Proceedings

Shotcrete for Underground Support XI

Engineering Conferences International *Year* 2009

CASE HISTORIES USING SYNTHETIC FIBER REINFORCED CONCRETE

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ABSTRACT

Synthetic fiber reinforced concrete has been used in shotcrete for many years. This paper discusses select project case histories from around the world. The discussion focuses on why fibers are used and explains how there are many benefits, advantages, and features regarding the choice of fibers. Also discussed is why and how the fibers affect the overall project performance, schedule, costs, and constructability. Further discussion shows that the fiber choice is in the details. The best fiber choice must meet certain project criteria established by all the decision makers involved in the project. Lastly, the versatility in the use of a specific blend of synthetic fibers in shotcrete shows the potential for even more diverse applications of synthetic fiber reinforcement.

INTRODUCTION

In 1978, FORTA Corporation, based in western Pennsylvania, USA, introduced the concept of three-dimensional synthetic fiber reinforcement to the construction market worldwide. FORTA obtained the rights from a company in Switzerland, in the country that this paper was presented in 2009 for Shotcrete for Underground Support XI. One of the successful early product applications was the use of synthetic fibers in a wide variety of shotcrete projects. These synthetic fibers have enjoyed widespread use since that time in both dry-mix and wet-mix shotcrete applications, including bridge deck toppings, lake and reservoir linings, and artificial rock and waterscape projects. In these instances, these standard-grade synthetic fibers were used in relatively low dosages (approximately 0.1% by volume) to primarily reduce plastic shrinkage cracking, reduce temperature and shrinkage-related cracking, reduce rebound, increase toughness, and increase long-term durability. There is no standard definition describing these initial synthetic fibers, but an easily understood and typically used term is to describe these fibers as micro fibers due to their small cross section.

Since 1993, another generation synthetic fibers have been developed with improved performance benefits that affect the structural properties of the concrete itself. These synthetic fibers have begun to play an important role in the shotcrete market by enhancing toughness and durability while offering a safer and easier alternative to conventional reinforcing steel. Again, there is no standard definition describing these synthetic fibers, but an easily understood and typically used term is to describe these fibers as macro fibers due to their larger cross section compared to the 1978 first generation, synthetic fibers. Again, the measured difference in cross section by some boundary or threshold has not been standardized.

Problems with Conventional Steel for Concrete Reinforcement

For lack of better alternatives, steel in the forms of bars and meshes, has been used as reinforcement in shotcrete products and applications for many years. Steel is primarily necessary to carry the loads after the concrete cracks and to hold together broken pieces of concrete. Steel forms of bars and meshes have a primarily two-dimensional functional use for reinforcement. However, some shotcrete applications are in structures requiring a three dimensional approach to reinforcement. Further, the use of steel in various forms, including steel fibers, has other problems related to either in-place performance or handling and placement including corrosion.

Corrosion of reinforcing steel is a concern, and it naturally affects the long-term durability and performance of any steel-reinforced concrete application. This corrosion concern is even more important in shotcrete applications that are constructed in a marine or water environment, or in an underground environment that is wet.

Steel rebar and mesh reinforcement must be cut, bent, spliced, and attached to the project substrate, which can be very difficult and labor intensive. The handling of steel also adds a common risk for injury and can be dangerous from strains and impalements. Also of concern is assuring the minimum necessary concrete cover of the steel mesh and rebar to protect it from the elements and project conditions. Costs, lead time for delivery, and availability issues with steel in all forms – bar, mesh (fabric), and fibers – also add to the concern regarding its use in many shotcrete project applications. Sometimes, configuration to the substrate by the steel does not happen because the steel is too stiff, and excess shotcrete material is used to cover the steel. Lastly, applying shotcrete through the steel “obstruction” makes the shotcrete system performance very dependant on the operator skill to reduce shadowing. These placement and performance deficiencies of steel reinforcement served as further incentive to develop a level of synthetic fiber reinforcement that could serve as a viable alternative.

DEVELOPMENT OF MACRO SYNTHETIC FIBER

During development of macro synthetic fibers, various approaches were used to establish features, advantages, and benefits as a basis for changing and improving important fiber characteristics. By maximizing each of these characteristic areas, macro synthetic fibers are a viable alternative and a complement to steel reinforcement from rebar, mesh, and fibers. A viable alternative is to use synthetic fibers as reinforcement to completely replace the steel reinforcement, and a complement is to use synthetic fiber reinforcement in conjunction with steel reinforcement.

Configuration

Fiber configuration is most critical with regards to anchorage and pullout of any fiber reinforcement. Fiber configuration issues are individual fiber cross-section, length, stiffness, and presentation. Fiber cross section and length are immediately self evident descriptions but relate to fiber count, anchoring efficiency (longer is more efficient), and development of the fiber strength from anchoring efficiency. Stiffness and presentation are more difficult to understand. Stiffness of the fibers themselves means deform-able or not. This stiffness is the ability of the fibers to conform around the aggregate (less stiff fiber) or the aggregate to conform around the fiber (stiff fiber). Presentation can be either mono or able to fibrillate. Mono is single or one, and able to fibrillate means the fibers are able to separate during mixing from a mesh or from a net of fibers. Fiber configuration also involves smooth or with deformations similar to rebar (with deformations) or smooth dowel bar steel.

Micro synthetic monofilament (single) fibers would not be expected to act as a replacement for structural steel, but they would offer a reduction in plastic shrinkage cracking and provide additional edge protection in shotcrete applications. Fibrillated (multiple fibers, hair net, or random opening mesh shaped) fibers offer a much greater resistance to pullout, and as a result, have proven their ability to replace non-structural steel such as wire mesh in a variety of shotcrete projects. To maximize resistance to pullout and obtain post-crack concrete reinforcement behavior, another fiber presentation used a blend of two fiber shapes: a fibrillated network configuration, along with an embossed (deformed) configuration monofilament. This unique blend of fiber shapes gives the synthetic fiber system the ability to control temperature-related cracking as well as affect the structural properties of the concrete.

Another aspect of configuration is presentation to the mixture for mixing. The first patented macro synthetic fibers emulated previous steel fibers in cross section and length and were collated with a circumferential wrap of dispersible tape, paper type material. Other patented presentations include twisted bundles, larger diameter fibers, glues, and dispersible paper bags. Larger amounts of loose fibers are difficult and time consuming to add to a mixer, and they are prone to fiber balling and clogging if proper care is not taken to meter the fibers into the concrete in small quantities.

Chemistry

The chemical make-up of any fiber is extremely important if the fiber is expected to hold up in the aggressive alkali environment of portland cement concrete. Most steel fibers will stain the concrete surface from products of corrosion. The depth of carbonation can also influence this amount of rusting. However, fibers in general are discontinuous and will not wick rust any deeper into the concrete. Most synthetic fibers are made from polymers or plastics and as such are inert and have no reaction to acids or alkalis. However, if the synthetic materials are made from recycled materials, the uniformity of the material behavior is questionable. Most synthetic fibers use virgin materials to guarantee performance as uniformly consistent. The polymers are typically single families or blends within family types called copolymers. Usually some blending will significantly change fiber material behavior emphasizing some aspects over other aspects. An example might be to change fiber elongation and strength by some combination.

Contents

During this next generation synthetic fiber research, it became apparent that micro synthetic fibers, monofilaments, and fibrillated fibers have a very high level of surface area on a per mass basis. As a result of this surface area, it becomes difficult to add sufficient quantities of these fiber types to approach structural reinforcement values without consuming too much of the paste content of the concrete mix. Standard dosage levels for these fibers are generally less than 0.2% (1.8 kilograms per cubic meter (kcm) or 3.0 pounds per cubic yard (pcy)). The unique blend of fiber shapes that make up the fiber blend described in these case histories minimizes the surface area issues, and allows dosage rates to be increased without significantly affecting the mixture workability. Dosage rates for this fiber blend in various shotcrete applications have ranged from 0.2 to 2.0% depending on reinforcement requirements.

Correct Length

With any fiber, the Critical Bond Length, which is the maximum length of fiber on either side of a potential crack, is an important consideration for long-term performance and post crack load carrying capability. Obviously development length in reinforced concrete is an issue, and with a change in scale for fiber reinforced concrete, longer fibers are better able to anchor within the concrete than shorter fibers that lose anchorage and pull out. Tests show that a fiber blend with a 54 mm length (nominal 2.25 inch) maximizes the fibers' Critical Bond Length, which allows the residual strength or post-crack performance to also reach higher levels.

TESTING

Since their 1978 introduction, synthetic fibers have been rigorously tested and evaluated in a wide variety of both laboratory and field situations. Macro synthetic fiber has consistently shown advantages and dramatic differences in the areas of ductility, impact resistance, shrinkage, and residual strength, as well as in areas of rebound reduction compared to other steel reinforcement types.

Compressive

The macro synthetic fiber blend was tested in compression cylinders (ASTM C39) at various dosage levels. At dosage levels of 0.25 to 0.50% by volume, there was a measurable increase in compressive strength. More importantly, the mode of failure was reported as an extremely ductile one at all fiber dosages, instead of a conventional brittle and sudden failure. This advantage of enhanced ductility and unique failure mode is naturally a very valuable feature to shotcrete project designers and builders.

28 day Compressive Strength		
% Fiber Volume	Ksi	Mpa
0.50	6.39	44.0
0.47	6.21	42.8
0.43	5.96	41.1
0.40	5.78	39.9
0.37	5.60	38.6
0.33	5.36	37.0
0.30	5.18	35.7
0.27	5.00	34.5

Impact

Macro synthetic fibers have also shown dramatic improvements to impact resistance as tested by the ACI Committee 544 Drop Hammer test. Most impressive is the fiber's ability to allow for specimen integrity, even after first crack. Resistance to shock and impact may play a valuable role in a variety of shotcrete applications.

Impact Resistance Test		
	Number of Blows	
% Fiber Volume	First Crack	Failure
2.0	220	460
1.5	100	400
1.0	90	350
0.5	80	190

Shrinkage

The unique fiber blend of monofilaments and fibrillated networks allows the macro synthetic fiber to offer structural performance as well as reductions to plastic shrinkage cracking. Conventional steel reinforcements, such as mesh, rebar, or steel fibers, are typically effective only after the concrete has cracked. Steel has less ability to reduce shrinkage-related cracking and may actually increase it due to restrained shrinkage and the stiffness of the steel material. This discussion is about before the concrete cracks and the probability of cracking, not after cracking which steel has an ability to control. Testing with 0.5% by volume of the synthetic fiber blend showed a remarkable 92% reduction in crack area caused by shrinkage cracking, and 100% at 2.0% by volume.

Crack Area Reduction	
% Fiber Volume	% Reduction
2.0	100
1.0	95
0.5	92

Average Residual Strength

Residual strength is a load deflection value obtained after the concrete has cracked. The test measures the amount of load carried by the cracked fiber reinforced concrete. Fibers are intended to hold cracks or broken pieces of concrete together as a necessary feature in a wide variety of shotcrete applications such as slope stabilization or tunnels. While micro synthetic fibers may offer residual strengths of low values, the macro fiber blend offers strengths 5 times higher with dosages normally considered for these applications. As in the details, this modified beam test (ASTM C 1399) serves as a benchmark test method to compare the post-crack behavior of various fiber types and brands. Users can confidently specify performance by a minimum residual strength value. Fibers can be considered as a steel reinforcement alternate by equating bending moments.

Average Residual Strength		
% Fiber Volume	Ksi	Mpa
2.0	0.65	4.5
1.5	0.48	3.3
1.0	0.48	3.3
0.5	0.27	1.9

Shotcrete Round Panel Test

The ability of the macro fiber blend to affect post-crack behavior is quite evident from load testing of the shotcrete round panel test procedure, similar to the residual strength testing. As dosages or volumes increase, the ability to sustain increased loading even after initial crack also increases, offering an enhanced performance value to a wide variety of shotcrete project applications.

Shotcrete Rebound

Due to the impact velocity of the shotcrete materials, rebound of the mixture ingredients from the construction surface is a normal occurrence, and might add to the waste quotient of this concrete construction method. In rebound testing, the fiber blend acts 3-dimensionally as a mechanical binder and cohesive agent, offering noticeable and significant reductions in shotcrete rebound quantities.

% Volumes	
Fiber	Rebound
2.0	3.8
1.5	3.1
1.0	2.3

SYNTHETIC VERSUS STEEL FIBERS

One of the driving forces behind the development of a structural synthetic fiber was to create a viable alternative to steel fibers frequently used in shotcrete applications. In addition to concerns regarding corrosion and rising costs, steel fibers can occasionally be challenging to add, mix, and shoot at the volumes 0.3% to 0.9% used in these types of applications. Concrete producers often encounter difficulties in adding steel fibers in a manner that will facilitate uniform distribution and minimize clumping and balling. Trucks and load restrictions on pavements can be an issue after adding additional mass to a mixture from the prescribed steel fiber dosage. In addition, steel fibers typically have little affect on the reduction of plastic shrinkage cracking, an area where synthetic fibers clearly out perform steel fibers.

Tests have been performed comparing the macro synthetic fiber blend to various types and brands of steel fibers to explore the differences with regards to dosages and also to compare performance levels in various tests. These tests have used the same shotcrete mix proportions and varied the fiber types and dosages, and all fiber-reinforced concrete specimens were mixed, placed, consolidated, finished, and cured under identical conditions. Tests were run for each fiber at dosages of 0.3% and 0.4% by volume of concrete, in areas of compression (ASTM C-39), flexural (ASTM C-1018), impact resistance (per ACI 544), and residual strength (ASTM C-1399).

Detailed test comparison results show the synthetic fiber blend versus each of the three steel fiber types. In general, the fiber blend compared extremely well in all test areas, and did so at a dosage rate of approximately $1/10^{th}$ (approximate ratio of the unit mass for synthetic and steel equal to 0.9/7.8) that of the respective steel fibers by mass. This means equal volumes of synthetic fiber equaled the same volume of steel fiber for tests done at any percentage by volume. Of special notice were areas of impact resistance and residual strength, where the fiber blend offered impressive results, even at lower dosages. For instance, in one case the synthetic fiber specimens at 0.3% recorded over 300 impact blows before failure, whereas its steel fiber counterpart at 0.3% showed approximately 175 blows at ultimate failure. The synthetic fiber at 0.4% showed approximately 425 blows, compared to approximately 225 blows for the steel fiber at a 0.4% volume. In residual strength testing to determine the fibers' load-carrying ability after first crack, the results suggest that the steel fibers should be added at a range of 8 to 11 times the dosage of the synthetic fiber blend to achieve equal residual strength performance. These comparative tests confirm macro synthetic fiber abilities to offer equivalent performance in areas of importance to shotcrete applications and projects, while adding other valuable benefits in the areas of cost as well as user-friendliness.

MACRO SYNTHETIC FIBER BLEND APPLICATIONS

Macro synthetic fibers have been used in a wide variety of shotcrete projects as a valuable performance-rated reinforcement that is extremely easy to add, mix, and shoot. In both above ground artificial rock and waterscapes (Cedar Point in Sandusky, OH, USA) and underground tunnel linings, the non-corrosive characteristic of a synthetic fiber is extremely attractive. This synthetic fiber blend has also been used successfully in thousands of cubic yards of wet-mix shotcrete that were produced from pre-blended dry-bagged materials, primarily in underground tunnel projects.

Higher dosages of polypropylene fibers have actually been utilized in shotcrete projects for many years, beginning with the re-lining for the river wall of the Thames River in England in 1968. More recently, in 1988, 0.6% by volume polypropylene fiber was used on the tunnel wall at the Oldman River Dam in southern Alberta, Canada. In this case, 0.6% polypropylene fiber served as a user-friendly and performance-surpassing alternative to the 0.9% steel fiber that had been used to start the project. The synthetic fibers also eliminated any risk of injury from rebounding fibers, and they were easy to add, mix, and shoot, without build-up in the mixer trucks or shotcrete lines. A total of 75 mm (3 inch) of shotcrete was applied to the interior horseshoe-tunnel walls that were approximately 3 meter (9 feet) in diameter and almost 1,524 meters (5,000 feet) in length.

Underground tunnel projects have become the largest volume users of the synthetic structural fiber in shotcrete applications for municipalities (city of Navarre, Spain), wineries (Clo de la Tech Winery, California, USA), railroads, and utility companies. The macro synthetic fiber blend is non-absorptive and non-corrosive. These characteristics are very valuable in these underground project conditions around the world. Over 1,100 kgs (2,500 lbs) of the macro synthetic fiber blend were used in a 2005 tunnel-lining project for a winery facility in Redwood City, CA. The synthetic fibers were used in lieu of other structural fibers due to their proven history of quick and uniform fiber mixing and distribution. These fibers were also used in a similar tunnel-lining project in Navarre, Spain, requiring over 3,000 cubic meters (3,900 cubic yards) of synthetic fiber-reinforced concrete. The fiber was used at a 0.5% volume to control shrinkage cracking and enhance concrete toughness properties.

The macro synthetic fiber blend has also been used in much smaller shotcrete projects due to the same ease-of-use and performance benefits, yet on a smaller scale. An example is a residential shotcrete in-ground swimming pool that was placed in June of 2001 in the Valley Brook section of Germantown, Tennessee, USA. The fiber was used at 0.66% volume, and offered no mixing or balling problems, and it caused no difficulties with the pool surface treatment.

Another small but very noticeable macro synthetic fiber reinforced shotcrete application is for man-made rockscapes. These have become very popular by truck dealers all over the USA. A dealer in Jacksonville, FL, USA, took the national-brand slogan “Like A Rock” to heart when he commissioned a former movie set designer to design and construct a fiber-reinforced shotcrete rock to effectively display their vehicles. A special mixture included 0.20 to 0.27% macro synthetic fibers, along with a unique texturing and coloring process, to create a very strong yet realistic concrete-rock structure. According to the constructor, the three-dimensional synthetic fiber reinforcement allowed for a wider range of form, shape, and creativity than conventional steel reinforcement.

MACRO SYNTHETIC FIBER BLEND REINFORCED CONCRETE ADVANTAGE

The structural synthetic fibers offer a range of economic, performance, and safety-related benefits to the shotcrete industry worldwide. These fiber advantages include a reduction of cracking, enhancements to ductility, toughness, and impact resistance, and the elimination of the potential for reinforcement corrosion. In addition, the project is also able to realize significant economic benefits as a result of reduced labor, reduced cracking, and an overall savings in reinforcement costs.

With the advent of this next-generation structural synthetic fiber blend, considerations for reductions in cross-section and for a much higher replacement level of conventional steel reinforcement are possible. The structural synthetic fiber is a viable, alternative, three-dimensional, shotcrete reinforcement.

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