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UNDERSTANDING FIBER REINFORCED CONCRETE

CONTENT

FIBER TERMINOLOGY

Aspect Ratio | The ratio of the length to the diameter of one single fiber. The diameter may be the actual or equivalent diameter, as defined below.

Crack | A complete or incomplete separation of concrete into two or more parts produced by breaking or fracturing.

Collated Fibers | Fibers that are held together prior to the mixing process by cross linking, by chemical or mechanical means.

Denier | The weight (in grams) of 9,000 meters of a continuous fiber filament. Irregular shaped fibers are measured through linear density method, or denier analysis.

Ductility | The ability of material to absorb energy and sustain loads beyond a yield point that defines the limit of elastic behavior (onset of cracking), i.e. as opposed to a brittle material that demonstrates abrupt loss of strength beyond the elastic range.

Equivalent Diameter of a Fiber | The diameter of a circle with an area equal to the average cross-sectional area of the fiber.

Equivalent Flexural Ratio (R_{e3} or $R^{D}_{T,150}$) | The ratio of the equivalent flexural strength (f_{e3} or $f^{D}_{T,150}$) and the flexural strength (modulus of rupture) of the concrete.

Fiber Count | Fiber concentration measured by the number of fibers in a unit volume of concrete.

Fiber Dosage Rate | The total fiber weight in a unit volume of composite (generally expressed as kg/m^3 or lb/yd^3).

Fiber Volume Fraction | The total fiber volume in a unit volume of composite (generally expressed as a percentage).

Fibrillated Fibers | A fiber configuration that has sections of the fiber splitting to form fiber branches.

Flexural Strength | The maximum flexural tensile stress achieved in a beam test, also referred to as the modulus of rupture (MOR).

Limit of Proportionality (LOP) | The point at which a load-deflection or stress-strain curve departs from the initial linear response.

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Mono-filament fibers | A single fiber, which may not be prismatic in cross-section.

Equivalent Flexural Strength (f_{e3} or $f^{D}_{T,150}$) | The flexural residual strength retained by fiber reinforced concrete after cracking from the ASTM C1609 beam testing.

Toughness | The ability of fiber-reinforced concrete to sustain loads after cracking of the concrete, i.e., energy absorption capacity. It should be noted that, in connection with fiber concrete, toughness is to flexural toughness or toughness in bending.

OVERVIEW

Fiber reinforced concrete (FRC) is not a new concept. Since biblical times, fibers were used in cement-based construction materials in the form of straw and horse hair. Today, there are a large variety of fiber options for reinforcing concrete available in the marketplace. These include micro and macro synthetic fibers, steel, and blended fibers, which are defined below. With so many options, it can be difficult to determine exactly what fiber is required for a given application. Examples of existing applications utilizing FRC include ground supported slabs, composite metal deck, pile supported slabs, mat slabs, pavements, bridge decks, tunnel segments, shotcrete, and various precast applications.

FIBER TYPE

The first step to choosing the right fiber is to understand the type of fiber required for your application. The main standard for fiber reinforced concrete is ASTM C 1116.

ASTM C 1116, Standard Specification for Fiber Reinforced Concrete and Shotcrete, outlines four (4) classifications of fiber reinforced concrete:

- Type I - Steel fiber reinforced concrete or shotcrete (ASTM A820)
- Type II - Glass fiber reinforced concrete or shotcrete (ASTM C1666)
- Type III - Synthetic fiber reinforced concrete or shotcrete (ASTM D7508, polypropylene based only)
- Type IV - Natural fiber reinforced concrete or shotcrete (ASTM D7357)

Micro fibers (see Figure 1) have a diameter that is less than 0.3mm. Micro fibers are either monofilament or fibrillated. Micro fibers should be used for plastic shrinkage control (cracking that can occur in the first 24 hours of concrete cure), impact protection, and fire explosive spalling protection. Micro fibers are not a structural reinforcing fiber and cannot be used to replace any structural steel elements, except the fibrillated micro fiber can be used to replace the lightest gage wire fabric (6x6 W1.6/W1.6) in slabs on ground.

Figure 1 | *Micro Fiber - Sika® Fibermesh®-150*

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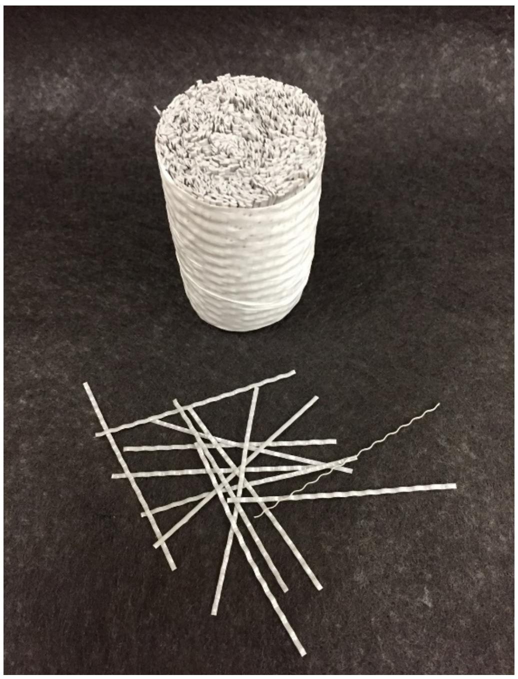

Figure 2 *| Macro Fiber - SikaFiber® Enduro® Prime*

Structural macro fibers (see Figure 2) can be steel or synthetic, have a diameter greater than or equal to 0.3mm. Macro fibers can be used as a replacement of mesh or rebar reinforcement in concrete or shotcrete. Macro fibers can resist tensile stresses and control crack development. Macro fibers are used where an increase in residual (post-cracking) flexural strength is required (ASTM C1609).

There are five types of steel fibers in ASTM A820:

- Type I - Cold Drawn Wire - Typically higher tensile strength due to drawing process (SikaFiber® Novocon® CHE or HE Steel fibers)
- Type II - Cut sheet (SikaFiber® Novocon® CS1000)
- Type III - Melt extracted (Typically not available in marketplace)
- Type IV - Mill cut (Typically not available in marketplace)
- Type V - Modified cold drawn (SikaFiber® Novocon® XR)

There are also blends of micro and macro fibers (see Figure 3). The blends utilize the crack control of both the micro and macro fibers. In short, fiber blends offer control of cracking that can occur in the first 24 hours of concrete cure (micro fiber) and long-term crack control due to loads (macro fibers).

Figure 3*- Blended Fibers - SikaFiber® Novomesh®-950*

FIBER PERFORMANCE

Fiber performance is influenced by three characteristics: tensile strength, aspect ratio (calculated as the length/diameter) and anchorage (hooked, crimp, emboss, fibrillation, etc.). One characteristic does not outweigh another; all three items must work together for optimal performance. Fiber reinforced concrete is a composite material and therefore, all fibers are tested in the concrete to prove their performance.

The higher the tensile strength of the fiber, the better the support structure. The anchorage ensures that the tensile strength of the fiber can be utilized. The higher the aspect ratio, the higher performing the fiber. The longer the fiber length, the more embedment of the fiber in the concrete. If the fiber is too long, it can be hard to mix. There is an optimal length for every fiber. Finally, the smaller diameter means more fibers per pound (higher fiber count), which leads to the ability to obtain more fibers over the crack.

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Steel fibers may be collated (glued) together in a clip (see Figure 4). Macro synthetic fibers may be wrapped or pucked together. The collated or pucked fibers do not improve performance of the fiber reinforced concrete. Collated fibers improve the ease of mixing of high aspect ratio fibers. Collated or pucked fibers are added to the concrete mix and the bundles are spread throughout the concrete. Continued mixing action breaks apart the clips or bundles to let the individual fibers separate quickly throughout the mix.

Figure 4 *| Collated Steel Fibers - SikaFiber® Novocon® CHE6560*

Fibers begin to function in a structural supportive manner when the concrete matrix starts to crack, just like traditional reinforcement. The crack has to occur for the load to switch from the concrete to the reinforcement. Unlike reinforcing bars, fibers are uniformly distributed in the concrete matrix; therefore, the distance between the fibers is much smaller and can intercept the crack much quicker. The fibers then produce ductility and support by bridging cracks and thus providing post crack strength to the concrete.

FLEXURAL TEST OF FIBER REINFORCED CONCRETE

When specifying with fibers for concrete reinforcement, you should not think in terms of dosage (pounds/cubic yard), but overall in toughness, also known as flexural capacity. The toughness and the energy which could be absorbed by the addition of fibers could be computed by determining the area under a stress-strain curve (from flexural strength beam test - ASTM C1609).

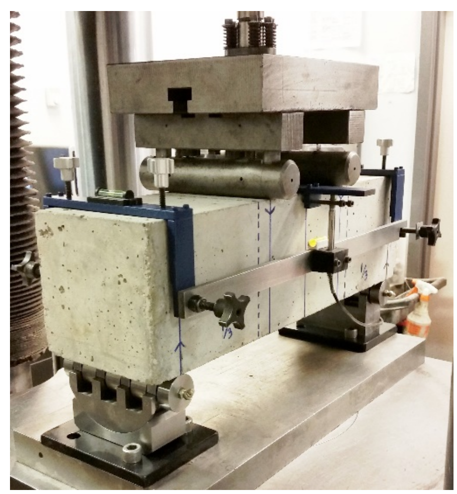

Figure 5 *| ASTM C1609 Beam Test*

The improved toughness from the addition of fibers is generated as the fibers gradually slip out of the concrete matrix. It is thus preferred that pull-out of the fibers occurs instead of fibers breaking. If the fibers break, bond strength (anchorage) between fibers and the surrounding concrete matrix is too high. In order to achieve optimum efficiency of the fibers, the bond strength between fibers and the concrete matrix needs to be as close as possible to the same value as the tensile strength of the fibers, but still less.

The standard industry performance indicator for FRC is the $R^D_{T,150}$ (R_{e3}) or $f^D_{T,150}$ (f_{e3}) value. R_{e3} and f_{e3} are measured with standard beam tests in a third point loading arrangement per ASTM C1609 (see Figure 5, Standard Test Method for Flexural Performance of Fiber Reinforced Concrete using beam with third point loading). ASTM C1609 replaced ASTM C1018, which was withdrawn in 2006. The f_{e3} (equivalent flexural strength) is the average flexural stress to deflect the beam up to 3mm after first crack. The R_{e3} (equivalent flexural strength ratio) is the ratio of the equivalent flexural strength (area under the load deflection curve) and the flexural strength of the concrete. The R_{e3} or f_{e3} values can be used in calculations per published guidelines; such as ACI 544 and ACI 360.

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The fiber supplier is typically asked, per the specifications, to present beam testing from third party certified testing facilities that clearly demonstrate the performance criteria (f_{e3} or R_{e3}) can be met. **Third party beam performance testing is important. Manufacturers should not supply beam testing from their own lab to ensure an impartial result.**

FLEXURAL TOUGHNESS OF FIBER REINFORCED SHOTCRETE

Shotcrete Quality Control is measured via post crack energy absorption testing (also called toughness) expressed in Joules. Toughness is tested using the ASTM C1550 Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (see Figure 6). The test was designed to replicate the typical shotcrete loading conditions. Fiber suppliers should supply documentation from third party testing facilities that their fiber can meet the required joule specification using one of these tests.

Figure 6 *| ASTM C1550 Shotcrete Round Panel Test*