FIP 8 – Design and Specification of Fiber-Reinforced Concrete

Increasingly, fibers are being used to replace temperature and shrinkage reinforcement in concrete and, in some applications, primary reinforcement. Several useful documents on fiber-reinforced concrete (FRC) have been developed by ACI Committee 544, Fiber-Reinforced Concrete, including a design guide, ACI 544.4R. Criteria for the use of steel fibers as shear reinforcement is now provided in ACI 318; and guidelines for fiber-reinforcement in non-structural applications are provided in other ACI publications such as ACI 360R, "Guide to the Design of Slabs-on-Ground" and ACI 506.1R, "Guide to Fiber-Reinforced Shotcrete." This FIP summarizes the design aspects of FRC and presents basic equations for design and guidelines for specifying fiber-reinforced concrete. Although several types of fibers are commercially available, the term "fibers" in this bulletin only refers to macrofibers, either steel or synthetic. Therefore, the design equations in this bulletin are only applicable to steel and synthetic macrofibers used in FRC that comply with ASTM C1116/C1116M.

Design of Fiber-Reinforced Concrete

Most often, fibers do not change the behavior of uncracked concrete. However, after cracking fibers bridge the cracks and carry the tensile stresses; providing load-bearing capacity to FRC in its cracked state. This is usually referred to as "residual strength" or post-crack strength. The level of this residual strength depends on the fiber material type and its properties, size, geometry, bond characteristics, dosage and, more importantly, their combined effect in hardened concrete.

Therefore, to characterize FRC, flexural tests are performed and post-crack parameters derived from the tests are used in design. The most common and preferred flexural test for FRC in North America is ASTM C1609/C1609M. In this test, the complete pre-crack and post-crack response of a 6-in. x 6-in. x 20-in. (150-mm x 150-mm x 500-mm) FRC beam loaded to a net deflection of 3 mm is obtained and the flexural residual strength at two deflection points, 0.75 mm and 3 mm, are determined. The flexural residual strength at a net deflection of 0.75 mm (1/600th of the span length between the supports) is referred to as f_{600}^{150} and that at 3 mm (1/150th of the span) as f_{150}^{150}. The latter parameter is commonly used in FRC design. It should be noted that while it is preferable to test panels for post-crack performance in shotcrete applications, 4-in. (100-mm) beams are sometimes obtained from the panels for testing.

Based on published research and now an accepted criterion, the tensile residual strength of FRC in ultimate limit state is approximately 0.37 times its flexural residual strength (Equation 1), which is obtained from a beam test. This equation can be used for converting steel bar or welded-wire mesh reinforcement to fiber reinforcement based on the tensile capacity.

$$f_{t-FRC} = 0.37 \times f_{150}^{150} \qquad \text{Equation (1)}$$

The moment capacity of FRC is also calculated based on its residual strength. For ultimate limit state design, the nominal moment of FRC is calculated using Equation 2 in which "b" is the width (or unit width) and "h" is the height of the concrete section. For continuously supported FRC members such as slabs-on-ground and shotcrete, an equivalent flexural strength, f_{e3}, that represents the total energy absorption, or flexural toughness, in a beam test at a deflection of 3 mm can be used in lieu of f_{150}^{150} in Equation (1) and (2).

$$M_{n-FRC} = f_{150}^{150} \times \frac{b.h^2}{6} \quad \text{Equation (2)}$$

Note: The design moment capacity of FRC, $\varphi.M_{n\text{-}FRC}$, should be greater than the factored applied moment, M_u.

For the design of slabs-on-ground with fiber reinforcement, ACI 360R Chapter 11 provides detailed information and calculations. The load capacity of a slab-on-ground is a function of its thickness, the subgrade modulus and the interaction between the slab and the subgrade. Based on a realistic assumption that concrete slabs crack, redistribution of stresses and the development of plastic hinges of cracked concrete sections can be a key factor in design. Macrofibers can contribute to stress redistribution and, consequently, enhance the flexural toughness of the slab after cracking. Therefore, a toughness parameter called "residual strength ratio" or $R_{T,150}^{150}$ (also referred to as R_{e3}) is commonly used. As shown in Equation 3, this parameter is the ratio of f_{e3}, the equivalent flexural strength (after cracking), and f_r, the measured flexural strength (at cracking). For a given concrete mixture with known flexural strength, higher dosages of macrofibers will provide higher toughness values.

$$R_{e3} = \frac{f_{e3}}{f_r} \quad \text{Equation (3)}$$

Yield-Line method is typically used for incorporating the FRC design for slabs-on-ground after cracking. It should be noted that slabs can crack for a variety of reasons such as plastic and drying shrinkage to thermal stresses or under ultimate loads. The value of R_{e3} can be calculated for a given slab with known subgrade modulus and the applied loads. Slab thickness may be reduced for significantly higher R_{e3} values.

Specifying Fiber-Reinforced Concrete

The specification of fiber-reinforced concrete should be performance-based and dependent on the application. Fibers should be specified based on the desired engineering performance if the purpose of fiber-reinforcement is to provide post-crack flexural and tensile capacity to a concrete section. Once proper calculations are conducted for the design of FRC, parameters such as residual strength must be used for specification. For example, use fiber at a dosage to provide a minimum residual strength, f_{150}^{150}, of 200 psi (1.4 MPa) in a 4,000 psi (28 MPa) concrete mixture. The fiber dosage will be determined based on ASTM C1609/C1609M data for specific fiber products in a concrete mixture with similar compressive strength. FRC can also be specified based on serviceability to meet specific crack widths instead of the deflection criteria used in ASTM C1609/C1609M. This alternate approach is mainly used for underground structures and other precast structures. For this case, a European notched beam test (BS EN 14651) is typically performed to determine the residual strength at given crack widths. In specifying FRC, other concrete properties such as compressive strength, flexural strength or shrinkage may also be specified for certain applications. For more information on the specification of FRC, refer to ACI 544.3R-08.

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Suggested Specification for Post-Crack Performance of Fiber-Reinforced Concrete

A. Steel Fibers

1. Shall conform to ASTM C 1116/C 1116M, Type I containing steel fibers meeting the criteria of ASTM A820/A820M, Type I, Type II, or Type V.
2. Shall provide a minimum average equivalent flexural strength, $f_{e,3}$, of ____ psi when tested in accordance with ASTM C 1609/C 1609M, using the roller support system in ASTM C1812/1812M.
3. Dosage shall be as recommended by the manufacturer.

B. Synthetic Macrofibers:

1. Shall conform to ASTM C 1116/C 1116M, Type III containing synthetic macrofibers meeting the criteria of ASTM D7508/D7508 for macro-chopped strands or hybrids chopped strands.
2. Shall provide a minimum average equivalent flexural strength, $f_{e,3}$, of ____ psi when tested in accordance with ASTM C 1609/C 1609M, using the roller support system in ASTM C1812/1812M.
3. Dosage shall be as recommended by the manufacturer.

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References

1. ACI 360R-10 “Guide to the Design of Slabs-on-Ground”
2. ACI 506.1R, “Guide to Fiber-Reinforced Shotcrete”
3. ACI 544.3R-08 “Guide for Specifying, Proportioning, and Production of Fiber Reinforced Concrete”
4. ACI 544.4R-18 “Design Guide for Fiber-Reinforced Concrete”
5. ASTM C1116/C1116M-10 “Standard Specification for Fiber Reinforced Concrete”
6. ASTM C1812/C1812M-15, “Standard Practice for Design of Journal Bearing Supports to be Used in Fiber Reinforced Concrete Beam Tests”
7. ASTM C1609/C1609M-12 “Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)”
8. BS EN 14651: “Precast concrete products – test method for metallic fiber concrete – measuring the flexural tensile strength”

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