A Brief History of Shotcrete in the Underground Industry

By Dudley R. (Rusty) Morgan and E. Stefan Bernard

It is now generally recognized that Carl Ethan Akeley (1864-1926) was the inventor of shotcrete (Teichert 2002). The process was originally developed for application of plaster to rehabilitate the façade of a building at the Field Columbian Museum in Chicago, IL, but was soon used to apply cementitious materials to various substrates, including wire and cloth substrates for building anatomical models of animals for museum exhibits. The gun invented by Akeley (Fig. 1) operated on the principle of a double chamber. The chambers were placed one on top of the other and were alternatively pressurized with compressed air. One of its earliest underground uses was for lining the Hunter's Brook Siphon for New York Water Supply.

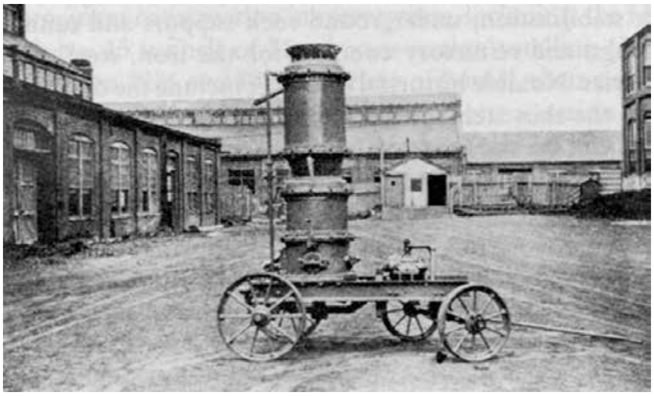

Fig. 1: Original double-chamber gun developed by Carl Akeley in 1907

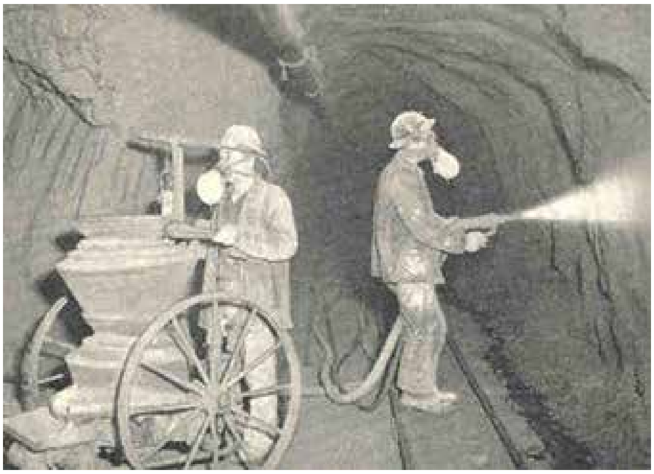

Fig. 2: Lining a tunnel with gunite using a double-chamber gun in the 1920s

In 1912, the Cement Gun Company in Allentown, PA, acquired the rights to Akeley's patents for the cement gun and trademarked "gunite." The gunite process found use in a wide variety of applications, including lining of sewer, water, and railway tunnels; ground support in mines; construction and repair of buildings; protection of structural steel against corrosion and fire damage; repair of bridges, dams, and canals; rock slope stabilization; and construction of water-retaining structures.

By the early 1920s, the use of gunite (Fig. 2) was widespread throughout North America and had expanded to Germany (1921), the United Kingdom (1924), and by the end of the decade, to other countries in Europe as well as India and South Africa. The use of the gunite process continued to expand throughout the world during the 1930s and 1940s, with the double-pressure chamber gun the predominant method for material delivery.

In the early 1930s, the American Railway Engineering Association adopted the term "shotcrete" to describe the dry-mix process and in 1951, the American Concrete Institute (ACI), to standardize terminology, also adopted the term "shotcrete." Initially, the term "shotcrete" applied only to the dry-mix process, but after World War II, with the development of the wet-mix process, ACI adopted the term "wet-mix shotcrete." In Europe, the term "sprayed concrete" is generally used instead of shotcrete.

MAJOR DEVELOPMENTS IN TECHNOLOGY

The development of shotcrete and its application in underground construction has been improved through the advent of a succession of key technologies. These include:

Wet-Mix Shotcrete

A major revolution in the shotcrete industry occurred with the development of the wet-mix shotcrete process. Various individuals and companies had experimented with this process as far back as the 1920s (Sprayed Concrete Association 1999), but it was not until the mid-1950s that the wet-mix process started to find significant application. Numerous equipment manufacturers modified concrete pump designs to make them better suited to wet-mix shotcrete application. It was primarily the development of the swing-tube concrete pump in the late 1970s (Fig. 3) that really made wet-mix shotcrete practical (Yoggy 2002). The cylinders were sized to make them suitable for conveying shotcrete at a rate that could be managed by a nozzleman for hand application. The rate of cycling of the swing tube controlled the surge and volume of shotcrete delivered per minute. With these refinements, the nozzleman could maintain precise control over placement of concrete in a wide range of different shooting conditions (for example, vertical, overhead, downward, open shooting, or shooting congested reinforcing steel and embedments) at a rate of productivity of about four times what was possible by the dry-mix shotcrete process. With the subsequent introduction of robotic manipulators in Norway (Woldmo 2008), which typically used bigger pumps and larger-diameter hoses, even greater rates of production were achievable. These machines are now used throughout the world.

Steel Fiber Reinforcement

The concept of reinforcing shotcrete with discreet, discontinuous fibers was first developed by the Batelle Research Corporation in the United States in 1971 (Morgan 2000). The first practical application of steel fiber-reinforced shotcrete (FRS) in North America was in 1972, when it was used by the U.S. Army Corps of Engineers for rock slope stabilization and lining a tunnel adit at the Ririe Dam on Willow Creek, a tributary of the Snake River in Idaho (Kaden 1974). The first use of steel FRS in Canada was in 1978, when it was used to stabilize a sloughing railway embankment in Burnaby, BC, Canada (Fig. 4).

Synthetic Fiber Reinforcement

Synthetic fiber-reinforced shotcrete first appeared in the 1990s as manufacturers developed products to compete with steel fibers (Bernard et al. 2014). There are basically two types of synthetic fibers: microfibers and macrofibers. Microsynthetic fibers can be used in both wet- and dry-mix shotcretes, but macrosynthetic fibers are mainly used in wet-mix shotcrete. Microsynthetic fibers are typically used at low addition rates of 1.7 to 3.4 lb/yd^3 (1 to 2 kg/m^3) to improve resistance to plastic shrinkage cracking, but in shotcrete they have primarily been found effective in increasing resistance to explosive spalling in tunnel linings subjected to high-temperature fires (Tatnall 2002). Macrosynthetic fibers are used at much higher addition rates of 5 to 15 lb/yd^3 (3 to 9 kg/m^3) and are employed for many of the same reasons as steel fiber reinforcement—for example, to improve toughness (residual load-carrying capacity after cracking) and impact resistance (Morgan et al. 1999; Morgan 2000).

Silica Fume

A milestone in the development of shotcrete technology was the incorporation of condensed silica fume as a supplementary cementitious material in the shotcrete mixture. This was first undertaken in Norway in 1975 (Garshol 1990). The first application of silica fume in shotcrete in Canada was in 1984, when it was used in shotcrete rehabilitation of a pier in the intertidal region in Vancouver Harbour, BC, Canada (Morgan 1995). It was found that the use of silica fume had major benefits, including enhanced adhesion and cohesion, with reduced rebound and fallout in the plastic shotcrete and increased strength and durability in the hardened shotcrete.

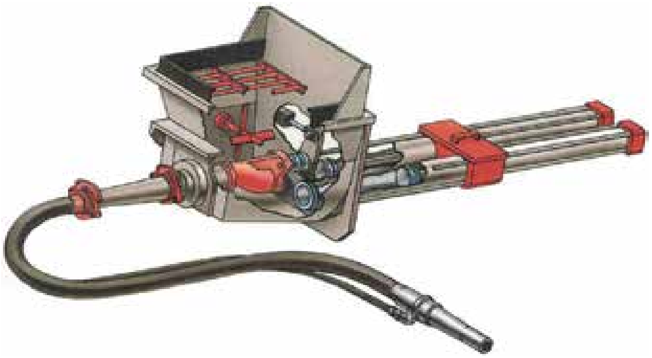

Fig. 3: Schematic of a wet-mix shotcrete pump with swing tube

Fig. 4: Dry-mix steel FRS lining of a railway embankment in Burnaby, BC, Canada, in 1978

Air-Entraining Admixtures

Air-entraining admixtures have been used in wet-mix shotcrete to provide freezing-and-thawing durability since the development of wet-mix shotcrete in the mid-1950s. Research at Laval University in Quebec, Canada, in the late 1980s and early 1990s showed that it was possible to entrain sufficient air in dry-mix shotcrete to provide good freezing-and-thawing durability and resistance to deicing salt scaling (Beaupre et al. 1994). Currently, most dry-bagged shotcrete materials for exterior applications in frost exposure environments are batched with dry powdered air-entraining admixtures (Vezina 2001).

Water-Reducing Admixtures

Conventional water-reducing admixtures have been used in wet-mix shotcretes since the 1950s. However, with the introduction of silica fume into shotcrete applications in North America in the mid-1980s, the use of conventional water-reducing admixtures alone was often insufficient to reduce water demand to the extent needed to provide a suitably low water-binder ratio (*w/b*). Therefore, in the mid-1980s, high-range water-reducing admixtures (also called superplasticizers) started to be used in conjunction with conventional water-reducing admixtures in wet-mix silica fume shotcretes.

Retarders and Hydration Controlling Admixtures

Wet-mix shotcretes typically take longer to discharge from transit mixers than conventional concretes because of the requirement to control the rate at which shotcrete is supplied to the nozzle. Thus, set-retarding admixtures have often been added to wet-mix shotcrete mixtures to extend the workability (pumpability) of the mixture, particularly in hot weather conditions. Conventional set retarders have, however, had their limitations, particularly in tunnel and mining applications, where there are often long delays (sometimes 4 to 8 hours) from the time of batching to completion of discharge of the shotcrete. The introduction of hydration controlling admixtures in the 2000s had a major beneficial effect on the shotcrete industry. It is now possible to put the shotcrete "to sleep" for 12 hours (or even longer, if required) and then instantly wake it up with shotcrete accelerator addition at the nozzle.

Shotcrete Set Accelerators—Underground

Shotcrete set accelerators are an essential component of shotcrete in underground applications, particularly for overhead applications in tunnels and mines. In dry-mix shotcrete, they can be added either as dry powdered materials to the dry-mix shotcrete materials before introduction into the shotcrete gun, or as liquids added at the shotcrete nozzle. In wet-mix shotcretes, they are added as liquids at the shotcrete nozzle (Fig. 5). Early (circa 1960s to 1990s) dry-mix shotcrete accelerators were mainly highly alkaline (>12 pH) sodium or potassium-aluminate-based dry-powdered products, or liquid-alkaline-sodium-silicate-based products. These tended to have detrimental effects on the longer-term compressive strength, permeability, and durability of the shotcrete, with the effect being more pronounced the greater the accelerator addition rate. A major advance in shotcrete technology was the introduction in the 2000s of so-called "alkali-free" shotcrete accelerators. These liquid accelerators are mainly based on aqueous solutions or suspensions of aluminum sulfate compounds and have a pH of approximately 3. They have less negative effect on the compressive strength, permeability, and durability of shotcrete (Millette and Jolin 2014) and are compatible with most hydration-controlling admixtures. They are now used widely throughout the world in underground applications.

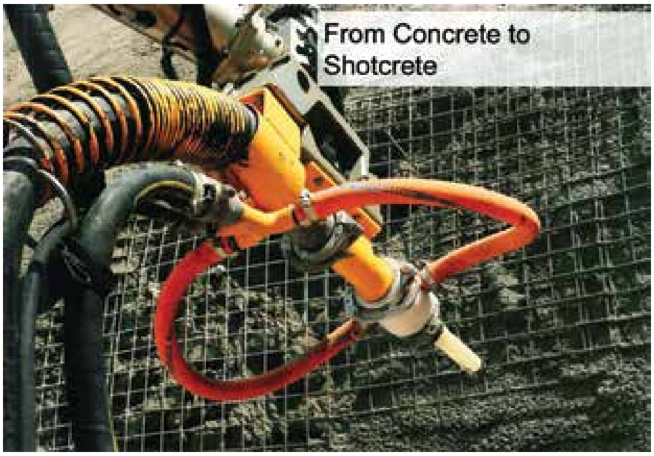

Fig. 5: Accelerator addition at nozzle in remote control wet-mix shotcrete

Fig. 6: Hand application of dry-mix shotcrete in a tunnel in British Columbia, Canada, in the 1970s

SHOTCRETE IN TUNNELS

The first reported use of shotcrete for underground support in North America was the use of gunite (dry-mix shotcrete) in the Brucetown Experimental Mine in 1914. It was used primarily to protect and maintain excavated rock surfaces from deterioration from exposure to water and air (Kobler 1966). Thereafter, for the next three decades, gunite continued to be used in underground applications in many tunnels and mines across North America, although mainly in semi-structural applications (Fig. 6).

Critical to the use of shotcrete in underground support was the development of design methodologies that allowed engineers to replace conventional steel sets and timber lagging-type designs, or cast-in-place reinforced concrete lining designs with rock bolt and shotcrete designs. Preeminent among these design methodologies was the so-called New Austrian Tunneling Method (NATM), which was developed by Rabcewicz and his colleagues in Austria in the late 1950s and early 1960s (Rabcewicz 1964, 1965). This was followed by the development of the so-called Norwegian Method of Tunneling (NMT) in the 1970s (Barton et al. 1995).

In North America, dry-mix shotcrete in conjunction with rock bolts and mesh reinforcement and other types of reinforcement (for example, lattice girders and/or steel sets) was used in construction of eleven Washington, DC, subway stations during the 1970s and 1980s (Plotkin 1981). In Canada, permanent dry-mix coarse aggregate shotcrete linings with mesh reinforcement and rock bolts was used in construction of the Canadian National Railways Tunnel (the Thornton Tunnel) near the Burrard inlet in Vancouver, BC, Canada in 1968 (Mason 1968). Also, mesh-reinforced dry-mix coarse aggregate shotcrete, in conjunction with steel sets, was used in construction of reinforced linings in a subway tunnel in Toronto in 1961 (Kobler 1966). The first major use of the NATM process in Canada (although the designers referred to it as the Sequential Excavation

Method [SEM]), was construction of the underground Grandin Metro Station in soft ground in downtown Edmonton, AB, Canada (Brandt and Phelps 1989).

NEW AUSTRIAN TUNNELING METHOD (NATM)

The NATM method was primarily developed for tunneling in weak or squeezing ground. Many hundreds of different tunnels and other underground openings have been constructed using the NATM method, most of them successfully (ITA-Austria 2012), but with some notable failures (Institution of Civil Engineers 1996). Conceptually, the NATM process involves stabilizing the ground around an underground excavation in the most safe and economic manner possible by using the bearing capacity of the ground with the help of shotcrete and other support elements, together with continuous measurement of ground and lining deformations and stresses during the construction process.

The Austrian Chapter of the International Tunneling Association publication *50 Years of NATM* (ITA-Austria 2012) provides many examples worldwide of completed NATM projects. It provides a comprehensive overview of the historical development and advances in the use of the NATM process over a 50-year period. In the United Kingdom, the term “sprayed concrete lining” (SCM) is sometimes used to describe the NATM process. In North America, the term “sequential excavation method” (SEM) is sometimes used to describe the NATM process.

Barton et al. (1995) provides a useful summary of the principles of NATM design together with some examples of different NATM projects. In Scandinavia (Barton et al. 1995) and North America (Chan et al. 2002a,b), permanent shotcrete linings with high quality, low permeability, low leachability, and good durability were being produced in the 1980s for underground support in tunnels and mines using steel fiber and silica fume. These projects demonstrated that it was possible to provide high-quality, permanent, durable shotcrete linings, with shotcrete mixtures well-suited to the construction process, using either the wet- or dry-mix shotcrete processes. These findings gave rise to an interest in the concept of a single shell shotcrete lining—that is, a lining comprised of a high-quality initial shotcrete lining (with or without a waterproofing membrane) and a final (inner) reinforced permanent shotcrete lining in lieu of a cast-in-place final concrete lining.

NORWEGIAN METHOD OF TUNNELING (NMT)

Much of the tunneling work done in the Scandinavian countries has been in harder, jointed rock, which had been excavated using drill and blast methods. This excavation process often resulted in overbreak, with irregular rock surface profiles. Such excavation profiles are not well-suited for use of the NATM process (Barton et al. 1995). Prior to the 1970s, such drill and blast-excavated tunnels, where required, were supported by rock bolts and mesh covered with a plain shotcrete. These single shotcrete lining systems, while they worked reasonably well, were not optimal from either a cost or technical performance perspective. This is because of the large volumes of shotcrete required to fill the voids behind the mesh, as well as the difficulties sometimes encountered in getting good bond of the shotcrete to the rock behind the mesh and fully encapsulating the mesh. With the advent of steel FRS in the 1970s (Vandewalle 1990), and later macrosynthetic FRS (Bernard et al. 2014), these concerns could be ameliorated.

These advances were critical in the development of the Norwegian Method of Tunneling (NMT) as we know it today. The NMT is based on a quantitative (numerical) rock mass classification system (the so-called Q-System), developed by Barton and his colleagues (Barton et al. 1974; Grimstad and Barton 1993). Briefly, this design method makes recommendations for various reinforcement categories depending on rock mass classifications (rock classes varying from exceptionally good to exceptionally poor), and the underground opening span or height divided by the excavation support ratio (ESR). Papworth (2002) published a modified version of the Q-system (Fig. 7) in which recommended toughness requirements were added based on tests conducted on FRS in accordance with ASTM C1550. There were some merits in this recommendation, but more appropriately, the varying energy requirements for FRS in Joules are best included in the different envelopes. By 2005, macrosynthetic FRS was becoming widely used underground, so the modifications suggested by Papworth (2002) were applied to shotcrete reinforced with both steel and macrosynthetic fibers.

The Q-System for rock mass classification has now been used for over 40 years for assisting in selection of reinforcement systems for rock tunnels and caverns. During the past 30 years, the use of mesh reinforcement has been largely eliminated in Scandinavia and most NMT tunnel design has been based on the use of FRS reinforced with either steel

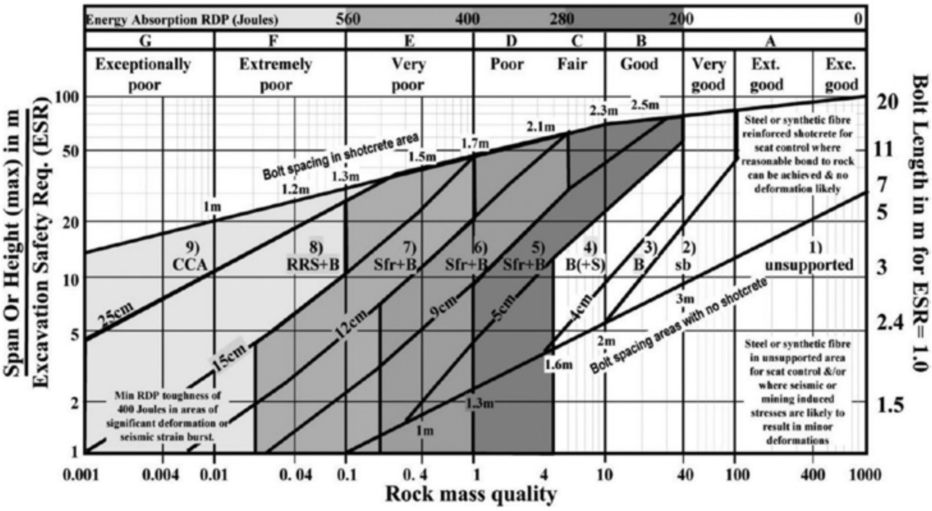

Fig. 7: Modified Barton Q-System Chart (Papworth 2002)

or macrosynthetic fibers. Many hundreds of underground structures and thousands of miles (km) of tunnels have been successfully constructed using the single-shell FRS NMT method in Scandinavia and elsewhere (Barton and Grimstad 2014). Much of the tunneling work carried out in hard rock tunnels and mines in North America since the early 1980s has also used FRS in single-shell lining systems analogous to the NMT designs.

SHOTCRETE IN MINING

The original sand-cement gunite (dry-mix shotcrete) system developed by Carl Akeley was used, albeit with advances in shotcrete mixture designs and application equipment, in underground mines in North America and elsewhere from 1911 through to the 1950s. During this period, however, it was not the primary means of ground support and control in underground mines. Traditional ground support and control methods, such as timber and/or steel sets and timber lagging and rock bolts and screen (heavy-duty wire mesh) were the predominant methods used. Gunite was used as an auxiliary component of the support system in selected applications. During the 1950s to 1980s, most shotcrete applied in underground mines was dry-mix shotcrete applied by handheld nozzles. By the early 1980s, however, specialized shotcrete-spraying remotely controlled manipulators started to be used in mines (FIg. 8) in both aboveground and underground applications (Rispin et al. 2005).

Fig. 8: Remote control wet-mix FRS ground support in mine in North America

Fig. 9: Large underground opening for workshop in mine in Sudbury, ON, Canada, lined with macrosynthetic FRS

This acceptance was not without its challenges, as initially many miners were skeptical about the ability of a relatively thin layer of reinforced shotcrete (typically 2 to 4 in. [50 to 100 mm] thick) to support the ground in challenging mining environments with high ground stresses and deformations and seismic (rock-burst) conditions. They were used to observing problem areas in the mines by the "loose" (fallen chunks of rock) found hanging in the overhead screen and many looked at shotcrete as hiding potential problem areas. It took many training sessions and seminars and case history examples to demonstrate the theory of how shotcrete worked to provide ground control and how it helped in locating problem areas by identifying visible cracks in the shotcrete when there was significant ground movement (Larsen et al. 2009). Ground support strengthening could then be installed in areas where the shotcrete displayed significant cracking. Thompson et al. (2009) provided a useful overview of how cracks develop in shotcrete in rock under high stress and dynamic conditions and what constitutes significant cracking that would give rise to the need for remedial works.

By the 1990s, wet-mix robotically applied shotcrete was enjoying widespread use in many of the world's large mechanized underground mines (Fig. 9). Larsen et al. (2009) reported that in the 2000s, the Vale Inco Frood and Stobie underground mines used between 7800 and 10,500 yd^3 (6000 and 8000 m^3) per year of robotically applied wet-mix FRS. In Australia, since 2000, approximately 650,000 yd^3 (500,000 m^3) of wet-mix FRS (initially steel fiber-reinforced but now almost all macrosynthetic fiber-reinforced) are applied annually in metalliferous mines (Bernard et al. 2014). Macro-synthetic FRS is also developing as an essential component of ground support and methane gas control in underground coal mines, replacing the previous reliance on mesh and stone flour.

SUMMARY

Shotcrete has come a long way since it was first developed by Carl Akeley in 1907. Modern underground support systems in tunnels such as NATM and NMT would not be possible without the use of shotcrete. Also, there are many underground mines around the world that would not exist were it not for the use of shotcrete to support underground openings during the mining cycle.

Acknowledgments

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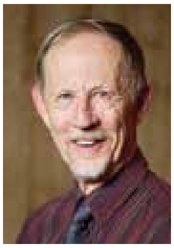

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