Evolution of Fiber Reinforced Shotcrete

Figure 1. Rock slope stabilization with SFRS, Snake River, Idaho, 1972.

Prior to the 1970's, shotcrete was typically reinforced with welded wire mesh fabric or conventional reinforcing steel. *Chicken wire* was sometimes used in some applications (e.g., artificial rockscape construction), and chain-link mesh was used in some mining applications where large deformations were expected and the cracked reinforced shotcrete had to continue to carry load.

by D.R. Morgan and R. Heere

The concept of reinforcing shotcrete with discreet, discontinuous steel fibers was developed by the Batelle Research Corporation in the USA in the early 1970's. The first practical application of steel fiber reinforced shotcrete (SFRS) was in 1972 when the US Army Corps of Engineers used dry-mix SFRS for rock slope stabilization and lining of a tunnel adit at the Ririe Dam in Idaho (1). A photo of this slope stabilization work is shown in Figure 1. In Canada, the first use of SFRS was in 1977 when work was conducted to stabilize a sloughing railway embankment in Burnaby, British Columbia. Figure 2 shows this work in progress. The first author of this paper was involved in this Burnaby project and has had the opportunity to examine it after 23 years of service. It is still performing well.

Applications

Since these early years, SFRC has evolved from a novel concept to a mature technology, with many hundreds of thousands of cubic meters of SFRS being used annually around the world on a wide variety of civil engineering and mining applications. Civil engineering applications include:

- Primary (initial) and final linings in road, rail, sewer, and water conveyance tunnels;
- Permanent linings in large caverns such as sports arenas, hydroelectric power houses, desilting chambers, railway stations, and military installations;
- Lining of ventilation shafts in road and rail tunnels and pressure surge shafts in hydro electric projects;
- Construction of water and ice control systems in road and rail tunnels;

Figure 2. Railway embankment stabilization with SFRS, Burnaby, British Columbia, 1977.

- Repair and seismic retrofit of infrastructure, including dams, bridges, and marine structures (2).

References 2 through 10 provide numerous case history examples of such SFRS applications in civil engineering projects. Figure 3 shows the final SFRS tunnel lining in one of the Stave Falls, British Columbia, hydroelectric pressure headrace tunnels (10). Figure 4 shows an architectural treatment on a permanent SFRS tunnel lining in the underground metro (passenger railway station) in Stockholm, Sweden.

In addition to civil engineering applications, SFRS is now finding increasing use in lieu of screen (welded wire mesh fabric or chain link mesh) in many mining projects worldwide. References 2,4,5,6,8,9,10,11,12, and 13 provide numerous examples of the uses of shotcrete in mining applications. In many mines, SFRS, used in conjunction with rock bolts and other ground support systems, where required (e.g., conventional reinforcing, lattice rib girders, cable lacing), has become the prime method of ground support in both permanent ways (drifts, raises, declines, shafts) as well as in ore extraction areas. A number of reports indicate that SFRS not only provides a more economical alternative to conventional ground support methods, but has also resulted in a marked reduction in injuries and fatalities in mines (8).

SFRS has also found increasing use in mines as a substitute for cast-in-place concrete in underground applications such as lining of crusher chambers, pump stations, ore bins, conveyor drives, and building of ventilation seals and drainage barricades (8).

Figure 3. SFRS final tunnel lining, Stave Falls Hydro Electric Project, British Columbia, 1998.

Figure 4. SFRS final tunnel lining of underground metro (passenger railway station) in Stockholm, Sweden.

Synthetic Fiber Reinforced Shotcrete

In the 1980's, synthetic fiber reinforcement started to be used as a shotcrete reinforcement (14,15). The first synthetic fiber reinforcement used was collated, fibrillated, polypropylene fiber. In research studies and early field applications, it was added to the shotcrete at addition rates ranging from about 4 to 6 kg/m^3 (7 to 10 lb/yd^3). Early applications of the technology included:

- Rock slope stabilization;
- Canal lining and creek channelization. (A 5 mile long water interceptor canal around a tailings dam at Lead, South Dakota was lined with SnFRS);
- Capping and sealing an exposed sandstone/mudstone in tunnel portal areas and a dam spillway at the Oldman River Dam in Alberta in 1986;
- Permanent lining of small 3 m (10 ft) diameter drainage tunnels at the Oldman River Dam in Alberta in 1987 (SnFRS).

In the mid-1990's, new generations of synthetic fibers were developed. These fibers were suitable for much higher addition rates to shotcrete than the earlier generation collated fibrillated fibers mainly because of their lower surface area. Some fiber types were able to be shot at fiber addition rates as high as 20 kg/m^3 (34 lb/yd^3), but most practical applications were for fibers at addition rates of between 7 to 13 kg/m^3 (12 to 22 lb/yd^3), with 9 kg/m^3 (15 lb/yd^3) or 1.0% volume of fiber being a fairly common addition rate for some of the better performing fiber types. Most of the new generation synthetic fibers are either monofilament type fibers, or bundled assemblies of fine fibers with a monofilament appearance. Some of the fiber types have a slight fibrillating characteristic on mixing and shooting. Currently,

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Figure 5: Preparation of shipping berth faces at Port of

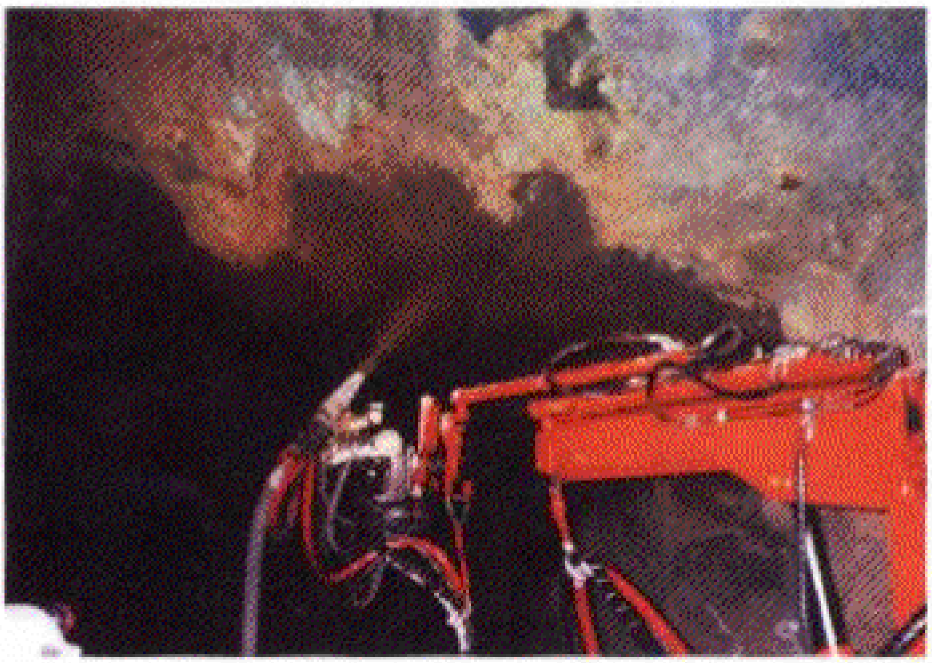

Figure 6: Manipulator arm application of SFRS in Deep Copper Shaft at Mt. Isa Mines, Queensland, Australia.

four fiber manufactures in North America are producing synthetic fibers for use in shotcrete at high addition rates.

Examples of applications of this new high volume synthetic fiber reinforced shotcrete technology in civil engineering applications include:

- Rock slope stabilization;
- Capping and sealing acid leachate generating rock in airfield and new highway construction in Nova Scotia, Canada (15);
- Capping and sealing municipal incinerator waste ash in a disposal cell, in Vancouver, British Columbia, to minimize generation of leachate;
- Repair of deteriorated shipping berth faces at the Port of Saint John, New Brunswick, Canada, and the Port of Montreal, Quebec, Canada (15); see Figure 5.

Extensive research has been conducted in South Africa (11,12) on the use of SnFRS in the deep gold mines. There, the deepest mines are currently operating at depths of around 4000 m (13,000 ft) beneath the surface. At these great depths, the rock temperature is around 60° C (140° F), and openings in the hard rock are vulnerable to pressure bursts. A great deal of effort is being extended into developing pseudo-ductile, insulated linings that will provide a suitable mining environment for miners. Insulating, fiber reinforced shotcretes made with either steel fiber or high volume synthetic fiber reinforcement, used in conjunction with other ground control methods, such as deforming rock bolts (cone bolts) and cable lacing, are being used to control rock-bursts and ventilation air refrigeration costs. Some of the South African gold mines are currently actively planning to mine at depths of up to 5000 m (16,400 ft) beneath the surface, where rock temperatures are about 70° C (160° F). Pseudo-ductile insulating shotcretes are likely to be an integral component of such developments, and the South African research (11,12) is helping to advance the state-of-the-art for fiber reinforced shotcrete in mining applications.

In addition to these high fiber volume SnFRS projects, extensive use is now being made of fine, low volume, 0.1 to 0.3% volume, or 1 to about 3 kg/m^3 (1.5 to 4.5 lb/yd^3) of either collated, fibrillated, or monofilament synthetic fibers. These typically shorter, 12 to 20 mm (½ to ¾ in) long fibers have been found to be very effective in mitigating plastic shrinkage cracking (13). They also provide improved rheological properties to the shotcrete, improving its *green strength* or cohesion. This increases the thickness of build-up achievable in a single pass, and reduces the incidence of *sloughing* (shotcrete fall out) during application and finishing operations.

Some research is now being conducted with *hybrid* fibers, i.e., combinations of steel fibers and typically lower volumes of synthetic fibers. Some of the early research data show a synergy between the two fiber types, i.e., benefits accrue that would not be provided by only one of the fiber types in isolation.

Summary

Great strides in the development and use of fiber reinforced shotcrete have been made since SFRS was first introduced in the 1970's and high volume SnFRS in the 1980's. The technology has evolved from a novel concept, to a mature industry, where many hundreds of thousands of cubic meters of fiber reinforced shotcretes are being used annually in civil engineering and mining applications around the world. In countries such as Norway, it is claimed that over 70% of all shotcrete installed is made with steel fiber reinforcement (6). Certain mines in Australia could likely not be mined were it not for SFRS, as traditional ground support methods (steel sets and lagging or screen and bolt) have not been able to maintain economical and safe working underground openings. In brief, the advantages of using SFRS or SnFRS over other conventionally reinforced construction methods have been demonstrated on numerous projects around the world for almost three decades. Even greater use of this technology is envisaged as more engineers and owners gain experience with this construction medium and the ever evolving new generations of enhanced fiber reinforcements find their way into the marketplace.

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