Fiber-Reinforced Shotcrete—Applications and Testing Overview

By Antoine Gagnon and William "Bill" Geers

The addition of fibers to concrete and mortars as reinforcement is not a new concept. The ancient Egyptians used straw to reinforce mud bricks for use in structures like the core walls of the pyramids. During the first century AD, the Romans incorporated horsehair fibers in the construction of structures like the Coliseum to help prevent drying shrinkage cracking of the concrete.

In the modern era, the first scientific studies on the use of steel fibers to reinforce concrete date back to the 1960s and 1970s.[1,2] The use of steel fiber-reinforced shotcrete (FRS) was first introduced in the 1970s.[3] The first documented use of FRS was in 1973 by the U.S. Army Corps of Engineers in a tunnel adit project at the Ryrie Reservoir in Idaho. Soon thereafter it became well recognized that soil and rock excavations could effectively be stabilized with steel FRS and its use and acceptance increased globally. In the mid-1990s, the use of macrosynthetic fibers in shotcrete was developed and has increased with particular success in temporary support in underground mines where large deformation capacity is desired. Since the 1970s, thousands of projects have been successfully completed using fibers as reinforcement, including shotcrete, slabs-on-ground, composite steel decks, slabs-on-pile, and precast elements.

Ground support is the most widely used application of fibers in shotcrete today. However, there are other applications where the use of FRS is on the horizon. In 2018, the American Concrete Institute's (ACI) Committee 544, Fiber Reinforced Concrete, published a new guide titled "ACI 544.4R-18: Guide to Design with Fiber-Reinforced Concrete."[4] The document abstract states:

> "New developments in materials technology and the addition of field experience to the engineering knowledge base have expanded the applications of fiber-reinforced concrete (FRC). Fibers are made with different materials and can provide different levels of tensile/flexural capacity for a concrete section, depending on the type, dosage, and geometry. This guide provides practicing engineers with simple, yet appropriate, design guidelines for FRC in structural and nonstructural applications. Standard tests are used for characterizing the performance of FRC and the results are used for design purposes, including flexure, shear, and crack-width control. Specific applications of fiber reinforcement have been discussed in this document, including slabs-on-ground, composite slabs-on-metal decks, pile-supported ground slabs, precast units, **shotcrete**, and hybrid reinforcement (reinforcing bar plus fibers)."

In the section on FRS, the guide discusses other applications where the use of FRS would be a possible benefit: "Fiber-reinforced shotcrete is especially suitable for pools and skate parks with many curves, as it is shot against excavated soil, eliminating the cost of forms and steel installation." This guide also mentions that FRS is a good technique when repair and restoration are being contemplated, especially if there are access issues.

CHALLENGES OF CHOOSING THE RIGHT FIBER

Various fiber material types can be used in shotcrete such as steel, glass, synthetic, and natural fibers—each of which lend varying properties to the concrete (Fig. 1). In addition, it must be clear that the character or properties of the FRS changes with both the mixture design and the fiber's properties, geometries, distribution, orientation, and dosage. Fibers are further classified as either macro- or microfibers. Fibers with an equivalent diameter greater than 0.01 in. (0.3 mm) are macrofibers and equivalent diameter less than or equal to 0.01 in. are considered microfibers. Fibers can be used in both dry-mix and wet-mix shotcrete applications. The two most common fiber types used in FRS structural applications today are polypropylene macrofibers and steel fibers.

FIBER PERFORMANCE IN CONCRETE

The choice of the fiber most appropriate for use in a specific application can be confusing and not always well understood. There are no good or bad fibers—just the right fiber for the right application.

Reinforced concrete/shotcrete (fiber or conventionally reinforced) is a composite material where the concrete is strong in compression but weak in tension. Under loading conditions, hardened concrete can crack once its tensile strength is exceeded. Fibers used as structural

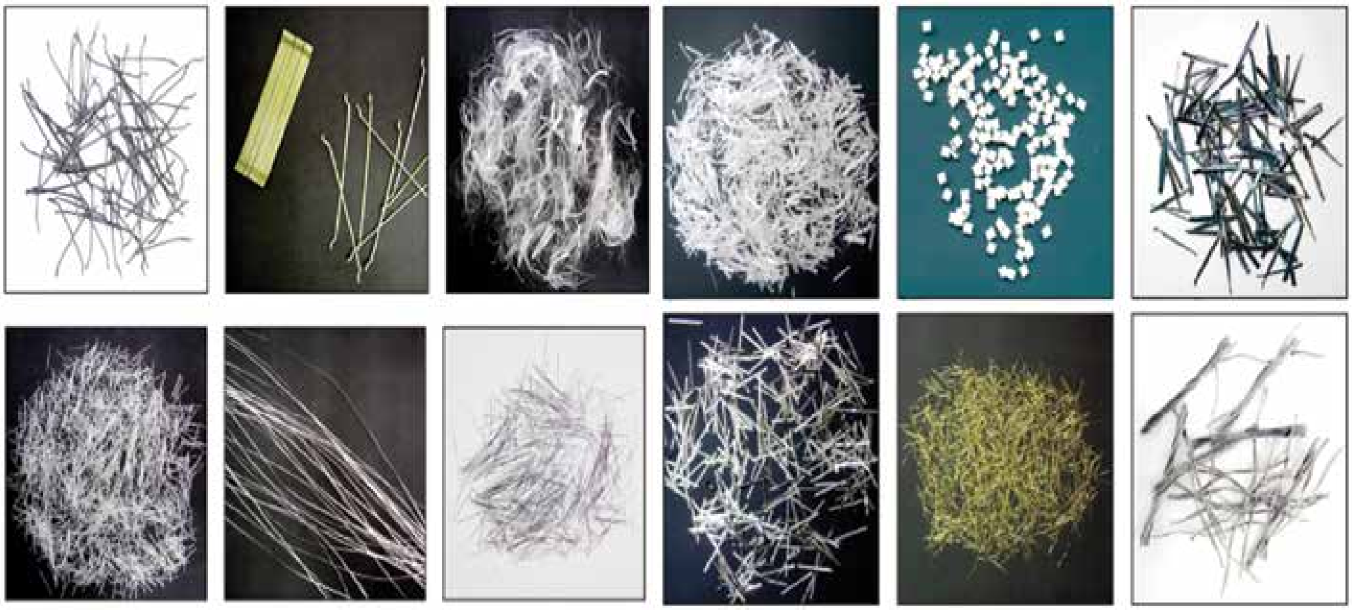

Fig. 1: Different types of fibers available

reinforcement are designed to provide tensile strength or energy absorption in the concrete matrix after the concrete cracks. As noted previously, the performance characteristics of the FRS is dependent on the mechanical properties of the fiber and the interaction between the materials within the concrete matrix. Understanding the fundamental differences in mechanical properties of a steel and a synthetic fiber, for example, may help in determining the right fiber to use in a specific application. Table 1 presents average Young's modulus and tensile strengths of hardened concrete and the two types of fibers, as well as the melting and creep temperatures of the fibers.

Understanding how the material properties impact the way that the fibers work within the concrete will help evaluate which fiber is best in a specific application. One of the key aspects to evaluate the performance of a FRS composite is the ratio between the Young's modulus of the fiber and the Young's modulus of the concrete. Note that the hardened concrete's Young's modulus is two to three times greater than the one of a synthetic fiber. What does this mean? While the FRS is in a plastic (fresh) state, synthetic fibers can provide better plastic shrinkage crack control. However, as the concrete hardens, and its Young's modulus exceeds the synthetic material's modulus—it takes more deformation for the synthetic fiber to provide its maximum tensile strength. This means that more deformation is usually necessary for synthetic fibers to provide an equivalent energy absorption. However, the anchor mechanism of any fiber and its ability to generate friction through deformation will affect the behavior of the composite.

On the other hand, a higher Young's modulus can create a different behavior in FRS. Steel fibers, for example, have a Young's modulus that is seven or more times greater than the concrete's. Steel fibers, unlike synthetics, are not used to provide plastic shrinkage crack control. However, as soon as the concrete hardens, and cracks begin to form in the matrix, the steel fibers more rapidly begin to absorb and then redistribute the tensile forces within the matrix. Steel fibers can hold cracks as they begin to form and keep them from opening further. This can also lead to multi-cracking and load redistribution in the structure. Controlling the width of cracks in a structural application is a fundamental difference between a steel and synthetic fiber. In a temporary ground support application where large deformations and crack widths can be required for a deformation driven system to work—in a mine, for example, synthetic fibers are very appropriate. However, in applications where crack width control is desired, steel fibers will be the preferred choice.

Another consideration when choosing the appropriate fiber, aside from crack widths or energy absorption, is the structure's exposure conditions. Essentially, in humid conditions with open cracks, synthetic fibers do not corrode

Table 1: Comparison of Material Properties: Concrete vs Steel Fibers vs Synthetic Fibers

Properties	Hardened concrete	Steel fibers	Synthetic fibers
Young's modulus (up to)	4350 ksi (30 GPa)	30,450 ksi (210 GPa)	1740 ksi (12 GPa)
Tensile strength (up to)	580 psi (4 MPa)	330 ksi (2.3 GPa)	95 ksi (0.65 GPa)
Material melting point	N/A	2732°F (1500°C)	329°F (165°C)
Material creep temperature	N/A	698°F (370°C)	>68°F (>20°C)

as carbon steel fibers can. When crack widths are small, however, corrosion usually doesn't affect long-term performance. On the other hand, because of the lower melting temperature and creep temperature of synthetic fibers, it may be less appropriate to use synthetic macrofibers as a structural reinforcement in a structure subject to elevated temperatures or fire. However, synthetic microfibers can help resist explosive spalling in high temperatures.

SPECIFICATION CHALLENGES

When it comes to specifying FRS, there are essential aspects to take into consideration. First, it is crucial for the engineer to define the intended purpose of the material in a structure, as it will influence the definition of its expected performance. It might appear trivial for some, but it is often overlooked or confused. For example, is it going to be used as initial lining for ground support or as final lining? Or is it going to be used as fire protection? FRS should be seen as a spectrum of mixture designs that can meet various needs. There is definitely no "one size fits all'' mixture in this spectrum.

In general, the design and specification of FRS is performance-based. This is usually more appropriate, as the interaction between the different ingredients and their synergetic effect can make a prescriptive specification ineffective and even unsafe. It is critical to understand the performance that is expected from FRS and, especially, how it will be assessed. This must align with the intended purpose of the material. Therefore, specifying the proper performance parameters and testing the right properties is of the utmost importance. For example, specifying the energy absorption (toughness) at 1.6 in. (40 mm) deflection in the ASTM C1550 test method on a round determinate panel (RDP) can be convenient for evaluating a mixture's performance at large deformation. However, it should not be used as a specification parameter for a mixture to be used as final lining in a civil structure where only very thin cracks are to be tolerated. In this case, the performance parameter—energy absorption at large crack openings (Fig. 2)—is not consistent with the intended purpose of the material. Specifying flexural strength at smaller crack width would be more appropriate in this situation.

Fig. 2: *Typical ASTM C1550 specimen (RDP) after testing*

These ideas highlight the fact that different people involved in a project can have different perspectives on a mixture's performance and on its specifications. Because of their background and their approach to a project, some engineers will focus more on the peak strength of the material while some others may be more concerned about the post-cracking behavior of the material. In the end, there must be a connection drawn between the purpose of the material, the performance that is specified, and the test method used to assess it. Another essential aspect that is sometimes overlooked is the definition of failure, which is closely related to the purpose of FRS and its specified performance. Failure can have many definitions when it comes to FRS; it can be when the concrete first cracks, it can be when a maximum crack width is reached, it can be when the structure can no longer support a defined load, or it can be related to deformation or creep. This is an aspect that can cause misunderstandings in different phases of a project and must therefore be addressed as early as possible in a project.

Through the work of their technical committees, ASA and ACI have published numerous guides and reports that can help better understand the specificities of shotcrete, fiber-reinforced concrete, and FRS, thus clarifying how to specify FRS. ACI Committee 506, Shotcreting, offers guidance on the use and specification of shotcrete in 506R, "Guide to Shotcrete," and 506.2R, "Specifications for Shotcrete."[5,6] It also provides documents on the use of FRS and its use for underground applications.[3,7] Additionally, ACI Committee 544 is a good source of information through its multiple documents.[4,8-13] The ASA Underground Committee has also recently published position statements on Spraying Shotcrete Overhead in Underground Applications and Spraying Shotcrete on Synthetic Sheet Waterproofing Membranes.[14,15]

CHALLENGES IN THE LAB/FIELD

To get reliable information on the performance of FRS, one must understand the importance of sampling operations. The idea is to prepare a sample of the material that is as close to its real placement conditions as possible. This is true for concrete in general, but is particularly important for the unique material that is FRS. This applies to both laboratory conditions and field conditions. In the case of FRS, there are two main aspects that are of interest.

First, the changes in the mixture proportions of the concrete during the shotcrete placement process can affect the performance of a sample compared to the performance of the material in a real-size structure. Depending on the consistency of the mixture, the aggregate gradation, and other factors, the variance of rebound can change the aggregate/paste proportion and the fiber content.

Secondly, the orientation of fibers in the material is dependent on the spraying technique and specifically the size and geometry of the sampling mold. This is an important aspect, as fibers tend to orient in a plane that is perpendicular to the nozzle axis through the shotcrete placement process. Also, boundary effects with the limited panel size can affect the orientation of fibers in a sample compared to a larger structure. For that reason, larger sampling panels are usually preferred (Fig. 3).

Thus, it is essential to anticipate these behaviors by using adequate sampling panels, proper spraying technique, and by selecting the right parts of the sample to be used. The best example for this is the preparation of beam specimens for flexural testing. Even though it may be more convenient, a mold of the final size of the beam cannot be filled directly with FRS, as it would greatly affect its final composition and the orientation of fibers, thus changing its performance. ASTM C1140/C1140M, "Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels," is an essential reference for this.[16]

Because the need for larger samples leads to heavy specimens to carry, there has been growing interest to reduce the size of specimens without losing the quality of results. For that reason, researchers and users have been working on new standard test methods over the past few years. For example, smaller versions of the RDP and cylindrical core specimens have been developed and are currently evaluated.[17,18]

Fig. 3: Large molds to be sprayed with FRS for testing in a research project at Université Laval's Shotcrete Lab

There are still challenges in the interpretation of results from all the test methods available with regards to the actual real-life performances. There should be more attention paid to the behavior of a mixture rather than absolute numbers. Also, there should be more effort put into understanding how test methods provide information rather than trying to correlate between them. However, increasing the quality of the sampling operations and the preparation of specimens can definitely help increase the quality of the results and allow one to make an informed choice based on them.

CONCLUSIONS

In conclusion, the addition of fibers in shotcrete creates a unique concrete material and valuable tool for many different applications. The availability of FRS increases the potential solutions in various projects. This composite is particularly useful in underground environments where it performs well as ground support. To get the most out of FRS, there are a variety of fibers—mainly synthetic and steel—that can suit various needs. What is essential is to connect the purpose of using FRS, with its specified performance and the associated test method to verify results and its interpretation. There are still challenges to overcome in terms of specification and testing. This highlights the need for a common language between different owners, engineers, contractors, and testing labs in the industry. With the available technical documents provided by ASA and ACI, there should be more consensus on the benefits of using FRS.

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