed air lines. Therefore, when there is no on-board air compressor, the operator needs to be aware of the potential fluctuations from mine air compressors during the shotcreting process.

Electric-hydraulic sprayers used in tunnel construction often have an electric on-board air compressor. These units are more independent and rely on the on-board produced compressed air with its more consistent airflow volume and pressure. Having a constant airflow makes the application easier to control and more uniform.

Concrete Pump & Lines

Concrete pumps for mechanical sprayers are usually hydraulic piston pumps with swing tubes. They have a hopper, mixing paddles, grate, and grate vibrator. Electronic control systems allow smooth concrete pumping and interface with other systems on the machine such as the accelerator dosage system. The main function of the concrete pump and conveying system is to deliver the concrete to the nozzle at the end of the shotcrete boom conveyed through steel elbows, reducers, and rubber hoses. These delivery line components wear over time and require regular inspection and replacement to ensure safe and productive operation.

In some cases, the concrete pump is mounted on a separate carrier from the boom. In this case, the pump is either a stand-alone pump or may be mounted on the concrete truck delivering the concrete.

Boom Manipulator

Mechanical shotcrete booms have joints or knuckles that allow them to collapse into a small package to reduce the overall size during transportation and to avoid damage while allowing complete coverage of large tunnels and mine cross-sections when unfolded.

The shotcrete boom manipulator is operated by a qualified nozzleman with a remote control whose primary function is to maintain the boom at a proper distance and angle from the receiving substrate. The nozzleman controls the concrete pump output rate, compressor operation, and accelerator dosage rate. The nozzleman can also operate a high-pressure water nozzle or hydro-scaler (which is a specialty tool option) to ensure the substrate is free of any loose materials, diesel particulate matter and dust and is sufficiently wet before shotcreting. Optimal bond between the shotcrete and substrate is achieved when the substrate is clean and wetted to a saturated surface dry condition.

Nozzle Manipulator

At the end of the boom manipulator, the nozzle body allows a mixture of air and liquid accelerator to be introduced into the concrete flow and propel the mixed materials at high velocity out the nozzle. Then, the nozzle body and tip direct the shotcrete towards the substrate at speeds of up to 100 ft/s (30 m/s) ensuring good compaction and bond to the substrate. A certain amount of rebound (5 to 20% of the overall shotcrete volume in wet-mix shotcrete) is normal and to be expected when applying the initial layer of shotcrete onto the substrate as the cement coated aggregates bounce off the hard surface leaving cement paste on the substrate. Subsequent passes of shotcrete build layers of the full concrete mixture onto the substrate. Generally thicker single-pass layers can be applied by mechanical sprayers as compared to hand application. Rebound of hand application by dry-mix method can range from 15 to 35% of the shotcrete volume applied. To provide an even distribution of the shotcrete and accelerator, the nozzle is typically rotated with a continuous circular motion around the central axis of the nozzle.

Accelerator System

At the nozzle, the pumped concrete becomes sprayed concrete or shotcrete with addition of a mixture of compressed air and liquid accelerator. The accelerator dosage is typically computer monitored and controlled. A constant accelerator dosage based upon the concrete's mixture design cementitious content, is maintained by the accelerator pump rate and adjusted to the concrete pump rate.[4]

The chemical additive or accelerator pump is a very important and critical component of either manual or mechanized shotcrete spraying process. When working properly and in synchronization with the concrete pump output, it is a very effective means of applying thick layers of sprayed concrete on the walls and roof of tunnels, mine drifts and other underground openings. Also, close calibration and synchronization of accelerator and concrete pumps provides higher and more consistent shotcrete early strength values.

Two common types of accelerator pumps are: peristaltic (also known as hose pumps) and positive displacement (also known as rotor-stator or Moyno pumps). Rotor-stator pumps are more accurate than peristaltic pumps but both are widely used.

Tanks holding accelerator are typically mounted on the carrier. Larger shotcrete tunnel sprayers will have a plastic tote or IBC (intermediate bulk container) which will hold typically 275 or 330 gal (1040 or 1250 l). Smaller units typically have a metal tank. Accelerator tanks can be made of plastic, mild steel, or stainless steel. Mild steel tanks can be lined with plastic to protect the metal from corrosion. Accelerator tanks should be vented. Stainless steel tanks are recommended for alkali-free accelerators.

REMOTE CONTROL UNITS

The nozzleman operates the boom and all other functions of the shotcrete process utilizing a joystick box that is either connected to the sprayer via cable or, more commonly, linked by radio control. The remote-control unit offers the nozzleman complete freedom and flexibility of boom movement in all directions[1]. Also, radio control units provide no tripping hazard when compared with cable connected units.

The use of the remote control allows the nozzleman to operate the equipment from a safe distance that still provides good visibility of the operation and a safe working environment for the nozzleman.

SENSORS AND DATA GATHERING

Many component options are available for mechanized shotcrete sprayers such as the hydro-scaling nozzle.

As indicated in the Accelerator System section, sprayers can be equipped with smart systems that help synchronize the pumping of the concrete with the dosing of accelerator. This is done to reduce pulsation and to avoid overdosing of accelerator into shotcrete at the nozzle. Overdosing of accelerator greatly reduces the strength of the shotcrete.

Another productivity tool available for sprayers is a scanner unit which is mounted in the front of the machine. It can map the receiving substrate before and after shotcreting to provide immediate shotcrete thickness and applied volume information. It gives the operator a color-coded 3-D view of the tunnel distinctively showing where application thickness has been less than desirable so nozzleman can address the issue by applying a remedial layer without delay. Scans can also be uploaded and included in as-built drawings.

Also available are intelligent spraying systems that automate some of the functions the operator must perform such as standoff distance from the substrate and maintaining the angle of nozzle 90° to the substrate. Ultimately a truly mechanical applicator using artificial intelligence is envisioned for the future.[1]

2. CONCRETE HAULERS -

Shotcrete support equipment, which is also known as the "remix truck" or "underground concrete transport," is used to bring concrete to the shotcrete sprayer. It can be a standard ready-mix truck if the tunnel's cross section dimensions are sufficiently large. The remix truck might also be used to transfer accelerator and form oil to the sprayer. Form oil helps to keep the boom and other sprayer parts free of shotcrete overspray and rebound and reduce maintenance issues. Form oil is applied at the beginning of shift and removed by pressure washing at end of shift. It helps to keep equipment free of hardening concrete as soon as possible.

In special cases, the concrete pump is also mounted on the concrete hauler and is not installed on the boom carrier. Also, there are a couple of units available on the market where the shotcrete hauler and sprayer are combined into a single unit.

EQUIPMENT OPERATION CONSIDERATIONS

A clean substrate, free of loose material, dust, rebound, and diesel particulates is critical for proper bonding between shotcrete and the substrate and to minimize fall out.

Selection of a suitable concrete mixture for shotcrete placement is critically important for a successful outcome in either manual or mechanical shotcrete applications.

As previously mentioned, there are a few reputable sprayer manufacturers offering different equipment package options to choose from. The choice of equipment depends on the project shotcrete specifications, required boom reach, application rate, shotcrete thickness, power availability, size of underground openings, distance to batch plant, and many other factors.

Operators need to be trained in the proper use of the equipment before the project starts. Ideal training involves shooting mockups of simulated underground headings and panels on the surface. ACI Shotcrete Nozzlemen certification in the shotcrete process (wet-mix or dry-mix) and orientation (vertical and overhead) is recommended for operators or operator trainers. Nozzlemen need to have a minimum of 500 hours of nozzle experience (with at least 200 hours of the total with hand nozzling) before applying for ACI certification. Hand application experience helps nozzlemen to learn the fundamentals of shotcrete placement that can then be applied when using mechanized shotcrete sprayers. Large projects typically hire certified trainers to spend time with new nozzlemen for several shifts and up to a couple of weeks depending on the crew size and project needs.

RECOMMENDATIONS FOR THE CONTRACTOR

When considering hand versus mechanical application of shotcrete, contractors should consider operator fatigue, dust, visibility, equipment safety components, equipment maintenance requirements, and equipment quality of manufacturing among other factors.

Also, they should take into consideration that the cost of mechanized sprayers is much higher than that of hand spraying equipment. Thus, factors including output requirements, single or multiple headings, shotcrete liner thickness, and others project specific considerations must be evaluated prior to deciding on manual versus mechanized systems.

Finally, for the reasons previously discussed, nozzlemen training is one of the most important aspects of mechanized shotcrete spraying. Thus, it is recommended that nozzlemen have handheld experience prior to performing mechanized shotcrete spraying. The operator with hand-held experience will have a better appreciation and understanding of what is required to consistently achieve a high quality shotcrete installation.

RECOMMENDATIONS FOR THE OWNER

Designers and owners need to keep up with the state-of-the-art and latest developments of mechanized shotcreting. There are several recent developments, such as final tunnel lining with shotcrete or composite liners (for example, shotcrete-sprayed waterproofing-shotcrete), that can reduce overall cost and project timeline. Also, utilizing a scanner can ensure the proper thickness is applied and mapped while reducing over spraying and shotcrete material costs.

CONCLUSIONS

Increasingly, mechanized shotcreting in underground projects is replacing manual shotcrete application with leading reasons including higher safety and productivity coupled with a lower cost of in-place shotcrete. Technological advancements are continually improving mechanized spraying. The overall goal is automating the shotcrete process as much as possible and keeping the operator safe while producing a high-quality shotcrete placement. Until a fully autonomous automation system is developed, the well trained nozzleman remains a very important component of the shotcrete process.

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