High Cost of Steel Not the Only Reason for Using Fibers as Shotcrete Reinforcement

by Robert C. Zellers

The rising cost of conventional steel reinforcement has dramatically increased the demand for synthetic, as well as steel, fibers as an alternative to wire mesh in shotcrete applications. More importantly, with the shift to fibers the shotcrete industry is discovering that fibrous reinforcement yields significant economic advantages, as well as definite engineering benefits for long-term shotcrete durability.

Significant economic benefits result from the elimination of placing wire mesh. In addition, the use of fibrous reinforcement in lieu of wire mesh reduces rebound from the receiving face by up to 20%.

Suitable shotcrete applications include slope stabilization, tunnel liners and water diversion channels, structural repairs, swimming pools, artificial rock, waterscapes, and thin overlays. These applications benefit from the three-dimensional network of reinforcement formed by the fibers, which reduces plastic shrinkage cracking and drying shrinkage cracking. The fibers also provide quantifiable toughness and enhanced durability, including increased surface abrasion resistance and impact resistance. Performance is predicated on the proper selection of the fiber type, length, configuration, and addition rate. Elimination of potential voids created by the wire mesh pattern is just one more advantage of using fiber.

General Product Information

There are three fiber types that contribute to the physical properties of shotcrete: steel fibers, micro-synthetic fibers, and macro-synthetic fibers.

Although the price of steel fibers has risen, the fact remains that the in-place cost of steel fiber-reinforced shotcrete is less than the cost of fixing and placing conventional steel. In general, steel fibers must meet the requirements of ASTM A 820 and may be manufactured from either drawn wire or slit sheet steel. Steel fibers, first introduced in the mid 1970s, are generally available in four lengths: 3/4, 1, 1-1/2, and 2 in. (20, 25, 38, and 50 mm). The standard unit of sale is typically 50 lb (22.7 kg) boxes or bags.

Micro-synthetic fibers can be nylon monofilament or polypropylene monofilament and fibrillated fibers. They have been in use since the early 1980s for secondary temperature-shrinkage reinforcement in shotcrete and concrete. The common specified length is 3/4 in. (20 mm) with products available in a range from 1/4 to 2-1/2 in. (6 to 64 mm). For secondary reinforcement, monofilament nylon and polypropylene fibers are typically introduced at the dosage level of one pound per yd^3 (0.6 kg/m^3) of mixture, with the fibrillated polypropylene introduced at the rate of 1.5 lb per yd^3 (0.5 kg/m^3). Synthetic fibers are often sold in shredable paper bags, which disintegrate in the mixer.

Macro-synthetic fibers are a newer entry in the industry. These are chemically identified as polyolefins (polypropylene and/or polyethylene) and are distinguished by their longer length (1-1/2 in. [38 mm] minimum), greater fibril cross-section, and higher dosage rates than micro-fibers—5 to 15 lb per yd^3 (3 to 9 kg/m^3) of mixture.

Wet-Mix Shotcrete versus Dry-Mix Shotcrete

Before exploring technical benefits further, it must be noted that fibers work better in wet-mix shotcrete versus the dry-mix for two reasons:

1. Wet-mix shotcrete allows a more uniform distribution of the fibers in the mixture; and
2. It prevents fly-away at the point of discharge from the nozzle (the reduction in rebound noted earlier is for fiber reinforced wet-mix shotcrete).

Wet-mix shotcrete technology ensures that the fibers are fully integrated with standard mixture ingredients and coated with mortar. It should be noted that successful dry-mix applications with steel fibers have been extensively documented.

General Properties of Fiber-Reinforced Shotcrete

One of the primary quantifiable contributions of fiber reinforcement to the long-term durability of shotcrete is the reduction in plastic and drying shrinkage cracking. Furthermore, fibers increase impact- and surface-abrasion resistance and fatigue strength, as well as reduce permeability.

At dosage levels of 60 lb per yd^3 (35 kg/m^3) and above, steel fibers add to the flexural strength of shotcrete. At elevated dosage levels, steel and macro-synthetic fibers contribute to the post-first-crack properties of shotcrete and concrete (refer to articles in the May 1999 and May 2000 issues of *Shotcrete*.)

Terms used to identify these post-first-crack properties include toughness and average residual strength. The data needed to determine these properties are generated by test methods specifically intended to provide load versus deflection data for three-dimensional reinforcement systems. These test methods are ASTM C 1018, C 1399, and C 1550. In general, they measure the ability of the fibers to support an externally applied load to a beam or panel specimen over a fixed deflection range.

Typically a shotcrete mixture starts with the selection of the aggregate gradation (refer to Table 2.1 in ACI 506, which provides three selections for aggregate gradations. Gradation No. 3, which allows 5 to 20% aggregate to be retained on the 1/2 in. (13 mm) sieve is, however, seldom used with fiber-reinforced shotcrete.) The application and other design factors dictate which gradation is suitable. Next in the process is the selection of the type of fiber, length, and dosage level needed to provide the engineering properties required. The length of the fiber should be matched to the shotcrete equipment used, the aggregate top size, and the quantifiable engineering properties specified. The design process is critical to ensure that shotcrete flow rates and discharge velocity at the nozzle are not compromised.

The longer steel or macro-synthetic fibers yield better post-first-crack results. Shorter steel fibers produce higher flexural strength, while the shorter micro-synthetic fibers reduce plastic and drying shrinkage cracking. Micro-synthetic fibers are typically used at 3/4 in. (20 mm) but are available in lengths from 1/2 to 1-1/2 in. (13 to 38 mm). Macro-synthetic fibers are typically specified at 1-1/2 in. (38 mm) but are also available in 2 in. (50 mm) lengths. Steel fibers are offered in lengths from 3/4 to 2-3/8 in. (20 to 60 mm). Shotcrete specifications tend to limit the usable range of steel fibers to 3/4 to 1-3/4 in. (20 to 45 mm), the most used lengths being 1 to 1-1/2 in. (25 to 38 mm). In general, Gradations 1 and 2 in ACI 506, Table 2.1 are specified with fibers. Shorter fibers work best with standard shotcrete placing equipment. However, longer fibers may be required to produce optimal toughness.

Critical to the design of a fiber-reinforced shotcrete is the quantity of mortar required to coat the surface area of the fibers. The specific gravity of micro- and macro-synthetic fibers range from 0.91 to 1.14, whereas steel fiber's specific gravity is 7.86. This means that there is a major difference in the weight-to-volume ratio, which will affect the surface area to be coated by the mortar, thus affecting the design mixture proportions. Some fiber providers have engineers on staff to assist customers in designing mixes. It is also important to follow

directions provided when introducing the fibers into the mixing system in order to achieve uniform distribution. Where safety is an issue, a flash coat of non-fiber-reinforced shotcrete can be applied over steel fiber-reinforced shotcrete to cover the exposed ends of the steel fiber.

A preconstruction test panel should be shot to verify the shotcrete mixture design produces a mixture that:

- Flows through the shotcrete equipment properly;
- Consolidates properly on the receiving face;
- Minimizes rebound; and
- Produces the engineering properties specified.

It is very import that the test panels be shot with the same mixture and equipment and by the same personnel employed on the project.

Micro-synthetic fibers are typically used within the range of 1 to 3 lb per yd^3 (0.6 to 1.8 kg/m^3) to modify the macro-micro cracking mechanism and enhance durability properties. The role of conventional wire mesh secondary reinforcement is to limit crack growth resulting from plastic and drying shrinkage. Note the requirement is to limit crack growth, not the number of cracks formed. Wire mesh, therefore, is reactive. Fibers, on the other hand, are proactive crack-fighters that increase the usable life of shotcrete and concrete.

Macro-synthetic fibers provide both shrinkage benefits and post-first crack advantages. Added at the rate of 5 to 15 lb per yd^3 (3 to 5 kg/m^3) of shotcrete or concrete, these "new generation" fibers provide an excellent balance of economics and engineering benefits. Furthermore, the added option of using fibers at elevated dosage levels may limit the damaging effects of a seismic event or concussive energy. Here the fibers hold the elements of fractured concrete together, reducing the potential for catastrophic failure as well as the danger of undirected shards flying away from the face of the shotcrete panel.

Steel fibers have been used in shotcrete since the early 1970s and to date, have an outstanding track record in shotcrete and have been the most used of all the fibers. The use of steel fibers in shotcrete tunnel liners at the dosage level of 100 lb per yd^3 (59 kg/m^3) seems to be common, although the usable range is 40 to 130 lb per yd^3 (24 to 77 kg/m^3). The performance requirements in the specification will dictate the quantity of fibers needed in the mixture design (for example, ASTM C 1018, C 1399, or C 1550) requirements. However, correct mixture design proportions are critical for a matrix to efficiently exit the equipment and consolidate on the receiving face.

Outlook

With an increasing inventory of commercially available fibers, there is great potential for discovering new and better applications for fiber-reinforced shotcrete. Engineers can be more confident in specifying fiber reinforced shotcrete, given the gains in product development, the increasing consensus in test methods for evaluating performance, the technical support from fiber providers, and materials testing companies and their ongoing research. Furthermore, the newly announced research agreement between the Fiber-Reinforced Concrete Association and Middle Tennessee State University's Concrete Industry Management Program is the perfect platform for communicating new advances in fiber-shotcrete technology. It will expand the engineering community's knowledge base for the benefit and growth of fiber reinforcement in the shotcrete industry.

References

Researchers have been busy testing fiber-reinforced shotcrete in both the laboratory and the field. ACI's document 506.1R is specific to the use of fibers in shotcrete. (It is currently in revision with the new version due in 2005.) The bibliography supporting ACI 506.1R is an excellent source of relevant information, as is the list of references found in ACI 554.1R, and the American Shotcrete Association (ASA) *Shotcrete* special addition on fiber-reinforced shotcrete, May 2000, and documentation of successful projects, both public and private, by fiber providers and the Fiber-Reinforced Concrete Association.

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