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Innovative Shotcrete Technologies for Advancement in Tunneling

By Nicolas Ginouse, William Clements, and Scott Rand

Sprayed concrete (shotcrete) is a well-established and proven component of ground support systems worldwide. Underground excavation projects currently involve more and more logistical and technical challenges to advance headings and keep the development cycles as short as possible.

In this context, the installation of ground support has become one of the longest components of the development cycle. In addition, larger headings and deeper excavations lead to larger volumes of material requiring transportation from the surface over longer distances. The use of shotcrete as a ground support technique has undergone several key technological advances that are explored in this paper, which include the reduction of rebound and dust, rapid strength gain shotcrete and ultra-high performance shotcrete materials for high stress conditions.

WET-MIX PROCESS

In non-accelerated wet-mix shotcrete, all the ingredients, including water, are mixed together before the delivery phase. The fresh mixture is then pumped through hoses or pipes to be sprayed onto a receiving surface using compressed air, which is introduced at the nozzle. In this case, the amount of mixing water added to the mixture is predetermined before the pumping and the shotcreting phases, which therefore makes the implementation of in-situ quality control quite simple. However, because of the material delivery phase, the wet-mix process requires management and control of all parameters influencing workability/pumpability of the mixture to ensure the material is delivered properly. Even if a mixture is found to be adequate for pumping, that does not necessarily mean that the same mixture is shootable and will adhere to the receiving surface after impact. In the case of accelerated wet-mix shotcrete, the set-accelerating admixture is introduced at the nozzle to provide rapid hardening while overcoming any potential issues with workability. Normal dosages of accelerator used within the industry are typically between 2 and 6% by weight of the cementitious content of the shotcrete mixture. In addition to the obvious impact on the final material cost, the dosage of set-accelerating admixtures must be carefully selected and monitored on site as higher dosages reduce the later age compressive strength and durability of portland cement-based concrete/shotcrete (Jolin, Melo, Bissonnette, Power, and Demmard, 2015).

In underground excavation projects, wet-mix shotcrete has become more and more popular. The popularity is mainly due to high application rates and the use of hydration-controlling admixtures. Hydration-controlling admixtures stabilize the shotcrete mix for long periods before spraying and provide additional flexibility/robustness in material delivery. However, the increased use of more sophisticated wet-mix shotcrete mixtures containing admixtures requires careful control. Increasing the dosage of hydration-controlling admixtures has an impact on cost, and requires a higher demand of set-accelerating admixtures to reactivate the hydration process and ensure rapid hardening during material placement.

Once again, as reported in the literature, the overdosing of set accelerator on site must be prevented/limited because of its detrimental effect on material porosity that could significantly affect the durability of the shotcrete lining (Jolin, Melo, Bissonnette, Power, and Demmard, 2015).

DRY-MIX PROCESS

Fundamentally different to the wet-mix shotcrete process, the dry-mix shotcrete process consists of pneumatically conveying the dry mixture through hoses and adding the mixing water generally 10 ft (3 m) before the nozzle outlet (Fig. 1). In this case, all the mixture ingredients, including the admixtures such as set accelerator, are conveyed in dry form using compressed air. Mixing water is then added to the dry mixture in a fraction of a second before impacting the receiving surface. Therefore, the dry-mix process allows for very efficient delivery over long distances, and robust placement of mixtures onto vertical and overhead surfaces with limited use of admixtures.

The dry-mix process has become very popular for shotcrete operations involving very challenging logistics and rapid mobilization, such as tunnel projects with difficult access and/or requiring long conveying distances with frequent/unscheduled starting and stopping. Dry-mix shotcrete has also been proven effective for overhead and vertical applications, where the use of set accelerator is restricted due to durability concerns.

FIBER-REINFORCED SHOTCRETE

The use of fiber-reinforced shotcrete (FRS) has been used for many years in underground excavation projects to replace mesh in gravity failure conditions, manage rock bursts and manage ground deformations in moderate stress conditions. FRS is also used as temporary ground support in conjunction with tunnel boring machines, or as first pass support in dynamic (high-stress) conditions to manage seismicity ensuring safer re-entry before permanent ground support installation.

From a technical standpoint, the use of fibers is mainly to improve flexural strength and toughness where ground conditions require energy absorption.

In most countries, the design of a FRS lining for tunneling applications is based on the modified Barton chart, which is illustrated in Fig. 2. The modified Barton chart provides general guidelines for designing the FRS lining considering the rock mass quality (Q), the opening configuration and the associated reinforcement provided by the bolting pattern and FRS lining. The rock mass quality (Q) is evaluated via the empirical rock stability classification (Q-System) developed by Barton et al. (1974) and updated in 1994. The reinforcement provided by the FRS is related to the flexural toughness/energy absorption in Joules, measured in accordance with ASTM C1550 (ASTM C1550, 2008).

This design approach appears to be less valid for high-stress/challenging ground conditions, such as deep tunnels where seismic events can produce high-intensity rockbursts, and deformations exceeding 3.94 in. (100 mm). In these conditions, the relative stiffness of the FRS lining, and its limited load bearing capacity at such large deformations, limits the contribution of the FRS lining to the dynamic ground support system. The brittle behavior of FRS under dynamic loading (high strain rate), and the relative low tensile strength, limits the use of FRS linings in such high-stress conditions due to the risk of surface spalling (refer to Fig. 3).

In dynamic loading conditions, FRS or plain shotcrete is usually combined with other systems such as yielding bolts, mesh, cable lacing or mesh straps that increase energy absorption and provide better control of large ground displacements.

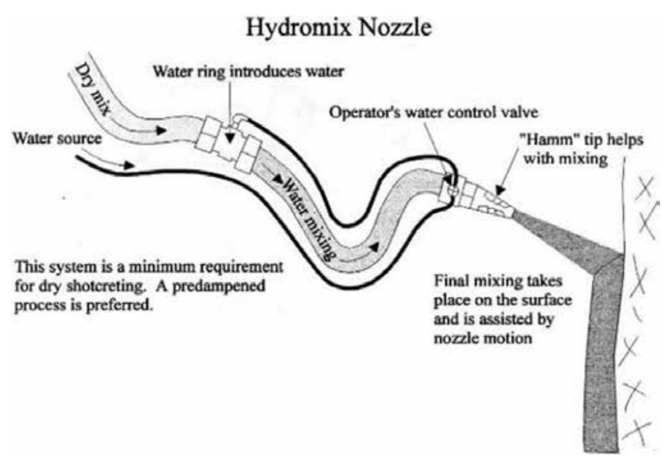

Fig. 1: Hydro-mix nozzle assembly (from ACI 506R-16)

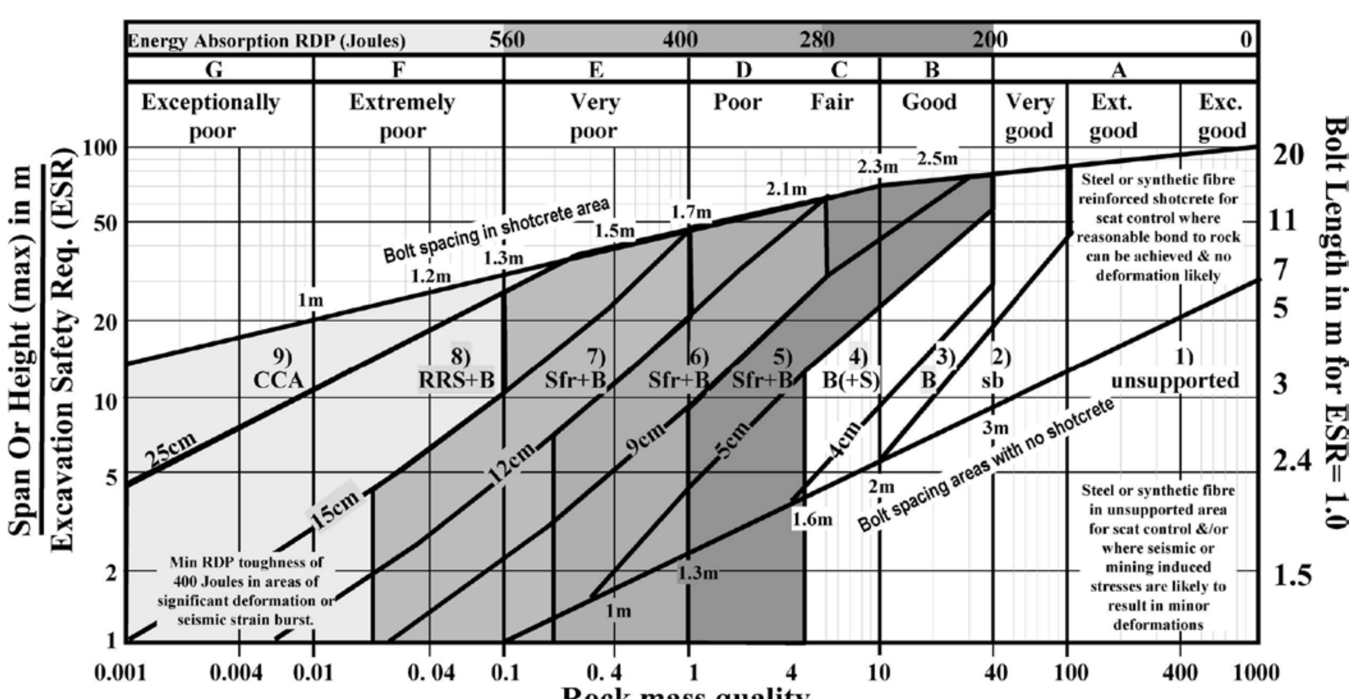

Fig. 2: Modified Barton Chart (from Papworth, 2002)

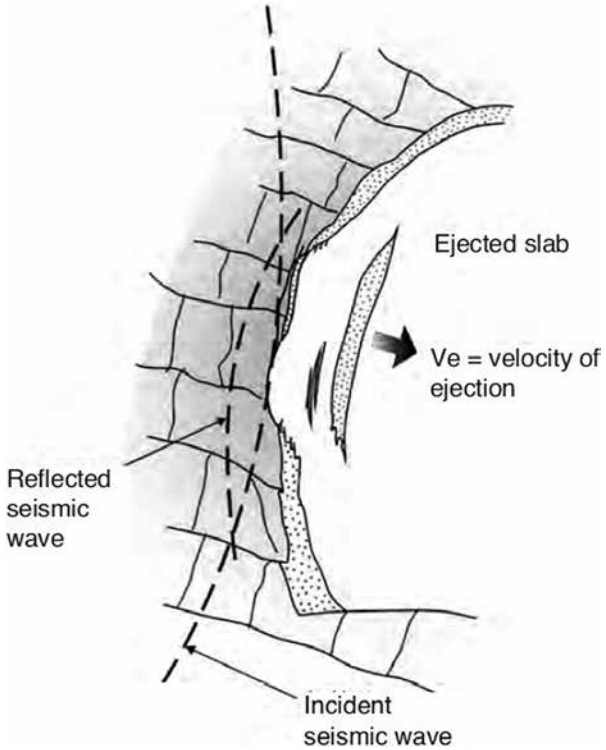

Fig. 3: Seismic spalling of brittle shotcrete lining (from Stacey, 2001)

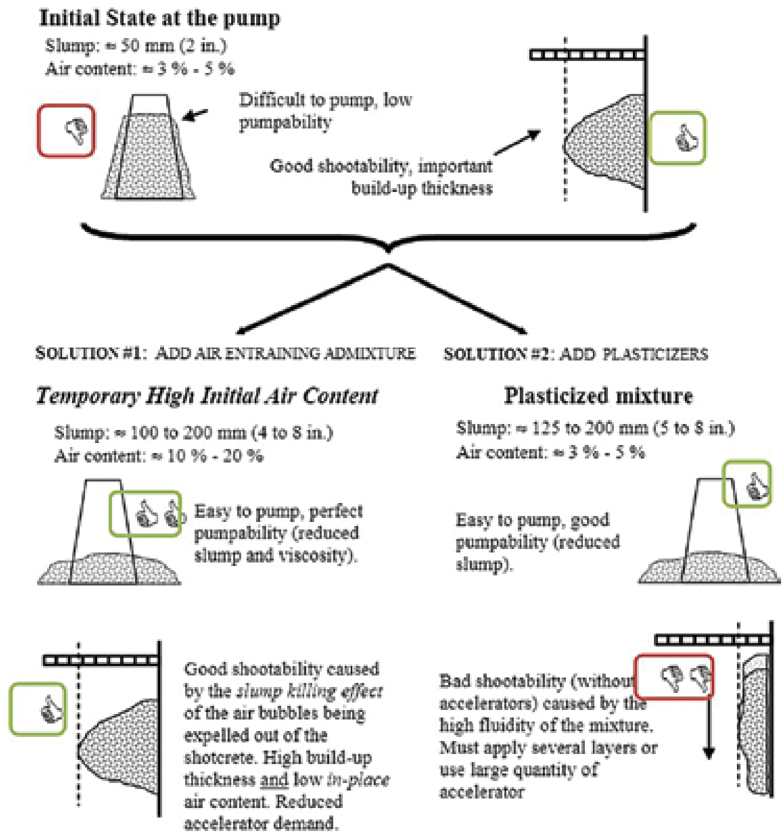

Fig. 4: Schematic illustration of temporary high initial air content concept (from Jolin and Ginouse, 2012)

SCOPE

The intent of the following sections is to provide a quick overview of emerging shotcrete technologies/practices offering solutions for these tunneling applications:

- Producing a highly durable shotcrete lining;
- Efficiently producing high quality shotcrete on-demand;
- Reducing rebound and controlling dust/chemical emission;
- Speed-up the development cycle and reduce the curing period of shotcrete before re-entry; and
- Improving the spalling/impact resistance of the shotcrete lining in challenging ground conditions.

INNOVATION IN SHOTCRETE TECHNOLOGIES

Highly Durable Shotcrete Lining

Several studies have proven that sprayed concrete materials can provide similar or better transport properties and durability than conventional cast-in-place concrete (Zhang, Morgan, and Mindess, 2016). This section briefly describes the key rules to follow produce a highly durable shotcrete lining.

MINIMIZING THE WATER-TO-CEMENT RATIO

Porosity in cementitious materials such as concrete/shotcrete is the first order parameter governing most of the material's performance, especially its durability.

Because porosity of concrete is directly related to the water-to-cement ratio (Neville, 2011), limiting the water content of sprayed concrete is the first preventive action to minimize porosity of the in-place material and therefore guarantee its performance in terms of mechanical properties and durability.

In the dry-mix process, even if the amount of water added to the dry mixture is controlled in real-time by the nozzleman, the placement mechanisms limit the water-to-cement ratio between 0.35 to 0.45 with 0.40 as typical value, which guarantees performance and durability (Zhang, Morgan, and Mindess, 2016). Even for overhead surfaces, the dry-mix process allows for instantly adjusting the plastic consistency to ensure proper build-up simply by reducing the amount of water added to the dry mixture. This straightforward and instant adjustment of the plastic consistency makes the dry mix process a very robust and reliable way to place durable shotcrete materials with low water-to-cement ratios. This is achieved with a limited amount of additives such as plasticizer and set accelerator.

In parallel, it is very common with the new generation of superplasticizers to produce good quality wet-mix shotcrete using typical water-to-cement ratios lower or equal to 0.40. However, as previously mentioned, highly pumpable concrete with a low water to cement ratio does not guarantee its shootability. In other words, the material can be very easy to pump but it can sag and not stick to walls especially overhead surfaces. If special care is not given to the mixture design of wet-mix shotcrete, one could incorrectly believe that adding plasticizing admixtures could be the solution to ensuring adequate pumping and shootability. As illustrated in Fig. 4, a highly plasticized mixture would generally exhibit poor shootability and would require higher dosages of set accelerating admixtures to ensure proper built-up onto the receiving surface particularly for overhead zones.

Minimizing the Set Accelerator Dosage and Avoiding Overdosing

The detrimental effect of overdosing set accelerators on shotcrete durability has been clearly demonstrated in literature (Jolin, Melo, Bissonnette, Power, and Demmard, 2015). In practice, the risk of overdosing is generally higher in the wet-mix process since the volume of accelerator is field controlled. In the dry-mix process, the set accelerator (when used) is pre-dosed/blended in dry form into the dry mixture before being used on site. In the dry-mix process, the plastic consistency needed for the desired material build-up is adjusted in real-time simply by adjusting the water content at the nozzle immediately before discharge. In contrast, in a highly plasticized wet-mix shotcrete, the material build-up during shotcreting is generally produced by the addition of set accelerator at the nozzle to achieve the desired stiffening/hardening effect. In wet-mix application, the risk of overdosing set accelerator is increased particularly when shooting overhead zones that require a higher degree of stiffening/hardening for build-up while reducing the risk of fall-out. The use of supplementary cementitious materials such as silica fume and/or fly ash and rheology modifier additives help to improve the material build-up process, and therefore reduce the set accelerator demand.

Fundamentally, the most efficient way to reduce set accelerator demand in wet-mix shotcrete, while ensuring both excellent pumpability and shootability, is the concept of temporary high initial air content, as illustrated in Fig. 4 (Jolin and Ginouse, 2012) developed over 20 years ago (Beaupré, 1994). As explained in Fig. 4, the high initial air content (10 to 20%) produces excellent pumpable material while ensuring good sag resistance and build-up once the material hits the surface. The air content typically drops to 4 to 6% during impact, which produces a "slump-killing effect" ensuring material consolidation without sagging or fall-out (Jolin and Beaupré, 2003). This concept significantly reduces the set accelerator demand to build thicker shotcrete layers per pass, particularly for overhead surfaces.

In practice, accurate control and monitoring on-site of the set accelerator dosage being added to the nozzle is critical for wet-mix shotcrete to limit the risk of overdosing, and the detrimental effect it can have on later-age performance and durability.

In comparison, the monitoring of set accelerator dosage is well controlled in the dry-mix process since the additives are pre-dosed/blended into the dry mixture before use on site.

Mobile Shotcrete Production Unit

For specific wet-mix projects, it is not always possible to order and receive wet-mix shotcrete from a ready-mix plant. Following is a partial list of potential situations when this is not possible:

Fig. 5: Mobile self-loading mixer with bulk bag lifter

- Projects in remote areas;
- Small volumes;
- Challenging schedules (difficult ground conditions, night shift, lane closures…);
- Local ready-mix producers do not have the knowledge and/or experience to produce high-quality specialty shotcrete mixtures;
- Limited availability of raw materials;
- Shotcrete mixture needs to be mixed on-site due to a short pot life; and
- Excessive dosage of hydration retarder and thus excessive accelerator dosage at the nozzle.

For these types of projects, it is currently possible to produce shotcrete on-demand, on-site using new types of equipment and dry pre-blended materials. Dry preblended material is usually produced in manufacturing facilities ensuring consistent raw materials, proven batching records and strict quality control.

Dry preblended wet-mix shotcrete material can be stored on-site in bulk tote bags, which are then available to be mixed on-demand using equipment such as the new mobile bag-lifting mixer (Fig. 5). A production ticket is printed and provided for each batch, allowing for the control and tracking of every batch produced.

This innovative system helps to reduce material waste and facilitate logistics in remote areas with difficult access for standard ready-mix trucks.

This type of system allows for the on-demand, on-site production of shotcrete minimizing the use of retardant and other admixtures traditionally used to offer logistical/delivery flexibility but also higher dosages of accelerator for overhead shotcreting and rapid strength gain.

It is also possible to use a mobile bulk dry-mix shotcrete sprayer. Using a bulk dry sprayer allows the user to take advantage of the robustness, flexibility and durability provided by the dry-mix process shotcrete while guaranteeing high application (output) rates and controlled dust emissions during spraying operations (Fig. 6).

This type of system can be loaded via bulk bins erected on-site (loading area) or by using bulk tote bags (McDonald and Cruz, 2015). These systems allow for on-demand production with optimized accelerator dosages in the dry preblended shotcrete mixture accurately dosed at the manufacturing facility. Thus, the accelerator dosage is not affected by any other admixtures or on-site conditions, and since the mixing water for dry-mix shotcrete is added at the nozzle, there is no need for the use of a retarder or hydration stabilizer. Additionally, the long-term durability of the in-place dry-mix shotcrete is not affected by the high porosity that can be the result of excessive accelerator dosage use in the wet-mix process (Jolin, Melo, Bissonnette, Power, and Demmard, 2015).

Fig. 6: Bulk dry shotcrete hauler/sprayer

Fig. 7: Adequate lighting and access to the shooting face in a tunneling application (from Croutch, 2014)

Practices for Reducing Rebound and Dust/Chemicals Emission

Proper shotcrete nozzling technique, including the encasement of embeds, openings and reinforcing steel is an important aspect of reducing shotcrete rebound. Adequate lighting and clear access to the shooting face are also important factors for allowing the reduction of shotcrete rebound (Fig. 7). Shotcrete used for ground support in mining and tunneling applications should be applied in accordance with ACI 506R-16, "Guide to Shotcrete." The ACI Shotcrete Nozzleman Certification Program developed and administered by ACI Committee C660 is an excellent program for qualifying and certifying shotcrete nozzlemen for most projects but does not directly cover all the requirements for a nozzleman working in mining and tunneling environments. For some large tunneling projects such as the Metropolitan Transportation Authority (MTA) CC/Long Island Railroad/East Side Access project in New York City, NY, it has become common practice for authorities to develop training and certification programs specific to the project (Drakeley and Rand, 2014). Specifying minimum requirements for shotcrete crew experience including nozzlemen, foremen and gun/pump operators also helps to ensure that the shotcrete will be applied properly.

The shotcrete mixture design used for tunneling applications can also be optimized for rebound reduction for both dry- and wet-mix shotcrete. The aggregate gradation should meet the requirements of Gradation No. 1 or Gradation No. 2 in accordance with ACI 506R-16, "Guide to Shotcrete." A properly designed shotcrete aggregate gradation will reduce rebound due to the optimal particle packing of the in-place shotcrete (Reny and Jolin, 2011). Supplementary cementitious materials used to replace Portland cement in the binder portion of the shotcrete mixture design can also help to reduce rebound. Silica fume has been shown to greatly reduce rebound in dry-mix shotcrete when used to replace a portion of the binder content (Wolsiefer and Morgan, 1993).

For dry-mix shotcrete, certain equipment choices and practices can also help dramatically reduce dust emissions in the underground environment. Using bulk pre-packaged tote bags in conjunction with a hopper hood manufactured to fit the receiving hopper of the shotcrete machine helps to seal the hopper and prevent the release of excess dust (Fig. 8). Proper maintenance and adjustment of the shotcrete equipment including the water ring in the nozzle, and the exhaust port, wear pads and wear plates on the dry-mix gun will also help to reduce dust emissions.

Pre-dampening equipment can also be used for dry-mix shotcrete to reduce the amount of airborne dust, as the

Fig. 8: Bulk pre-packaged tote bag with hopper hood

material is mixed with a small amount of mixing water prior to being introduced into the shotcrete machine (Fig. 9).

The use of a hydro-mix shotcrete nozzle improves particle wetting prior to exiting the nozzle, by moving the water ring roughly 10 ft (3 m) back from the nozzle exit and allowing for increased mixing potential between the mixing water and dry-mix shotcrete (Fig. 10).

Adequate ventilation and dust control devices such as a water atomizer that generates ambient fog is an efficient standard practice used in the mining industry to help control dust during shotcrete operations (Fig. 11).

When using wet-mix shotcrete in tunnel applications, it is typical to use many different liquid chemical admixtures including retarder to increase the pot-life for long underground travel times. Set accelerator would then typically be added at the nozzle to improve early age strength development. Chemical additives can become airborne in the underground environment once atomized in the air stream during the spraying process. Therefore, it is important to minimize the amount of additives as much as possible and as previously mentioned; these chemical additives can be significantly reduced and potentially even removed in the dry-mix process. In the wet-mix process, additives are critical to producing good quality material and use of admixtures can be minimized when using an optimized aggregate gradation, supplementary cementitious materials to facilitate pumping and reduce rebound, and by increasing the initial air content of the shotcrete to improve pumpability.

Ultra-Rapid Performance Gain Shotcrete

Among the existing techniques to speed up the development cycle of underground excavation operations, the use of ultra-rapid strength gain shotcrete is beginning to receive more traction in the industry. By manipulating the cement chemistry and mixture design, this innovative technology allows much earlier re-entry to headings after the completion of shotcrete operations.

Using current portland cement technology, high early strength cement (Type III or Type HE) and a high accelerator dosage, it is possible to provide a shotcrete mixture design capable of reaching early age compressive strengths of up

Fig. 9: Shotcrete pre-dampening gunning rig with dry-mix shotcrete machine

Fig. 10: Hydro-mix nozzle for dry-mix shotcrete (from Hutter, 2014)

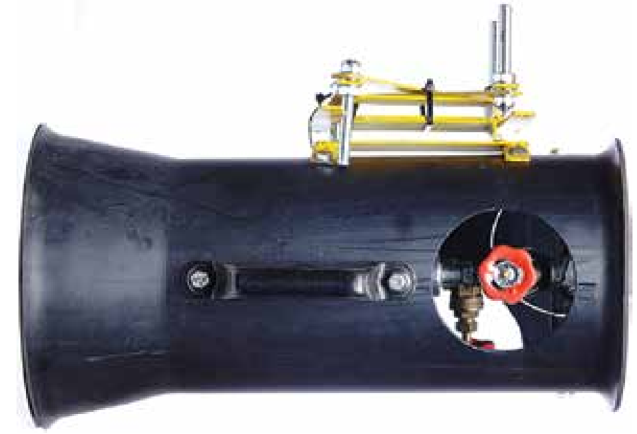

Fig. 11: Water atomizer used to reduce airborne dust

to 1000 psi (7 MPa) at 4 hours. This is possible in both the wet- and dry-mix processes. However, to exceed this early strength level, the cement technology needs to be reviewed. From a cementitious matrix standpoint, the use of an ettringite-based cement such as calcium sulfo-aluminate (CSA) cement can provide very rapid strength gain compared to high early strength portland cement (Type III or Type HE) with a high accelerator dosage (Reny and Ginouse, 2014). At early ages, this rapid strength gain is mainly due to a rapid formation of ettringite, which occurs when the CSA based cement comes into contact with the mixing water.

Unfortunately, the rapid formation of ettringite is also accompanied by a quick decrease in the workability of the mixture, leading to placement issues (Lemay, Jolin, and Gagné, 2014). Even though it is possible to increase the workability period by using retarding admixtures, their use also generally increases set time and therefore delays strength gain. To overcome this workability issue while ensuring a rapid hardening behavior, the use of dry-mix process has been shown to be the ideal choice since the mixing water is added to the mixture in a fraction of a second before impacting the receiving surface. By using ettringite based dry-mix shotcrete, it is typically possible to obtain approximately 2900 psi (20 MPa) after only 2 hours (Reny and Ginouse, 2014) in contrast to 1000 psi (7 MPa) after 4 hours with accelerated portland cement-based shotcretes.

This makes the combination of CSA cement technology with the dry-mix shotcrete process an ideal solution for reducing the mining and tunneling cycle times. This technology is commonly referred to in the industry as RS Shotcrete technology.

RS shotcrete technology has been successfully introduced and used in Canadian mines to accelerate the development cycle of daily underground operations and to increase the speed of construction for critical permanent infrastructure. Reaching 2900 psi (20 MPa) after 2 hours allows for a much quicker re-entry time under the sprayed openings/zones and leads to reduced lead-time to the next development step.

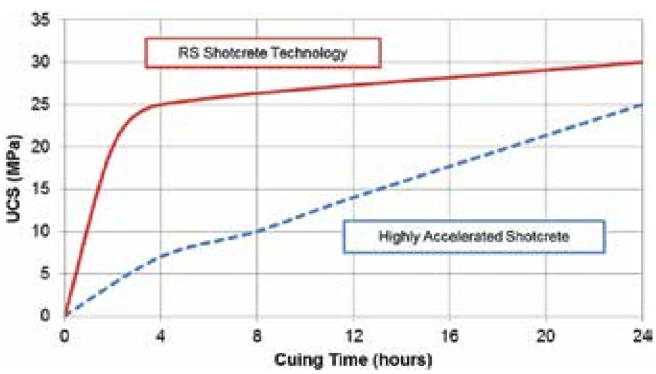

Fig. 12: Typical early age strength gain provided by RS shotcrete technology and highly accelerated portland cement shotcrete

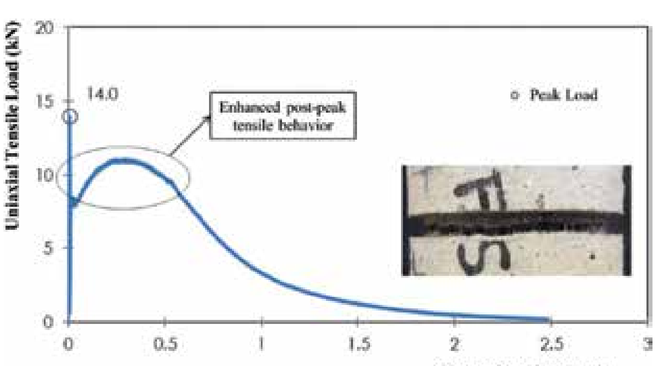

Fig. 13: Improved post-peak tensile strength of engineered high-performance shotcrete (from Ginouse, Reny, and Jolin, 2015)

Combined with structural fibers, the RS Shotcrete technology allows for developing ultra-rapid flexural toughness in challenging ground conditions requiring structural support and energy absorption as early as possible (Ginouse and Reny, 2015).

This technology has also been tested (Ginouse and Clements, 2015) and used successfully for rapid repairs of critical civil infrastructure requiring fast re-opening to traffic and services (Jolin, 2016).

Engineered High Performance Shotcrete

Using design principles similar to ultra-high performance concrete (De Larrard, 1999), recent advancements have been made to adapt this technology for ground support lining in underground projects (Ginouse, Reny, and Jolin, 2015).

This technology provides much higher tensile/flexural performance (see Fig. 13) than regular FRS resulting in higher spalling/impact resistance and energy absorption. On one hand, the overall ground support performance against seismicity and high-stress conditions are greatly improved. On the other hand, the technology is paving the way for thinner support innings, resulting in significant savings in material consumption, labor, time of application and overall logistics.

This novel shotcrete technology has been recently been introduced and successfully tested in Canadian mines facing very challenging ground conditions requiring high performance ground support with minimal amounts of material required to be transported underground from the surface.

Similar technology has been successfully used in tunnel repairs and surface protection in both Japan and the United States to extend durability of tunnel linings (Li, 2003).

Conclusions

Dry- and wet-mix shotcrete are practical, proven and well-adopted methods for ground support in underground excavation projects.

Among the different innovative technologies presented in this article and introduced during the past decades, here are the main technical, logistical and operational solutions/advancements available for underground projects:

- Enhanced shotcrete lining durability obtained using low water-to-cement ratio, supplementary cementitious materials, optimized aggregate gradation, high initial air content concept and minimal dosage of set accelerating admixture accurately monitored on-site in wet-mix shotcrete.
- Flexible and robust shotcrete operations using the dry-mix process or hydration control additives in wet-mix shotcrete to extend pumping life.
- High production of shotcrete material on-demand using either a bulk dry-mix loading/hauling/spraying system or a mobile self-loading mixer producing high quality wet-mix shotcrete on-demand using dry pre-blended materials.
- Low-rebound shotcrete by following good industry practices, properly trained crews, well-maintained equipment and an optimized mixture design.

- Low dust and chemical emissions by following best industry practices, closed bulk dry-mix system, pre-dampening equipment and an efficient water atomizer.
- Rapid development cycle and accelerated tunnel repairs using ultra rapid strength gain dry-mix shotcrete allowing for much faster re-entry and re-opening to traffic/services.
- High-spalling/cracking-resistant shotcrete for challenging ground conditions and protective lining layer using engineered high-performance shotcrete providing enhanced tensile/flexural performance and high-energy absorption.

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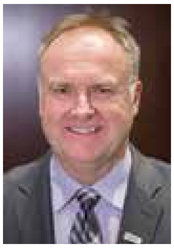

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