# NPCA Fibers White Paper

Precast ... The Concrete Solution

# Section I – What Is Fiber Reinforcement?

Fiber-reinforced concrete (FRC), sometimes called fibrous concrete, is defined by the American Concrete Institute as concrete containing dispersed randomly oriented fibers. Fibers are defined by the American Society of Testing and Materials (ASTM) as slender and elongated filaments in the form of bundles, networks or stands of any natural or manufactured material that can be distributed throughout freshly mixed concrete.

The use of fibers and their ability to reinforce materials dates back for thousands of years. The ancient Egyptians used natural fibers such as straw and horsehair to reinforce and improve the properties of mud bricks. The first patent for FRC was granted in 1874. Commercial use of asbestos fibers in cement paste became more common with the invention of the Hatschek process in the late 1890s. For obvious reasons, alternate fiber types have been researched and implemented throughout the 1960s and 1970s. Today many industries such as aerospace, sporting goods and

the military use various fibers in their materials. In the construction industry, where new materials may take more time to gain acceptance, fiber- reinforced concrete is making progress in gaining acceptance.

Fibers have very good tensile strengths relative to conventional reinforcing steel and are fairly simple to work with, which makes them attractive for use in concrete. Fibers can be very beneficial in improving concrete's shrinkage, impact, abrasion and fire resistance. Fibers can also improve concrete's flexural strength and durability. However, due to their random orientation and discontinuous nature, their structural contribution cannot be assessed with the same methodology as continuous reinforcement and should require proof of design testing.

# Section II – Characteristics And Types Of Fibers

All fiber types have various characteristics that affect their performance in concrete. Some primary characteristics include geometry, aspect ratio and material type. Fibers come in many geometries including rectangular, flat, cylindrical, and variations or combinations for these. Fiber geometry can affect workability, resistance to pull-out forces and overall performance. Another characteristic is aspect ratio or the ratio of the length to diameter. Typically, for the same mixture proportions, as the aspect ratio increases so does the potential for balling of fibers in the mixing process and slump loss.

There are many types and manufacturers of fibers for commercial and experimental use. In general, these fiber types are broken into four main categories, as described in ACI 544.1R. These categories are steel, glass, synthetic and natural fibers.

**Steel fibers:** ASTM A820 provides five general classifications for steel fibers – cold drawn wire, cut sheet, melt-extracted, mill cut and modified cold-drawn wire. Cold-drawn wire, also designated as Type I, is the most common steel fiber used in precast concrete due to the high tensile strength found in the cold-drawn wire source products. These types of fibers generally have deformations to improve mechanical anchorage in a concrete matrix. Lengths of these fibers will typically vary from 0.25" (6 mm) to 3" (75 mm). Per ASTM A820 the average tensile strength shall not be less than 50,000 psi (345 MPa), and the tensile strength of any one fiber shall not be less than 45,000 psi (310 MPa). Steel fibers are typically used in precast, slab and shotcrete applications.

**Glass fibers:** The most common use for glass fiber is in the manufacture of architectural building panels referred to as Glass Fiber Reinforced Concrete (GFRC). The primary type of glass fiber used in concrete production is alkali-resistant (or AR) glass fiber. These fibers are typically used in a spray-up process by mixing them into a concrete mixture during application.

**Synthetic microfibers:** These products are generally man-made fibers of various petrochemical and textile material compositions with different lengths, chemistries, colors and forms. Fiber types include acrylic, aramid, carbon, nylon, polyester, polypropylene and polyethylene fibers. Traditionally, the bulk of synthetic fiber use has been limited to various forms of monofilament (single-strand fiber) and fibrillated forms of polypropylene fibers. Fibrillated fibers are a slit-film fiber where sections of the fiber peel away, forming branching fibrils. These types of synthetic micro-fibers are commonly used for secondary reinforcing of concrete.

Synthetic macrofibers A recent development in the field of synthetic fibers has included the emergence of larger, coarse synthetic fibers (macrofibers:equivalent diameter ≥ 0.012" (0.3 mm)) capable of providing toughness and performance characteristics similar to those of steel fibers at elevated dosage levels. Synthetic fibers are typically used in precast, slab and shotcrete applications and range in size from 4 to 3,000 denier and in length from 0.25" (6 mm) to 3" (75 mm). Denier is a term used with synthetic fibers to describe the weight in grams of 9,000 meters of a single fiber

**Natural fibers:** Many forms of natural-based fiber materials are used in concrete production and include coconut, sisal, bamboo, jute, flax, plantain and several other naturally occurring materials. Fiber lengths will generally range from very small to as much as 3" (75 mm) depending on the type of fiber used. Several of these fiber types may absorb water or are chemically unstable in concrete and are therefore not as widely accepted as steel, glass and synthetic fibers.

## Section III – How Fibers Work In Concrete

Fibrous concrete can be readily cast in irregular shapes and cross sections. It can be made as flowable as plain concrete with the use of chemical admixtures. Fibrous concrete can be produced with low shrinkage and may be less vulnerable to segregation, even with extreme applications of vibration. The uniformly dispersed, discontinuous tensile reinforcement provides for the redistribution of tensile and creep strains.

Fibers benefit concrete by two primary means. First, fibers are strong in tension, in some cases as much as 10 times that of reinforcing steel. Second, fibers are distributed throughout a concrete matrix, which essentially means, fibers can benefit the entire concrete member. Of course, these are both dependant on many things including type, size, aspect ratio and concentration of the fibers as well as the mixture proportions of the concrete.

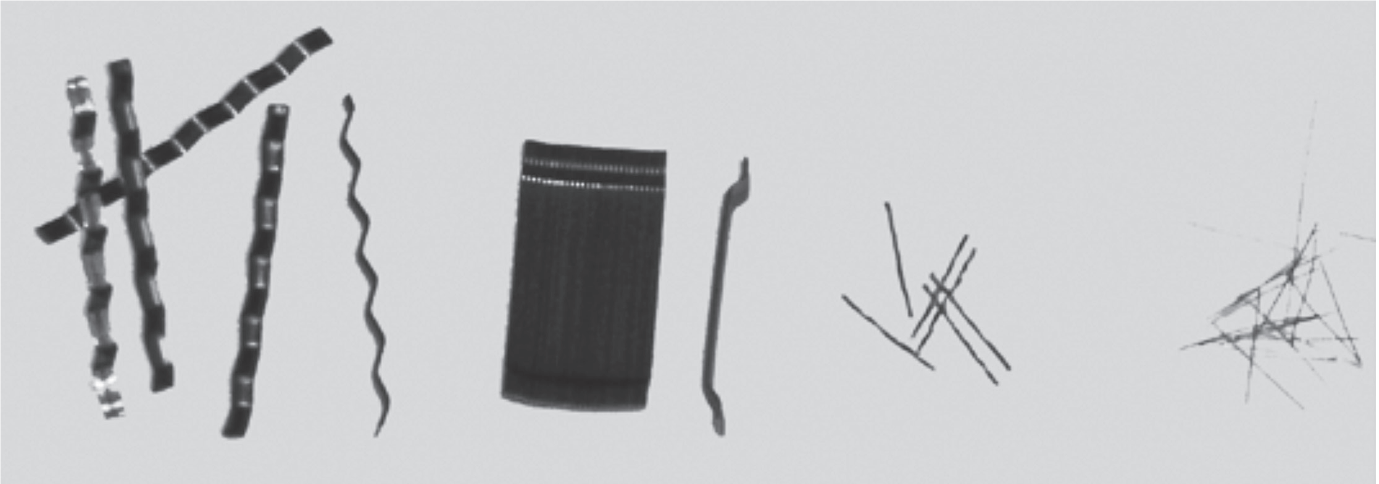

**FIGURE 1:** Steel and synthetic fibers.

In almost all instances, in order for fibers to be effective, stress must transfer from the concrete into the fiber. This is achieved through bond, th same way it is achieved with conventional reinforcing steel. Bond is developed through physical deformations, such as crimping or texturing of the fibers, fiber geometry, aspect ratio and the orientation of the fibers within the concrete.

Fibers can improve cracking resistance. As concrete cracks, stress transfers into the fibers. The fibers essentially bridge the cracks, holding the concrete together. The stress is then redistributed into the surrounding area. Typically, fibers reduce the size of the cracks thereby increasing the durability of the concrete. This is very beneficial where shrinkage cracks or handling stresses are of concern. Without fibers, cracks may become large and allow moisture and chemicals quick access to the interior of the concrete and the reinforcing steel, which can result in degradation.

This same concept of distribution and crack bridging helps improve concrete's impact resistance. Since the fibers are located throughout the matrix, it becomes more difficult to fragment the concrete. The fibers essentially help hold the concrete together. This attribute improves concrete's abrasion resistance as well.

Fibers improve concrete's fire resistance in a couple of ways. During a fire, moisture inside of concrete vaporizes and expands, increasing the internal pressure. Certain types of fibers assist in preventing fragments of concrete from exploding and becoming projectiles. Fire resistance can also be improved by synthetic fibers, which melt and provide channels for hot gases and moisture vapor to escape, thus reducing the internal pressure. Ultimately, fibers can help maintain the protective concrete cover over the reinforcing steel during a fire.

Also, since fibers are present throughout the concrete matrix, they improve the ductility of the concrete member. Concrete is a brittle material and fractures when its peak strain capacity is reached. After it cracks, it has no additional tensile capacity unless it has other reinforcement in it. Tests have shown that fibers increase concrete's residual flexural strength after cracking. The fibers hold the concrete together and take up the tensile forces, enabling the concrete to continue to carry some of the load and avoiding an abrupt, catastrophic failure.

# Section IV – How Should Fibers Be Used In Precast Manufacturing

Fibers have been used for many years in precast and have a successful track record of enhancing concrete properties such as abrasion resistance, crack control and durability. The technology of fiber reinforcement is continually being advanced in order to further improve these and other characteristics, including flexural strength, toughness and impact resistance.

It is important to note that the concrete property or characteristic to be improved is highly dependent on the type of fiber, or combination of fibers, to be used. For a precast manufacturer to benefit from the use of fibers, there needs to be a clear objective regarding the desired result. The objective may be based on a problem occurring in production or it may be to satisfy a particular design specification or performance criteria. For example:

- A product continually displays evidence of cracking or spalling as it is removed from the mold.
- Random cracks appear on flat slabs due to drying shrinkage or plastic shrinkage.
- A customer is proposing a precast product for use in a highly abrasive environment.
- A product may be subject to significant impact from debris, such as during a hurricane.

The first two examples represent problems occurring in production. The other two examples represent performance issues. Each of these conditions can be satisfied or improved with the effective use of fiber reinforcement.

So, how should a precast concrete producer use fibers? First, establish that there is indeed a need that can be resolved or improved with the use of fibers. If there are no specifications calling for the use of fibers, or if there are no issues related to handling stress or shrinkage cracks, then there may be little advantage to be gained by adding fibers to the concrete.

Assuming that a specific need has been established, the next step is to select the appropriate product and dosage. This is best accomplished by working closely with one or more manufacturer's representatives, reviewing product literature and testing various products. The best product for the application will not only meet the desired performance requirement, but will do so without creating additional problems with placement, finishing or other concrete properties. If the goal is to reduce or eliminate handling damage or drying shrinkage cracks, then trials should be conducted during production in order to determine which product, and at what dosage, produces the best results. If the need is specification or performance related, then product data from the manufacturer, preferably supported by research, should be submitted to the owner for review and approval.

Fibers may also be used to replace secondary reinforcement as required for temperature and shrinkage. However, this typically applies only to non-structural products and, therefore, may have limited opportunities for use. Currently, neither ACI 318 nor AASHTO Specifications for Highway Bridges, which are the two most common standards for structural concrete design, have any provision for the use of fiber in lieu of reinforcing steel. Note: Based on a large database of test results for shear strength of steel fiber-reinforced concrete (SFRC) beams, the list of beams exempt from the minimum shear reinforcement requirement in Section 11.4.6.1 of ACI 318-08 and later editions includes beams that are constructed with SFRC. This addition to ACI 318 represented the first permitted structural use of SFRC in the ACI Building Code.

The replacement of reinforcing steel (primary or secondary) with fibers should be evaluated by a structural engineer to ensure that the product complies with all applicable codes and specifications and also to ensure that the structural integrity of the product is not degraded in any way. Steel fibers and synthetic macro fibers have received third party review, from entities like ICCES (International Code Council Evaluation Service) and Uniform ES (Uniform Evaluation Service), for primary and secondary reinforcing steel replacement and code compliance. Stamped engineering designs, that follow accepted design documents, such as ACI 544.4R and include proof testing in accordance with the applicable ASTM Standards noted in Section VI

## Section V – Mix Design And Production

In North America, the use of fibers for precast applications must be in compliance with ASTM C1116, Standard Specification for Fiber Reinforced
Concrete and Shotcrete.

Mix designs and production procedures must be carefully adjusted before placing into full production. Follow the manufacturer's recommendations regarding material handling and safety procedures.

The addition of fiber to concrete requires modifications to your mix designs. More slurry or paste is required to coat the fiber just as the aggregates are coated in a well-graded mix. There are three ways to achieve this: first by adding more cement and water, second by adjusting the ratio of the coarse aggregates (if more than one is being used), and third by adjusting the ratio of fine to coarse aggregates. Mix times may increase when fibers are introduced into the mix. The mix time depends on when the fibers are introduced and the efficiencies of the equipment being used.

Fibers can be used in self-consolidating concrete (SCC). Keep in mind that SCC fiber mix design development may take longer to fine tune than traditional mixes. Fiber mixes tend to have reduced spreads and are more sensitive to water. Material tolerances must be consistent to be successful. If the batch plant cannot repeatedly measure ±1% of the desired ingredients, you may not be able to achieve an SCC-fiber combination. Ask the fiber and admixture representatives to assist in modifying the mix designs for maximum mix efficiency, proper yields, plastic workability and final product finishes.

Once mix designs are dialed in, the production process for fiber-reinforced concrete does not differ much from traditional concrete. The transporting, placing, vibrating and curing processes are all the same. The difference is in the mixing process, how and when to add the fiber to the mix. Fiber can be added manually or by using an automated system. Most synthetic fiber companies package their products in pre-weighed bags that dissolve in water. This feature is ideal for adding fiber to the mix, is safer, and lends itself to custom automation for plant-by-plant situations. Bulk fiber and fiber automation systems are available, however the majority of precasters are manually placing fibers into each batch. The time in which the fiber is added to the batch is important. Typically, fibers are added with the aggregates, however manufacturer's recommendations should be followed.

When using fiber-reinforced concrete, the exposed surfaces may look and finish differently depending on the dosage of the fiber. However, the traditional characteristics of compressive strength and mold surface finishes should not be affected.

## Section VI – Tests For Fiber-Reinforced Concrete

To date, there are three ASTM test methods for evaluating the performance of fiber-reinforced concrete in the hardened state. These are C 1609, C 1399 and C1550. Each of these test methods is summarized below. All three methods require some specialized testing apparatus. C 1609 also requires a closed-loop or servo-hydraulic compression testing machine. Closed-loop or continuous-loop testing machines transmit multiple signals from input devices such as load cells, strain gauges or Linear Variable Displacement Transducers (LVDTs), which ultimately control the load rate, deflection and other variables, depending on how the test has been set up. These machines are typically attached to a computer with software designed to manage the system. As such, some tests are performed by larger testing facilities, rather than standard precast plants. Many of the standard concrete tests are still used for evaluation of FRC. For example, ASTM C 143 can be used to determine slump of FRC. There are a multitude of test methods and standards used to evaluate the fibers themselves.

**ASTM C 1609** "Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) – This test method evaluates the flexural performance of fiber-reinforced concrete using parameters derived from the load-deflection curve obtained by testing a simply supported beam under third-point loading using a closed-loop, servo-controlled testing system. This test method provides for the determination of first-peak and peak loads and the corresponding stresses calculated by inserting them in the formula for modulus of rupture. It also requires determination of residual loads at specified deflections, the corresponding residual strengths calculated by inserting them in the formula for modulus of rupture. It provides for determination of specimen toughness based on the area under the load-deflection curve up to a prescribed deflection and the corresponding equivalent flexural strength ratio..

**ASTM C 1399** "Standard Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete – This method is similar to ASTM C 1609 using only 4 in. by 4 in. by 14 in. beams, however a steel plate is used to absorb the energy released from the first crack. The result from this test determines the average residual strength (ARS), which is based on the averaged loads at key deflections during the test. This test method may be performed without a servo- controlled testing machine and may be the best test method for precasters. The results from this test method may be used to make relative comparisons between fiber-reinforced concrete mixes and for quality control purposes. The results may also be correlated with other test data to assist in the design of fiber-reinforced concrete mixtures.

**ASTM C 1550** "Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel) – This is a plate test used for simulated bi-axial behavior of fiber-reinforced slabs, tunnel linings and shotcrete applications. The results are in the form of energy absorbed by the fiber system or flexural toughness, which is the integration of the load-deflection curve.

**Vacuum Testing** – Any containment vessel that can be sealed is a candidate for vacuum proof testing. Pipe, manholes, septic tanks, burial vaults and utility boxes can be structurally tested by vacuum loading. The ASTM Specification for Precast Concrete Septic Tanks, C 1227, introduced vacuum testing to check leakage and for structural proof testing. The vacuum loads established for septic tanks may be adopted for burial vaults. Vacuum is commonly measured in "inches of mercury" units. The stress imposed on a container by one inch of mercury (Hg) vacuum is equal to
0.49 pounds per square inch (psi). Proof testing (when performed) should be reviewed and signed-off by a licensed engineer.

**Preparation of test specimens** – In general, specimens can be prepared in accordance with ASTM C 31, C 42, C 192, C 1609, C 1399 and C
1550. Specimens should be consolidated using external vibration whenever possible. Internal vibration is discouraged and rodding is not permitted. These methods may cause non-uniform fiber distribution and alter the orientation of the fibers.

## Summary

Fiber reinforcement and conventional reinforcing steel (rebar or wire mesh) are two different types of reinforcement with very different purposes. Concrete is weak in tension and requires reinforcing steel in order to be used in many structural applications or whenever the tensile force is expected to exceed that concrete's capacity. Conventional reinforcement is continuous, placed in specific locations within the concrete and used as primary reinforcement to resist tensile and shear forces.

Fibers are discontinuous and randomly distributed throughout the concrete matrix. This means they can distribute tensile stresses throughout the concrete better than conventional reinforcement. However, they may not handle the concentrated tensile forces of primary reinforcement and therefore proof of design testing should be performed to ensure the concentrated tensile forces can be handled. Fibers affect concrete on a more localized level, such as a small fraction of the concrete member. Conventional reinforcement affects the global capacity of the concrete member. Fibers are added during mixing, therefore they are usually easier to place and require less labor than conventional reinforcement.

Fiber technology continues to advance every day. For more information on the use of fibers in precast concrete contact NPCA at (800) 366-7731 or visit us on line www.precast.org.