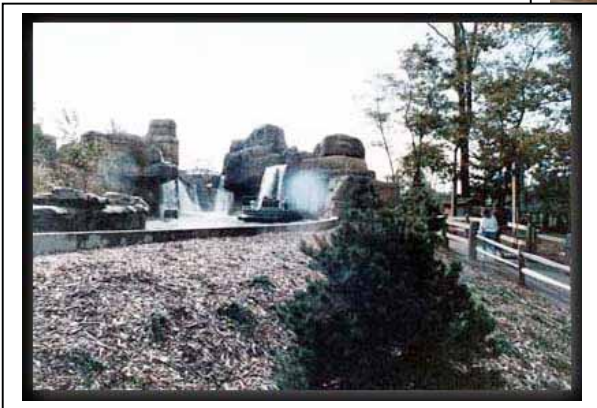




FORTA Corporation Technical Report

Fiber-Reinforced Shotcrete





FORTA Corporation TECHNICAL REPORT

FIBER-REINFORCED SHOTCRETE

Introduction

In 1978, FORTA Corporation introduced the concept of three-dimensional synthetic fiber reinforcement to the construction market worldwide. One of the successful early product applications was the use in a wide variety of air-placed concrete projects. The FORTA[®] family of standard synthetic fibers has enjoyed widespread use since that time in both dry-mix gunnite and wet-mix shotcrete applications, such as 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 reduce temperature and shrinkage-related cracking, reduce rebound, and increase toughness and long-term durability.

During that time, FORTA[®] continued to study and develop a second-generation synthetic fiber that could offer improved performance benefits and affect the actual structural properties of the concrete itself. In 1999, FORTA[®] introduced FORTA-FERRO[®] - a structural synthetic fiber that lives up to its name – “Strong As Steel”. This fiber has begun to play an important role in the air-placed concrete market by enhancing toughness and durability while offering a safer and easier alternative to conventional reinforcing steel.

Problems With Steel

For a lack of a better alternative, steel in various forms has been used as reinforcement in shotcrete products and applications for many years. Though some primary steel is necessary for various reasons, much of the steel reinforcement is superfluous to the critical design of the shotcrete application. (FORTA[®] engineers can assist project designers and specifiers in determining proper levels of steel replacement with structural synthetic fibers.) The use of steel in various forms, has brought with it a complimentary set of problems related to either in-place performance or the actual handling and placement of the steel.

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

Steel reinforcement must be cut, bent, spliced, and attached to the project substrate, which is very difficult and labor intensive. The handling of steel also adds a common risk for injury and can be extremely dangerous. Also of concern is assuring the minimum necessary

concrete cover of the steel to protect it from the elements and project conditions. Rising costs and increasing availability difficulties of steel in all forms – bar, fabric, and fibers – also add to the concern regarding its use in many shotcrete project applications. These placement and performance deficiencies of steel reinforcement served as further incentive for FORTA Corporation to develop a level of synthetic fiber reinforcement that could serve as a viable alternative.

Development of FORTA-FERRO®

During the development of the FORTA-FERRO® structural synthetic fiber, FORTA® utilized their 4-C's Fiber Performance Formula as a basis for improving each important fiber characteristic. By maximizing each of these characteristic areas, the FORTA-FERRO® fiber is able to improve on the level of steel replacement possible.

Configuration

The shape of the fiber is one of the most critical aspects with regards to anchorage and pull-out of the fiber reinforcement. Monofilament fibers that are very fine in diameter and round in shape do not anchor in the concrete as well as heavier, deformed fibers. Normal monofilament fibers would not be expected to act as a replacement for handling or structural steel, but would offer a reduction in shrinkage cracking and provide edge protection in air-placed concrete applications. Fibrillated net-shaped fibers offer a much greater resistance to pull-out, and as a result, have proven their ability to replace non-structural handling steel such as wire mesh in a variety of shotcrete projects. To maximize resistance to pull-out and post-crack behavior, the FORTA-FERRO® fiber involves a blend of two fiber shapes: a fibrillated network configuration, along with an embossed (deformed) configuration in a heavy-duty filament size. This unique blend of shapes gives the FORTA-FERRO® fiber the ability to control temperature-related cracking as well as affect the structural properties of the concrete.

Chemistry

The chemical make-up of the fiber is extremely important if the fiber is expected to hold up in the aggressive alkali environment of Portland cement concrete. The fibrillated-net portion of the FORTA-FERRO® blend is made of 100% virgin polypropylene, which is inert to alkali and chemical attack. The heavy-duty filament portion is comprised of a proprietary blend of two synthetic monomers, resulting in a high density, high modulus copolymer. This copolymer is also inert to chemical and alkali attack, and creates a very high-strength fiber to improve performance and residual strength benefits.

Contents

During FORTA®'s structural fiber research, it became apparent that standard synthetic fibers such as fine monofilaments, and even fibrillated-network fibers, consist of a very high level of surface area on a per pound 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 robbing too much of the paste content of the concrete mix. Standard dosage levels for

these fibers are generally 1.0 lb./cu. yd. for fine monofilaments, and 1.5 lbs./cu. yd. for fibrillated networks with upper dosage levels in the range of 3.0 lbs./cu.yd. The unique blend of fiber shapes that make up the FORTA-FERRO[®] grade of fiber helps minimize the surface area levels, and allows dosage rates to be increased without affecting the rheology of the mix. To date, dosage rates for FORTA-FERRO[®] in various shotcrete applications have ranged from 3 to 30 lbs./cubic yard depending on reinforcement requirements.

Correct Length

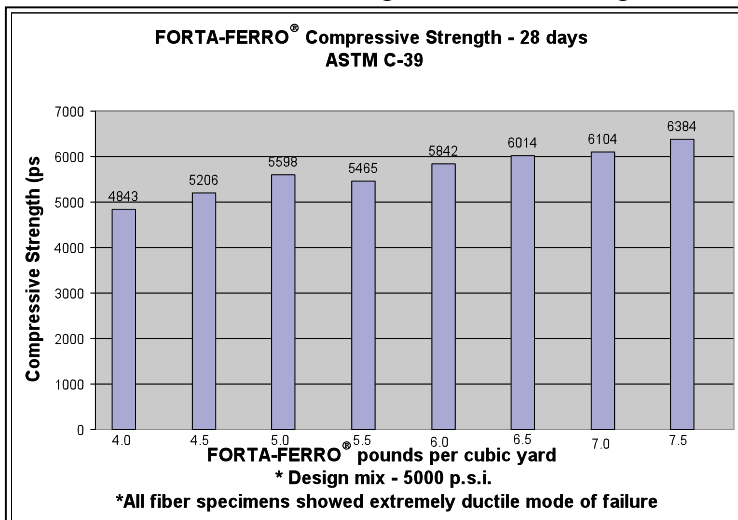
With any fiber, the Critical Bond Length, which is the maximum length of fiber on either side of a potential crack, is an important consideration for long-term performance. Obviously longer fibers are better able to anchor within the concrete than short fibers that tend to lose their grip and pull out. The FORTA-FERRO[®] length of 2 1/4" (54 mm) maximizes the fibers' Critical Bond Length, which allows the residual strength or post-crack performance to also reach their highest levels.

FORTA[®] Testing

Since its inception, the FORTA-FERRO[®] structural fiber has been rigorously tested in a wide variety of both laboratory specimen and actual field test procedures. FORTA-FERRO[®] fiber has consistently shown dramatic advantages in the areas of ductility, impact resistance, shrinkage, and residual strength, as well as in areas of rebound reduction.

Compressive

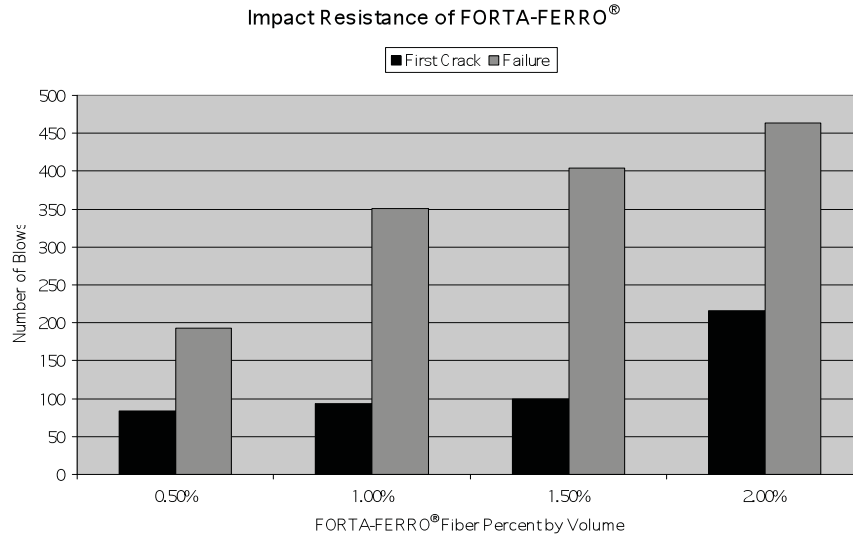
FORTA-FERRO[®] was tested in compression using standard 6" X 12" cylinders (ASTM C39) at various dosage levels. At dosage levels of .25-.50% by volume, or 4-7.5lbs./cu. yd., there was a marked increase in compressive strength performance.



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.

Impact

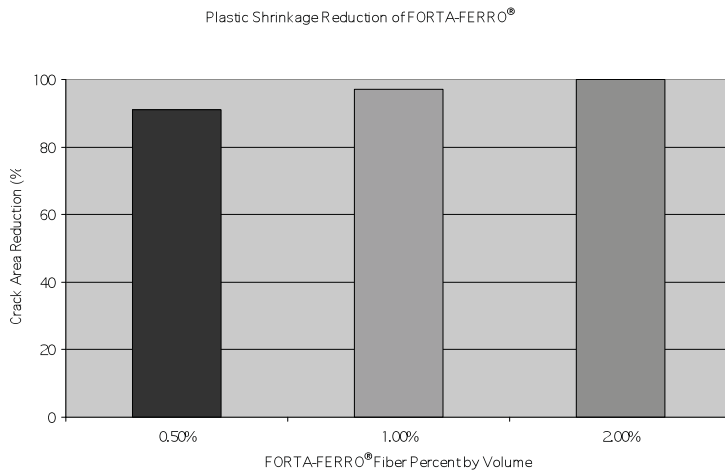
FORTA-FERRO[®] has also shown dramatic improvement to impact resistance as tested by the ACI Committee 544 Drop Hammer test. Most impressive is the fiber's ability to



allow for specimen integrity, even after first crack. Resistance to shock and impact may play a valuable role in a variety of shotcrete applications.

Shrinkage

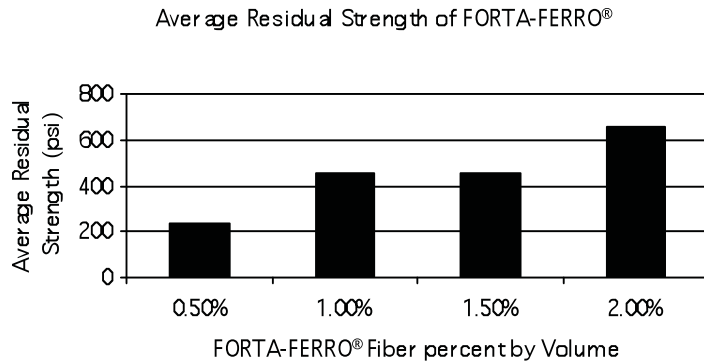
The unique fiber blend of heavy-duty filaments and fibrillated networks allows the FORTA-FERRO[®] fiber to offer structural performance as well as reductions to plastic shrinkage cracking. Conventional steel reinforcement, such as mesh, rebar, or steel fibers, has



no ability to control shrinkage-related cracking, and are typically effective only after the concrete has cracked. In testing at 7.5 lbs. per cubic yard, FORTA-FERRO[®] showed a remarkable 92% reduction in crack area caused by plastic shrinkage, and approached 100% at dosages of 30 lbs. per cubic yard (2.0% by volume).

Residual Strength

Residual strength is the amount of load in p.s.i. that can be carried by the fiber reinforcement after the concrete has cracked. Fibers' ability to hold cracks tightly together is a necessary feature in a wide variety of shotcrete applications such as slope stabilization or tunnels. While standard-grade synthetic fibers may offer residual strengths of 25 to 75 p.s.i., the FORTA-FERRO® structural fiber blend offers strengths of 250 to over 600 p.s.i. at the

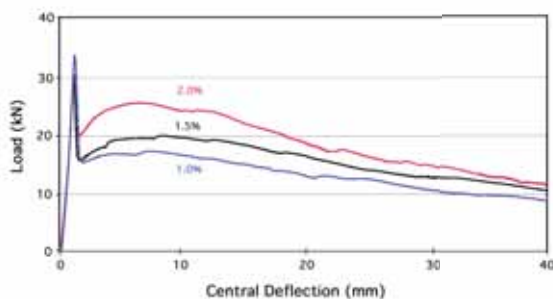


higher dosages normally considered for these applications. In the future, this modified beam test (A.S.T.M. C 1399) may also serve as a benchmark test method to compare the post-crack behavior of various fiber types and brands. Specifiers could confidently call for a performance-rated standard by using a minimum (p.s.i.) residual strength value, when fibers are being considered as a steel reinforcement alternate.

Shotcrete Roundtable Test

The ability of the FORTA-FERRO® fiber to affect post-crack behavior is quite evident from load testing of the shotcrete roundtable test procedure. As dosages of this long-length,

FORTA-FERRO® Shotcrete Round Table Test

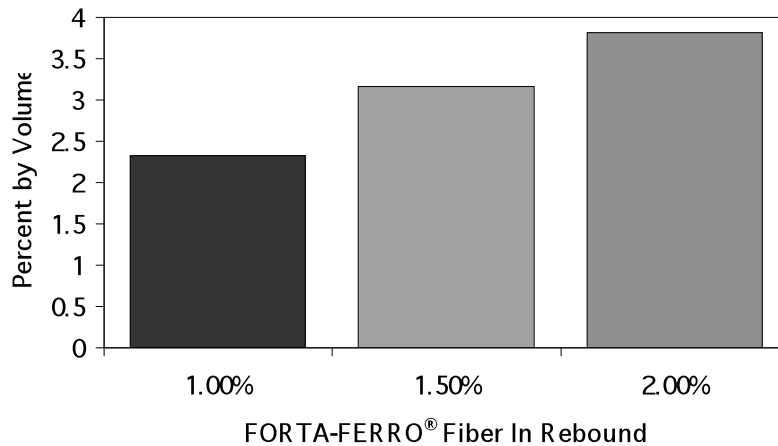


heavy duty fiber increase, the ability to sustain increased load even after initial crack also increases, offering a powerful performance value to a wide variety of shotcrete project applications.

Shotcrete Rebound

Due to the impact velocity of the shotcrete materials, rebound or bounce-off of the mix ingredients from the construction surface is a normal occurrence, and adds to the waste quotient of this air placed concrete construction method. In rebound testing, the FORTA-FERRO[®] 3-dimensional fiber acts as a mechanical binder and cohesive agent, offering noticeable and significant reductions in shotcrete rebound quantities.

Shotcrete and Rebound of FORTA-FERRO[®]



FORTA-FERRO[®] vs. Steel Fibers

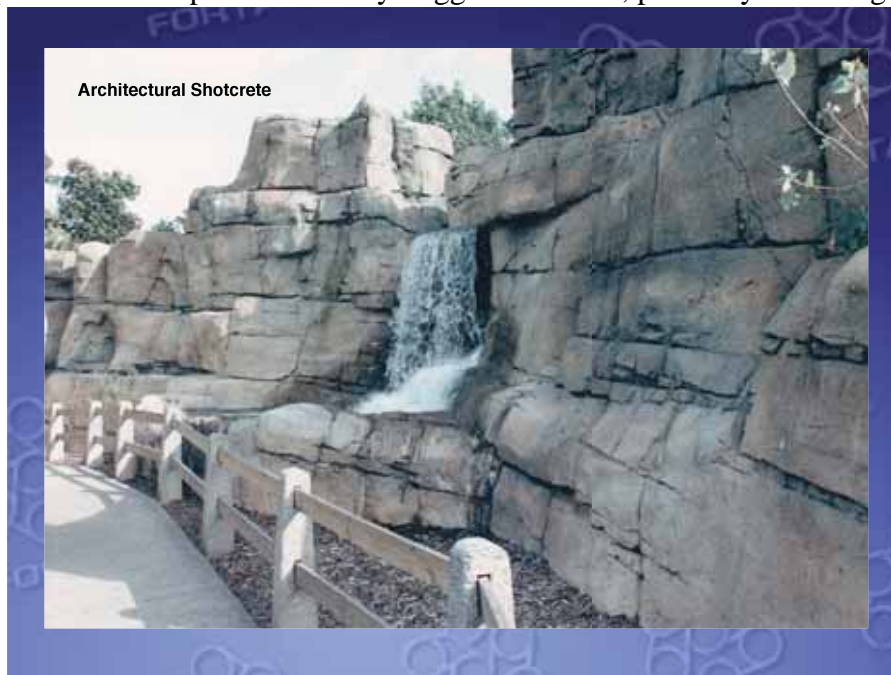
One of the driving forces behind the development of a structural synthetic fiber was to create a viable alternative to steel fibers frequently used in shotcrete applications. In addition to concerns regarding corrosion and rising costs, steel fibers can be challenging to add, mix, and shoot at the elevated dosages (50 to 120 lbs./cu. yd.) used in these types of applications. Ready-mix concrete producers often encounter difficulties in adding steel fibers in an even manner that will facilitate uniform distribution and minimize clumping and balling, and must monitor truck load restrictions after adding 500 to over 1,000 pounds of additional weight to a 10 cubic yard load due to the high dosage levels. In addition, steel fibers typically have little if any affect on the reduction of plastic shrinkage cracking, an area where synthetic fibers shine.

As a result, FORTA Corporation performed comparative tests on various well-known types and brands of steel fibers to explore the differences with regards to dosages and also to compare performance levels in various testing areas. These tests used the same shotcrete mix proportions except for the different 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 showing the FORTA-FERRO[®] fiber vs. each of the three steel fiber types are available by contacting FORTA Corporation (U.S.A. Test Reports #20-02/F, 20-02/N, and 20-02/B.) In general, the FORTA-FERRO[®] compared extremely well in all test areas, and did so at a dosage rate of approximately 1/10 that of the respective steel fibers by weight (i.e., 0.3% = 4.5 lbs./cu. yd. FORTA-FERRO[®] = 40 lbs./cu. yd. steel fiber; 0.4% = 6.0 lbs./cu. yd. FORTA-FERRO[®] = 50 lbs./cu. yd. steel fiber). Of special notice were areas of impact resistance and residual strength, where the FORTA-FERRO[®] fiber offered impressive results, even at considerably lower dosages by weight. For instance, in one case the FORTA-FERRO[®] specimens at 4.5 lbs./cu. yd. recorded over 300 impact blows before failure, whereas its steel fiber counterpart at 40 lbs./cu. yd. showed approximately 175 blows at ultimate failure. At 6.0 lbs./cu. yd., the FORTA-FERRO[®] showed approximately 425 blows, compared to approximately 225 blows for the steel fiber at a 50 lb./cu. yd. dosage. 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 FORTA-FERRO[®] fiber to achieve equal residual strength performance. These comparative tests confirm FORTA-FERRO[®]'s ability 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.

FORTA-FERRO[®] Applications

FORTA-FERRO[®] has been used in a wide variety of air-placed concrete projects as a valuable performance-rated reinforcement that is extremely easy to add, mix, and shoot. In both above-ground artificial rock and waterscapes, and underground tunnel linings, the non-corrosive characteristic of FORTA-FERRO[®] is extremely attractive. FORTA-FERRO[®] 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.



FORTA[®] reinforced shotcrete artificial rockscape at Cedar Point in Sandusky, OH

High dosages of polypropylene fibers have actually been utilized in shotcrete projects for many years, beginning with the air-placed re-lining for the river wall of the Thames River in England in 1968. More recently, in 1988, 10 lbs. per cubic yard of heavy-duty polypropylene fiber were used on the tunnel wall at the Oldman River Dam in southern Alberta, Canada. (See attached article “Case history: High-volume polypropylene reinforcement for shotcrete”.) In this case, 10.1 lbs. of the FORTA[®] polypropylene fiber served as a user-friendly and performance-surpassing alternative to the 118 lbs. of steel fiber per cubic yard that had been used to start the project. The synthetic fibers also eliminated any risk of injury from rebounding fibers, and were easy to add, mix, and shoot, without build-up in the mixer trucks or shotcrete lines. A total of 3” of shotcrete was applied to the interior horseshoe-tunnel walls that were approximately 9 feet in diameter and almost 5,000 feet in length.



- 10.1 lbs./cubic yard of FORTA[®]-reinforced shotcrete was applied at the Oldman River Dam tunnel project in Alberta, Canada.

Underground tunnel projects have become the largest volume users of the FORTA-FERRO® structural fiber in shotcrete applications for municipalities, wineries, railroads, and utility companies. FORTA-FERRO®'s non-absorptive and non-corrosive characteristics are very valuable in these underground project conditions both here in the United States and abroad. Over 2,500 lbs. of the FORTA-FERRO® fiber were used in a 2005 tunnel lining project for a winery facility in Redwood City, CA. The FORTA-FERRO® fibers were used in lieu of other structural fibers due to their proven history of quick and uniform fiber mixing and distribution. FORTA-FERRO® was also used in a similar tunnel lining project in Navarre, Spain, requiring over 3,000 cubic meters of fiber-reinforced concrete. The fiber was used at a dosage of 4.5 Kg/cu. m. (7.5 lbs./cu.yd.) to control shrinkage cracking and enhance concrete toughness properties.



FORTA-FERRO®-reinforced tunnel lining
for
Clo de la Tech Winery in California



Over 30,000 lbs. of FORTA-FERRO® fiber were
used to line a tunnel for the city of Navarre, Spain.

FORTA-FERRO® 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, TN. The FORTA-FERRO® fiber was used at a dosage of 10 lbs. per cubic yard of concrete, and offered no mixing or balling problems, and caused no difficulties with the pool surface treatment.



FORTA-FERRO® reinforced swimming pool – Germantown, TN

Another small but very noticeable FORTA-FERRO® reinforced shotcrete application is for man-made rockscapes, that have become very popular by SUV and truck dealers all over the country. A Chevrolet dealer in Jacksonville, FL took the national-brand slogan “Like A Rock” to heart when he commissioned Al Mango, a former movie set designer for Universal Studios, to design and construct a fiber-reinforced shotcrete rock to effectively display their vehicles. Mango’s firm, Terra Scena Inc., uses a special mix that includes 3 to 4 lbs. of FORTA-FERRO® fiber per cubic yard, along with a unique texturing and coloring process, to create a very strong yet realistic concrete-rock structure. According to Mango, the three-dimensional synthetic fiber allows for a wider range of form, shape, and creativity than conventional steel reinforcement.



FORTA-FERRO® reinforced rockscape – Marine Chevrolet, Jacksonville, FL

The FORTA-FERRO® Advantage

FORTA-FERRO® structural synthetic fibers have offered a range of economic, performance, and safety-related benefits to the shotcrete industry world-wide. 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, considerations for reductions in cross-section and for a much higher replacement level of conventional steel reinforcement are possible. The FORTA® technical and engineering team is available to assist specifiers, buyers, and code authorities in preparing project-specific calculations to evaluate the FORTA-FERRO® structural synthetic fiber as an alternative shotcrete reinforcement. For additional information on testing, trials, and performance comparisons, please contact your local technical representative or the FORTA Corporation engineering department



FORTA-FERRO®

FACT-DATA[©]

MANUFACTURER

FORTA CORPORATION, 100 Forta Drive, Grove City, PA, U.S.A., 16127-6399
TELEPHONE: 1-800-245-0306, (724) 458-5221; FAX: (724) 458-8331; www.fortacorp.com

GENERAL DESCRIPTION

FORTA-FERRO® is an **easy to finish**, color blended fiber, made of 100% virgin copolymer/ polypropylene consisting of a twisted bundle non-fibrillating monofilament and a fibrillating network fiber, yielding a high-performance concrete reinforcement system. **FORTA-FERRO®** is used to reduce plastic and hardened concrete shrinkage, improve impact strength, and increase fatigue resistance and concrete toughness. This **extra heavy-duty** fiber offers maximum long-term durability, structural enhancements, and effective secondary/temperature crack control by incorporating a truly **unique synergistic fiber system** of long length design. **FORTA-FERRO® is non-corrosive, non-magnetic, and 100% alkali proof!**

APPLICATIONS

FORTA-FERRO® is mainly used with performance concrete applications such as industrial floors, bridge decks, shotcrete, loading docks, precast products – anywhere that steel reinforcement reduction or replacement is the objective. Contact FORTA Corporation for design assistance.

INSTALLATION

Recommended dosage rate of **FORTA-FERRO®** is **0.2% to 2.0% by volume of concrete** (3 to 30 lbs. per cubic yard) added directly to the concrete mixing system during, or after, the batching of the other ingredients and mixed at the time and speed recommended by the mixer manufacturer (usually four to five minutes).

PHYSICAL PROPERTIES

Materials.....	Virgin Copolymer/Polypropylene	Color.....	Gray
Form.....	Monofilament/Fibrillated Fiber System	Acid/Alkali Resistance....	Excellent
Specific Gravity.....	0.91	Absorption	Nil
Tensile Strength.....	90-110 ksi. (620-758 MPa)	Compliance.....	A.S.T.M. C-1116
Length.....	2.25" (54mm), 1.5" (38mm)		

AVAILABILITY

FORTA-FERRO® can be purchased from FORTA Corporation or an authorized FORTA® products distributor, dealer or representative. Orders are shipped within 24 hours by small package services, commercial carrier, or air freight.

PACKAGING

Convenient incremental pound or kilogram mixer-ready bag packaging.

WARRANTY

FORTA® products are warranted to be free of defects in material and meet all quality control standards set by the manufacturer.

FORTA Corporation specifically disclaims all other warranties, express or implied. The exclusive remedy for defective product shall be to replace the product or refund the purchase price. No agent or employee of this company is authorized to vary the terms of this warranty notice.

FORTA Corporation has no control over the design, production, placement, or testing of the concrete products in which FORTA® products are incorporated, and therefore FORTA Corporation disclaims liability for the end product.

U. S. Patent No. 6,753,081. Additional patents pending.

FORTA®

FORTA-FERRO®

FORTA Corporation's technical recommendations regarding synthetic fiber characteristics are based on years of engineering research and scores of concrete projects. FORTA® has developed a simple "4-C's" formula to help the specifier choose the right fiber for any concrete project application. By making a decision with each of the FORTA® "4-C's" categories – **C**onfiguration, **C**hemistry, **C**ontents, and **C**orrect Length—specifiers are assured of obtaining the desired fiber performance level for a given project. The following 4-C's Formula Specification has been prepared to accommodate the stated reinforcement objective for this FORTA® product grade.

REINFORCEMENT OBJECTIVE: To inhibit plastic and settlement shrinkage cracking prior to the initial set, and to reduce hardened concrete shrinkage cracking, improve impact strength, and enhance concrete toughness and durability as an alternate secondary/temperature/structural reinforcement.

DIVISION – CONCRETE
SECTION – CONCRETE REINFORCEMENT
SUB-SECTION – SYNTHETIC FIBROUS REINFORCEMENT

Synthetic fibrous reinforcement shall be used in the areas denoted in plans, and shall comply with the following fiber characteristics:

1. **Configuration** – Fiber shall be a synergistic combination of a twisted-bundle non-fibrillating monofilament and a fibrillating network fiber system.
2. **Chemistry** – Fiber shall be made of 100% virgin materials in the form of fully-oriented copolymer/polypropylene, gray in color.
3. **Contents** – Fiber shall be used at a dosage rate of 0.2% to 2.0% by volume of concrete (3 to 30 lbs. per cubic yard).
4. **Correct Length** – Fiber Length shall be 2.25" (54mm).

Compliance: Fibers shall comply with A.S.T.M. C-1116 "Standard Specification for Fiber Reinforced Concrete and Shotcrete". The approved product is FORTA-FERRO® structural fiber as manufactured by FORTA Corporation, Grove City, PA, U.S.A. Phone: 1-800-245-0306 or 1-724-458-5221; Fax: 1-724-458-8331.

FORTA Corporation

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