Underground Shotcreting

By George D. Yoggy

Many tunnels and mines constructed throughout North America in the last 20 years have successfully used shotcrete as a major element of support during excavation and as part of the lining system. Shotcrete has reached the century mark, and its use to build new concrete structures and restore and repair existing structures is well known and documented. Although this versatile method of placing concrete is widely accepted by the construction industry, shotcrete for ground support in tunnel and mine operations is perhaps less known by the general contracting community. Underground shotcreting, however, consumes the largest volume of concrete of all pneumatic applications. Today, nearly all tunnels under construction in North America will use shotcrete as part of their support system. And rather than a cast-in-place concrete lining, a shotcreted final tunnel lining, installed after the ground support system is in place, is also practical and gaining acceptance.

When shotcreting underground, the nozzle operator must address joints in the rock and assure proper coverage to provide support to the ground

Technical Advancements

The development of rotary-type gunning equipment in the 1950s, which allowed continuous material feed, higher outputs, and the use of larger aggregate mixtures, is the greatest contributor to the wide use of shotcrete for ground support in tunnel construction.

The development of the New Austrian Tunneling Method (NATM) in the late 1950s, as well as similar engineering philosophies, has contributed to making shotcrete a vital part of tunnel support and lining. NATM and the Sequential Excavation Method (SEM) are systematic design and support methods that integrate the behavior of the geology and monitoring of the performance of support during excavation and construction. Shotcrete, a primary component of the tunnel construction system, results in time and cost savings and allows greater use of underground space. Several soft ground and "mixed face" tunnel projects presently being constructed are possible because of this technology.

Over the last two decades, advancements in concrete technology, shotcreting equipment, and application methods have contributed to the growth of shotcrete as a primary support element in tunnel and mine applications. Advances in the wet process, particularly in the use of admixtures, have allowed higher volume capabilities, more versatile mixture designs, and more effective use of steel fibers as integral reinforcement. The dry-mix process, however, is still effective and efficient in some areas of tunneling and is the predominant method in many parts of the world for ground support in mines. Because access to deep mine areas is limited (usually through a vertical shaft that may extend to depths of several thousand feet), delivery of a dry mixture from the surface to the point of placement eliminates the set time limitations of wet shotcrete. On some projects, transporting materials to the point of use can take hours or days.

Why Shotcrete Is Ideal for Ground Support

The American Concrete Institute (ACI) defines shotcrete as "…concrete or mortar applied to a surface at high velocity." Spraying concrete onto a surface at high velocity is, in theory, the perfect concrete placement method. Individual aggregate particles of various sizes, coated with cement paste, are driven into place to form a void-free mass of fully compacted concrete. This strong, dense, well-bonded material is ideal for rock and ground support and lining.

Tunnels are generally permanent or long-term structures designed as conduits for cars and trucks, trains, water, waste, or power. Mine openings are typically designed to have shorter life spans because their primary purpose is to allow retrieval of minerals. The role of shotcrete is similar in both applications—to serve as a structural support element alone or in harmony with other support systems.

Excavation of rock or ground to form a tunnel can take place in several ways, nearly all of which can use shotcreting as support to maintain the opening. Shotcrete is most often used in drill-and-blast excavations but is also applicable in mechanical excavation of soft ground or mixed-geology conditions, such as recent projects in Seattle and ongoing tunnels in San Francisco and near the U.S. Capitol.

During the excavation process for a mine or tunnel, the ground is disturbed, sometimes violently. After a section or "round" is excavated, shotcrete is applied as an initial cover to prevent the rock from reacting to a changed environment. Early application of shotcrete effectively seals the ground against air slaking (a change in moisture and plastic properties) and assists in distributing forces in the surrounding rock or ground mass. When shotcrete is sprayed onto the surface, the mortar and fines-dominated matrix fills tiny fissures and openings that occur naturally or have resulted from the excavation process.

Depending on a variety of conditions, such as the size of the opening, rock mass quality, and rate of tunnel advancement, additional support elements may need to be installed. As Fig. 1 shows, rock anchors or bolts are commonly used to work in concert with shotcrete. Often, two or more layers of shotcrete are applied, depending on the design criteria, construction cycles, and tunnel end use. Welded-wire fabric, traditionally used as part of the first step in ground support in tunnel construction, has now been almost totally replaced by the use of steel fibers in shotcrete. Steel and some synthetic fibers are also being used to replace mesh in mine excavations.

To ensure proper adhesion on vertical and overhead surfaces, set accelerators are introduced into the nozzle to alter the setting characteristics of the shotcrete

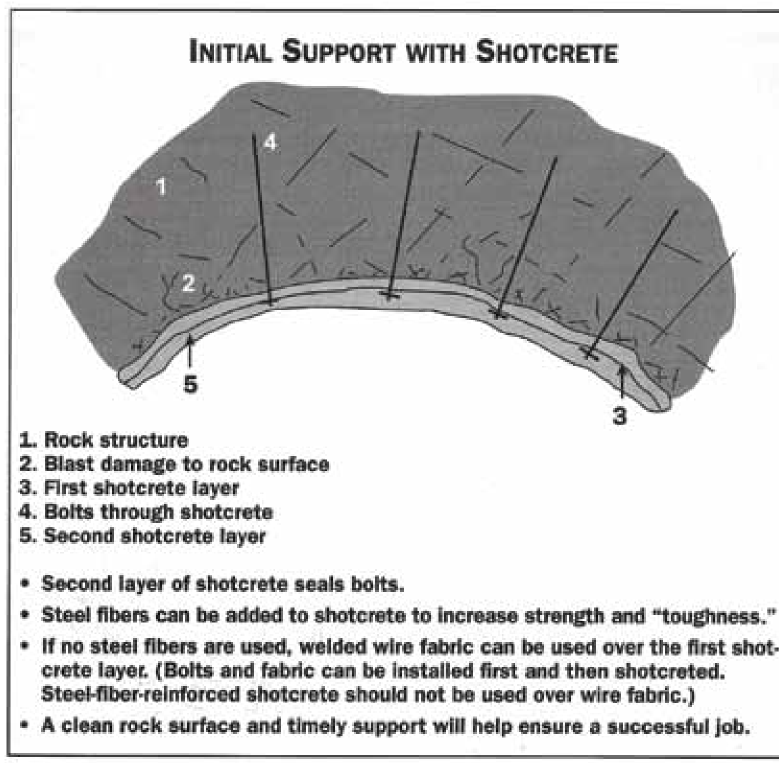

Fig. 1

Mixture Design Requirement

To meet the requirements for ground control in the difficult, often hostile underground environment, concrete mixtures that are to be applied to surfaces using the shotcrete method must be carefully designed to satisfy exacting criteria. The contractor will be responsible for conducting a variety of preconstruction tests to prove performance, and the concrete producer is responsible for supplying a mixture dictated by project requirements and conditions. Attention to such factors as the water-cement ratio, cement and aggregate proportioning, environmental conditions in the tunnel or mine, time/life cycle of the concrete, and use of chemical admixtures is extremely important to achieving a quality product.

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Modern transit projects require large caverns for stations. Shotcrete and modern shotcreting equipment make this possible

The conveying and application systems for shotcreting, both wet and dry, typically use hoses and nozzles with inner diameters of 2 to 3 in. (50.8 to 76.2 mm). Therefore, all mixtures must be designed with a maximum aggregate size of 3/8 in. (9.53 mm). Because mixture designs for shotcreting consist of small aggregate, more surface area to coat requires high cementitious content and careful attention must be given to water requirements, particularly in mixtures for wet process. Water-reducing admixtures are a must for producing quality material that will be pumpable and capable of passing through reduction components between the pump piston and the hose and hardware used for placement.

Mixture designs for dry-process shotcrete must contain properly graded aggregates and known moisture content. When oven-dried, packaged materials are used, predampening with control is a must. How water and additives are measured and introduced into the mixture and at the nozzle are very important considerations for quality and performance. Dosing of accelerating additives at the nozzle for the wet process must be exact and controlled. Therefore, pre-job tests involving the engineer, contractor, materials supplier, and equipment supplier are essential.

Silica fume improves the performance of all shotcrete by reducing rebound, increasing density, and greatly improving bond. Its microparticles of cementitious material adhere better than plain cement to the roughened rock surface left by the excavation process and enhance the overall performance of shotcrete for rock support. Because of its fineness, however, silica fume demands more water than ordinary cement mixtures and requires special care in design of mixtures. The contractor must know how to introduce admixtures that will allow lower water contents, improve pumpability, and control accelerator dosing requirements.

Shotcrete mixtures are generally designed to be flowable, pumpable, and sprayable for easier application. But because underground shotcreting requires application of concrete to vertical and overhead surfaces, these plastic characteristics must be reversed almost immediately after the shotcrete leaves the nozzle to assure that the material adheres to the rock surface and builds strength quickly.

Set-accelerating additives introduced at or near the nozzle are used to alter the setting characteristics of shotcrete in a matter of minutes. And modern chemistry used for this purpose is safe and user-friendly to the applicator and the concrete.

Challenges of Working Underground

In some parts of the world, it is possible for a tunneler to employ specialty shotcrete contractors. But due to the complexity of underground shotcreting, safety risks, equipment requirements, and access problems associated with excavation and advancement cycles, few shotcrete contractors specialize in tunnel projects.

Shotcreting in a tunnel requires that the applicators know as much about the rock surface and its general makeup as they do about the concrete being applied. The complex, broken rock surface dictates that the nozzleman or robot operator “read” the rock so the direction and buildup of shotcrete will form a complete, homogeneous member. Whether a wet or dry process is used, rebound and overspray must be monitored and controlled. Ninety percent of all shotcrete rebound occurs in the first 10% of application. As the larger particles in the mixture strike the hard surface and bounce off, they shed their cement paste coating, driving the fine, rich mortar matrix into the intricate surface (refer to Fig. 2). This filling of joint planes binds together loose or partially supported fragments of rock and prevents further deterioration and movement. As the layer of concrete builds, a structural member is created with predesigned and predictable results, without the aid of forms. The shotcreter must also anticipate where dust and overspray may coat a surface and interfere with concrete bond or sound concrete buildup. These are but a few important steps in assuring quality and performance.

Other factors contributing to successful tunnel shotcreting include:

- A clear understanding of the concrete components and mixture design;
- A clean rock surface to ensure bonding of the concrete and filling of fissures and surface breaks;
- Careful planning of the batching, transport, and application time for the concrete based on the logistics of the project;
- A familiarity with the conditions and safety requirements of the underground environment; and
- Proper and ample training and education. This is not a do-it-yourself construction method!

Shotcrete can perform many useful functions in underground construction because its mixture design can be adjusted to accommodate the demands of the project, the equipment used for placement, and the environment in which it is applied. As in all areas of concrete construction, however, successful and proper application requires both sound theoretical knowledge and a great deal of practical experience.

***George D. Yoggy** has been directly involved in shotcrete and concrete applications for more than 40 years. Yoggy retired from Master Builders in 2000 and is a consultant to the tunnel and shotcrete industries. He lectures at various training programs on the use of shotcrete, is an approved ACI Examiner, and serves on several technical committees for ACI, ASTM International, ASA, and the American Underground Construction Association. He continues to be an active participant and respected leader in industry initiatives.*

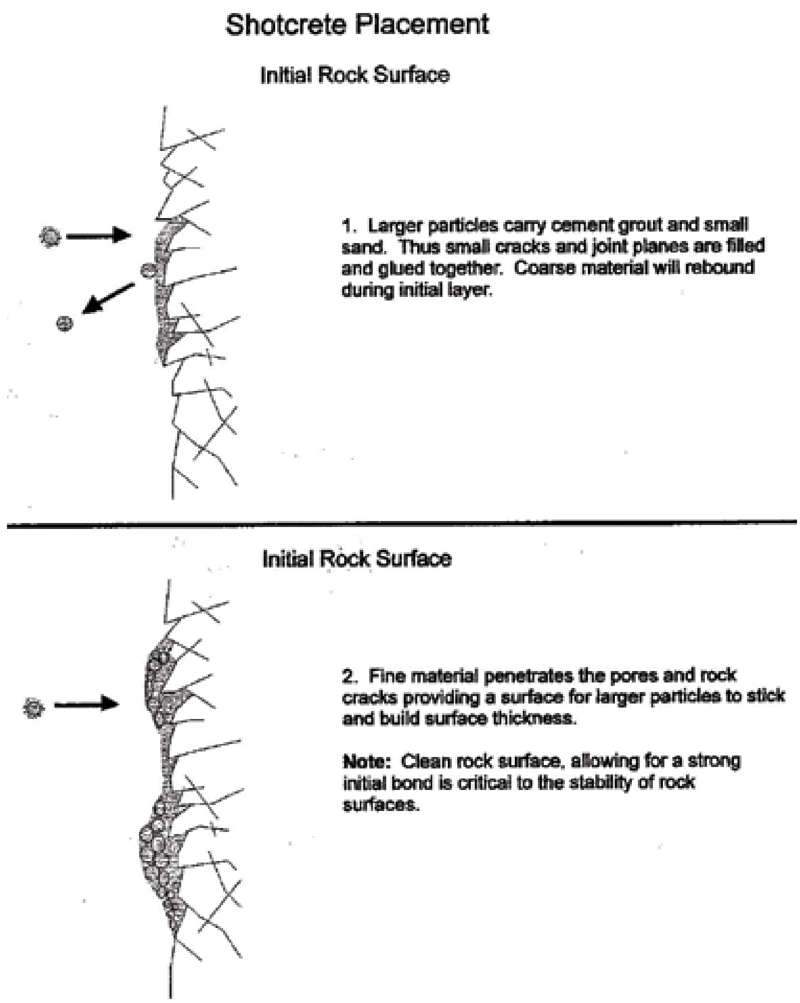

Fig. 2

Spraying concrete onto excavated ground at high velocity effectively fills surface fractures and joints and assists in distributing forces in the surrounding rock mass