Fiber-Reinforced Shotcrete for Underground Mines in the New Millennium

by Mike Ballou

Shotcrete mixture designs for underground applications vary from mine to mine throughout North America, based on the mine location, the production capacity of the mine, and the potential return on investment for underground mining, depending on current metal and mineral prices. Other things to take into consideration include geological conditions of each specific mine, specific shotcrete mixture aggregate strength, cement types, sand type and grading, and water purity/quality.

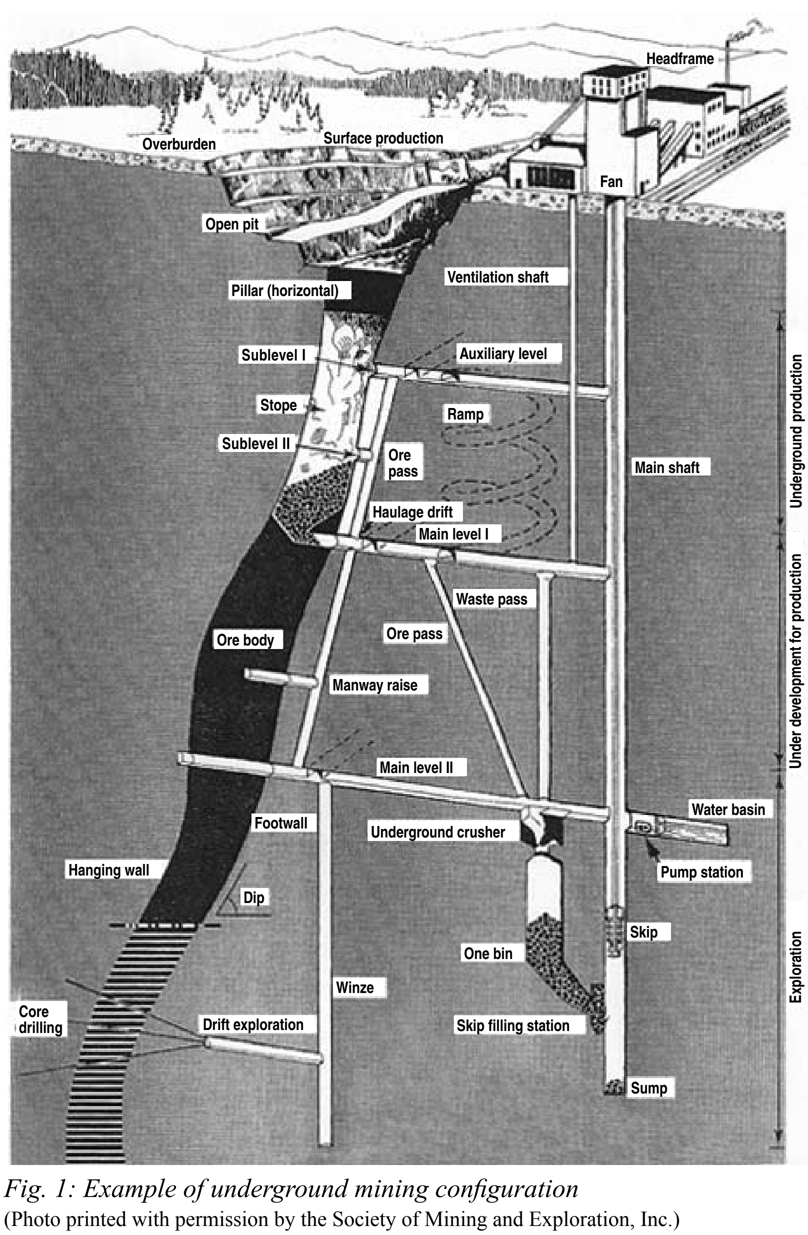

Fig. 1: Example of underground mining configuration
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There are several methods used for ground control in underground mining such as rock and cable bolts, steel rib sets, and lattice girders, as well as a variety of combined methods. Shotcrete is sometimes used in conjunction with mechanical devises that are designed to stabilize the ground so that mining can be accomplished safely. Also, shotcrete may be applied simply as a covering layer on an exposed excavated surface to protect an area from exposure to air, and as a protective measure to keep excavated areas safe by helping to prevent loosened rocks and debris from falling on to miners or equipment.

Because shotcrete or concrete is a brittle material by nature, measures are taken to provide a way for the shotcrete to develop tensile strength and toughness to make it more tough so that it doesn't break apart, spall, and fall when it is disturbed in some way. Often shotcrete is made tougher by adding either steel or macrosynthetic fibers to the mixture. This article discusses types of fibers that can be used in shotcrete and provides recommendations on when it may be an advantage to use fiber-reinforced shotcrete (FRS). Plain shotcrete is defined as shotcrete that does not have fibers added to it. FRS is defined as shotcrete that has had fibers, either steel or macrosynthetic, added to the mixture. Applications for FRS are discussed for practical, economic, and safety reasons.

Mining Methods: Drill, Blast, Muck, Protect

The purpose of underground mining is to extract ore from the earth's crust through a series of tunnels, or drifts, which are defined as horizontal or nearly-horizontal openings in underground mining.

Ore exists in ore bodies that are either horizontal or in vertical shapes such as reefs, which vary in thickness and depth. Most mines begin when ore is discovered on or near the surface. An effort is then made to extract the ore that exists in these formations (refer to Fig. 1). Sometimes, when it is economically feasible, methods of underground mining are employed. This means that either a shaft is excavated or sunk from the surface or there is a ramp or a decline, both of which are excavations, usually from the surface or some other part of the mining area. From the shaft or the ramp, the mining is done by drifts (through the rock) and stopes (through to ore). It is sometimes confusing to differentiate between drifts and stopes, but for reasons of clarity, we will use the term "excavation" to mean both drifts and stopes.

When mining an underground excavation, it must be determined how large an opening should be made to excavate through the rock or other material to access the ore body. Mining is mostly done with large equipment, so if large equipment is to be used, it makes good sense that larger openings must be excavated to accommodate the larger equipment. There are times when miners reason that they can advance through an area more quickly if they make a smaller opening. This reasoning seems normal, but sometimes it can be a costly mistake when an excavation is too small to get equipment in and out so that proper mining techniques can be employed. The method of advancing usually involves the use of drilling equipment to drill into the rock. Once that is done, then an explosive material is placed into the drilled-out holes. When the explosive is detonated, depending on the mining method, there is usually a new opening formed. After the fractured rock or muck is moved away, the new opening must be supported. This is done with a variety of methods, one being FRS.

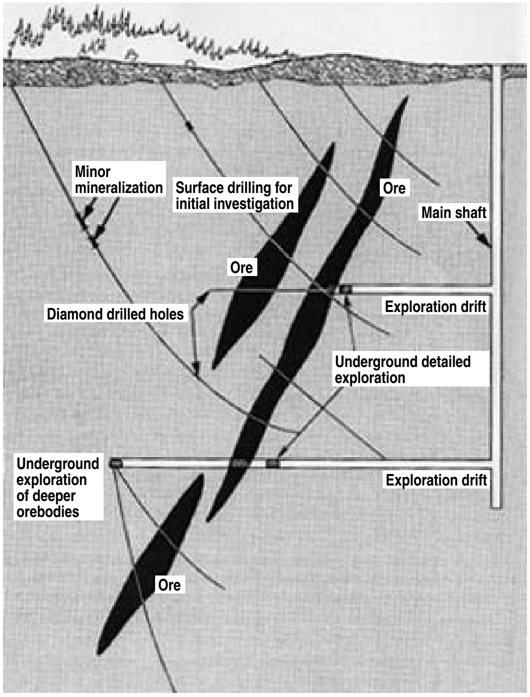

Fig. 2: Example of drift configuration
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Which Type of Shotcrete to Use: Dry- or Wet-Mix?

There are two methods of shotcreting, namely the dry-mix and wet-mix methods. Both methods are successfully used in North American mines.

Dry-mix shotcrete is generally a preblended dry mixture, hence the name, which is delivered to a mine in bulk bags from preblending dry shotcrete manufacturers or suppliers. These suppliers have manufacturing facilities throughout North America, and the bags are transported either by truck or train to mine sites. The bags are taken underground either down the shaft in the cage or down a ramp. From here, the shotcreteing is accomplished with a dry-mix shotcrete gun, usually with a predampener to control dust, and can be sprayed successfully either with or without fibers. Steel fibers have been used for years in shotcrete but macrosynthetic fibers are also being used in the dry-mix method. Sometimes, depending on the shotcrete mixture design and the shotcreting equipment rebound, fly away tends to be quite high with the synthetic fibers. Sometimes the macrofibers do not go through the openings of the shotcrete gun very well and the equipment clogs, so previsions should be taken to prevent the guns from clogging, which is discussed later.

Wet-mix shotcrete is a preferred method of shotcreting for a variety of reasons, but the main reason is that there is usually less dust and rebound related to wet-mix shotcrete either with or without fibers. Wet-mix shotcrete is either batched on the surface or sent down a bore hole of some sort or it is batched underground with the preblended dry products that are sent down separately. Wet-mix shotcrete has the consistency of normal concrete and is treated as such. It is heavy because of the water and other ingredients in it and must be transported underground by special trans-mixers that revolve to keep the shotcrete particles in suspension. Equipment to transport and spray wet-mix shotcrete is designed for the rough conditions of underground mining. Fibers can be added at the surface in the concrete trucks or batching system or as an ingredient in the batching process underground. Most often fibers are added to the mixture on the surface because of space restrictions underground.

Types of Fibers

Since the beginning of the use of fibers for shotcrete, there has been quite a lot of discussion regarding which fiber is best suited for underground mining. There are a few rules of thumb when deciding on a fiber for ground support. Let's make one thing clear: only high-quality steel or macrosynthetic fibers should be considered for fiber shotcrete for ground control for underground mining. Microsynthetic fibers are generally not used in underground mining as they do little to toughen the shotcrete mixture.

Steel Fiber Advantages and Disadvantages

Steel fibers are successfully used throughout mines because they mix well in both the dry- and wet-mix methods of shotcreting. The steel fibers do not normally pose a problem in the milling and process systems of mines.

However, all steel fibers are not the same just because they are made of steel. There are several good choices of steel fibers for underground mining, but the most important quality of any steel fiber is the quality of the steel or raw material used to make the fiber. Only high-quality steel fibers should be considered for use in underground mining (refer to Fig. 3 through 5).

Most steel fibers are made of a material that can rust and because most mines in North America are damp, measures need to be taken to ensure that the steel fibers are kept dry. This is done by using bags or tarps placed over the pallets or bags of fiber shotcrete to keep the moisture out. Stainless steel or galvanized steel fibers work really well, but tend to be too expensive to be practical for most mining applications. Steel fibers tend to wear out pumps and gaskets for shotcrete equipment at a much faster rate than plain shotcrete. Wear pads in dry-mix equipment should be replaced with a tougher wear-resistant material to account for the extra wear or the crews will have to change worn-out

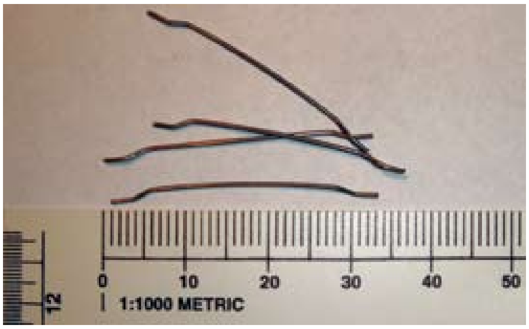

Fig. 3: Hooked end Type I steel fiber

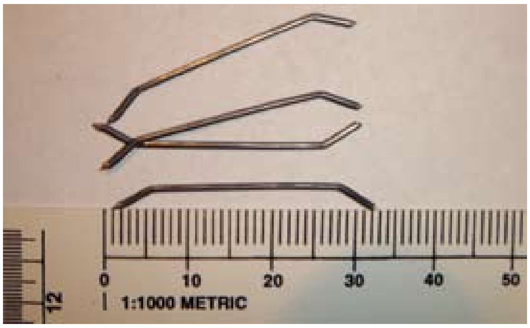

Fig. 4: Bent end Type I steel fiber

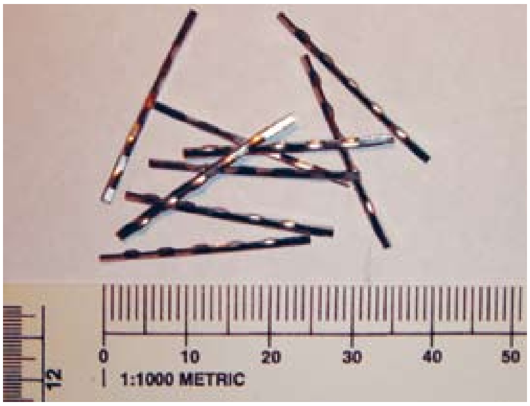

Fig. 5: Deformed Type II steel fiber

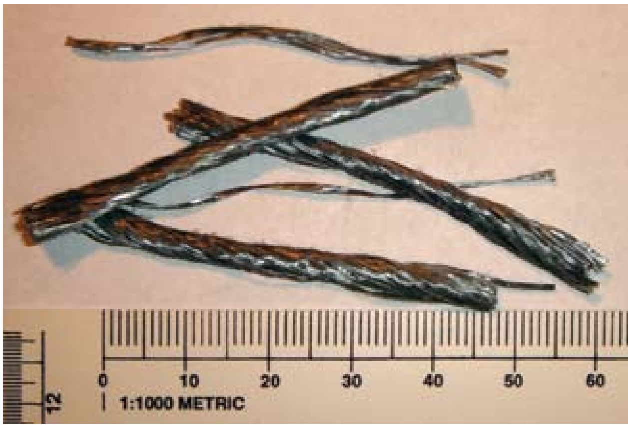

Fig. 6: Twisted and bundled macrosynthetic fibers

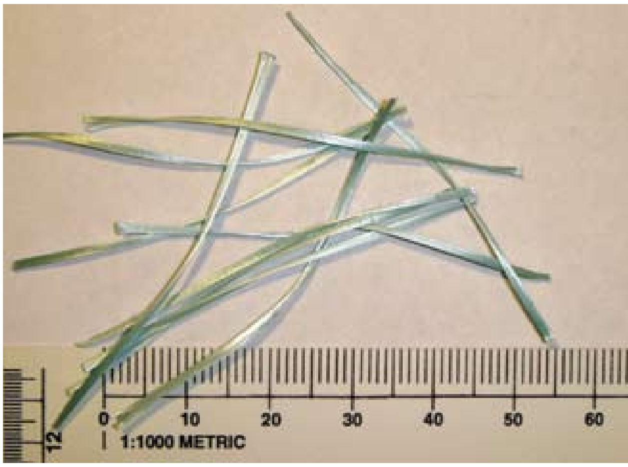

Fig. 7: Twisted loose macrosynthetic fibers

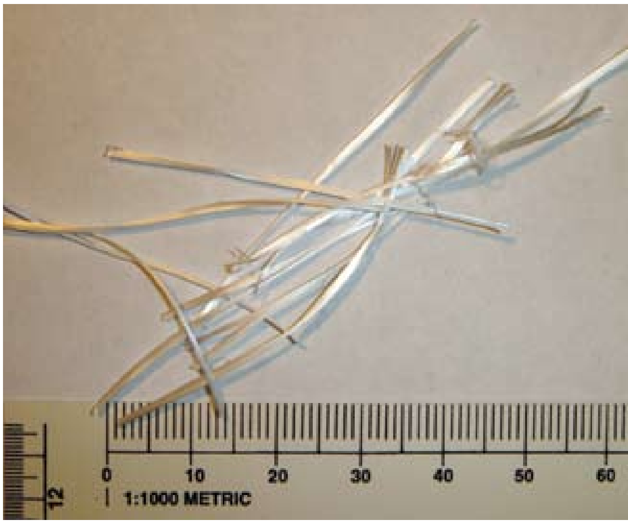

Fig. 8: Loose, slight twisted macrosynthetic fibers

gaskets and pads often. Steel fibers are heavy and usually a dose of 88+ lb (40+ kg) are placed in each batched cubic yard (cubic meter) of shotcrete. The fibers need to be warehoused and kept dry and take up quite a lot of storage space.

Synthetic Fiber Advantages and Disadvantages

Macrosynthetic fibers, sometimes referred to as structural synthetic fibers, have been used in several mines in North America with good success. The macrofibers have been designed to give a tremendous degree of added toughness to shotcrete, even at large deformations. Because synthetic fibers don't rust, they keep working long after they may be exposed to the damp mining conditions. They are lightweight and easy to transport. If the fiber packages get wet as they some times do, the fibers still work fine, so accidental or inadvertent wet conditions that rust steel fibers pose no problem to synthetic fibers (refer to Fig. 6 through 8).

Unless special thought is given to dry-mix shotcrete equipment, synthetic fibers are not a good choice as they bridge upon each other and sometimes do not flow easily through portals in the bottom of dry-mix guns. Also, if synthetic fibers are used in the dry-mix process, a predampener, as mentioned previously, is commonly used to ensure the product is thoroughly predampened to avoid excessive fiber rebound. Another problem with synthetic fibers is that sometimes, depending on the fiber, the fibers tend to float to the top of the mixture during transport underground unless a proper circulating trans-mixer is used. All of these things can be dealt with, but the one important item to keep in mind with synthetic fibers is that sometimes they foul up the dewatering pumps as the rebound fibers flow with water as it is being drained. Predampening of dry-mix shotcrete is always recommended because with some ore processing methods, synthetic fibers can clog up guns or systems where steel fibers go through the system easily.

Suggestions for When and When Not to Use Fiber Shotcrete

If a mine plans on using wet-mix fiber shotcrete, then there needs to be a way to transport the shotcrete mixture underground to where it can be sprayed, such as a bore hole from the surface to somewhere in the mine. The shotcrete then needs to be dumped into a trans-mixer, which is a rotating concrete mixer, with the shotcrete that is transported to where it is to be sprayed. Sometimes this is done from the surface by means of a ramp, but it is not common to send shotcrete down a ramp as it is not generally economically feasible. If a mine has a bore hole or other way to get the shotcrete underground easily, it makes sense that fiber shotcrete (and not mesh) should be the first choice for all ground support measures whenever possible. This is a bold statement, but here are the facts to back it up:

- A proper wet-mix fiber shotcrete ground control system with proper rock bolting is less expensive than mesh and rock bolts because it takes less time to do it; and
- The rate at which fiber shotcrete can be applied is about 29.5 ft (9 m) of drift per shift. The rate that mesh-reinforced shotcrete can be applied is about 10 ft (3 m) of drift per shift. This was shown in three case studies at the Sweden Malmberget Mines.

Failure modes are used to properly evaluate when FRS should not be used and when potential failure of the shotcrete should be evaluated. There are many types of failure, from wedge slipping to plane failure. All of these are due to stresses caused by stopping, drifting, and mining. Shotcrete failures in mining ground support due to rock loading are generally either shear failures or debonding causing flexural failures. Underground mining practices vary a great deal from mine to mine because a successful mixture in one mine may not be applicable to a different set of mining conditions. Therefore, a design-as-you-go method is commonly employed, and trial and error is practiced as follows:

1. Unless an area has already been noted for large deformations where cracks of several inches (millimeters) occur, the first alternative is to use FRS together with rock bolts;
2. If the FRS fails, and it is designed to fail slowly, where the fibers deform suddenly, breaking rather then slowly pulling out, then a layer of mesh can be placed over the FRS and fastened with bolts or mechanical devices of the miner's choice. The mesh size is determined by the practicality of the equipment to install the mesh;
3. If the mesh fails, a layer of plain shotcrete can be sprayed through and over the mesh to completely encapsulate the mesh; and
4. If all three of these fail, and an area still needs to be kept open, then still another layer of heavy-gauge welded-wire mesh can be installed. This plan is only practical where there are large deformations in an area that must be kept open. If failure in the rocks is severe enough, or if there is serious danger threatening the miners, then mining that area should be abandoned.

Unlike tunneling in civil applications such as roadways and rail tunnels, where the tunnel must be completed directly through the path designated, when mining for ore, other factors need to be examined, such as if it is profitable and safe to mine an area and how long an opening is to be used. Not all underground openings in mines are used to extract ore. Some openings are built for support purposes such as underground shops or relief areas. These shops or warehouses can be quite large and careful planning needs to be employed before they are excavated and lined.

Conclusion

As a supplier and former mining contractor, it has been my pleasure to see the use of FRS grow each year in underground mining. Many of the most profitable underground mines in North America and around the world are making fiber shotcrete their first choice for ground control together with rock bolts or other mechanical devices. With the increased demand for mined materials, it makes good sense to use the best strategy for the highest yields and highest overall profits without compromising the safety of underground miners.

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