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Report on Measuring Mechanical Properties of Hardened Fiber-Reinforced Concrete

Reported by ACI Committee 544

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This report provides a synopsis of the existing testing methodologies for the determination of mechanical properties of hardened fiber-reinforced concrete (FRC). This report applies to the mechanical properties of conventionally mixed and placed FRC, including fiber-reinforced self-consolidating concrete (FRSCC), or fiber-reinforced shotcrete (FRS) using steel, glass, polymeric, and natural fibers.

The objective is to enable manufacturers to characterize the mechanical properties of hardened FRC and encourage researchers and testing laboratories to adopt common and unified test methods to build a meaningful database of mechanical properties of hardened FRC materials and products. Test results from the test procedures used in this report are not intended for the design of FRC structures, but to gain a better understanding of factors influencing the determination of their mechanical properties and of FRCs and FRC products.

Keywords: compressive strength; fiber pullout; fiber-reinforced concrete; flexural fatigue resistance; flexural strength; impact resistance; multiaxial behavior; shear and torsion; tensile strength; toughness.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The use of fiber-reinforced concrete (FRC) has evolved from small-scale applications to routine factory and field applications that involve the global use of tens of millions of cubic yards (meters) annually. This growth of application, in conjunction with new fibers, admixtures, and mixture designs, has created an urgent need to review existing test methods and, where necessary, develop new methods for determining the fresh and hardened properties of FRC.

1.2—Scope

This report documents the determination of mechanical properties of hardened FRC. The objective is to characterize these mechanical properties and encourage common and unified test methods. This objective builds a meaningful database of mechanical properties of hardened FRC materials and products. Further, the results should not be taken out of the context presented for illustrating the tests and not for comparing fibers out of context. The results from the tests and procedures used in this document are not intended to be used for the design of FRC structures. The purpose of this document is to gain a better understanding of the many factors influencing tests for the determination of mechanical properties of FRCs and FRC products.

Although most of the test methods described in this report were developed initially for steel FRC (SFRC), they are applicable to concretes reinforced with glass, synthetic/polymeric, and natural fibers, except when noted. In Fig. 1.2, an example of different types of fibers commonly employed in FRC is provided.

This report applies to the mechanical properties of conventionally mixed and placed FRC or fiber-reinforced shotcrete (FRS) using steel, glass, synthetic/polymeric, and cellulose/natural fibers.

Some newer test methods and evaluation procedures under development are not included in this report. Examples of this are tensile creep and flexural creep of concrete where the section has cracked and the bridging fibers are carrying loads.

This report does not discuss test methods for thin glass FRC or mortar products produced by the spray-up process. The Prestressed Concrete Institute (PCI MNL 128) and the International Glassfibre Reinforced Cement Association (2016a,b) have prepared recommendations for test methods for these spray-up materials.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

a, b = dimensions, in. (mm)
b = width, in. (mm)
d = depth, in. (mm)
d_f = fiber diameter, in. (mm)
f_1 = first cracking nominal stress (as from results of flexural tests according to ASTM C1609/C1609M), psi (MPa)

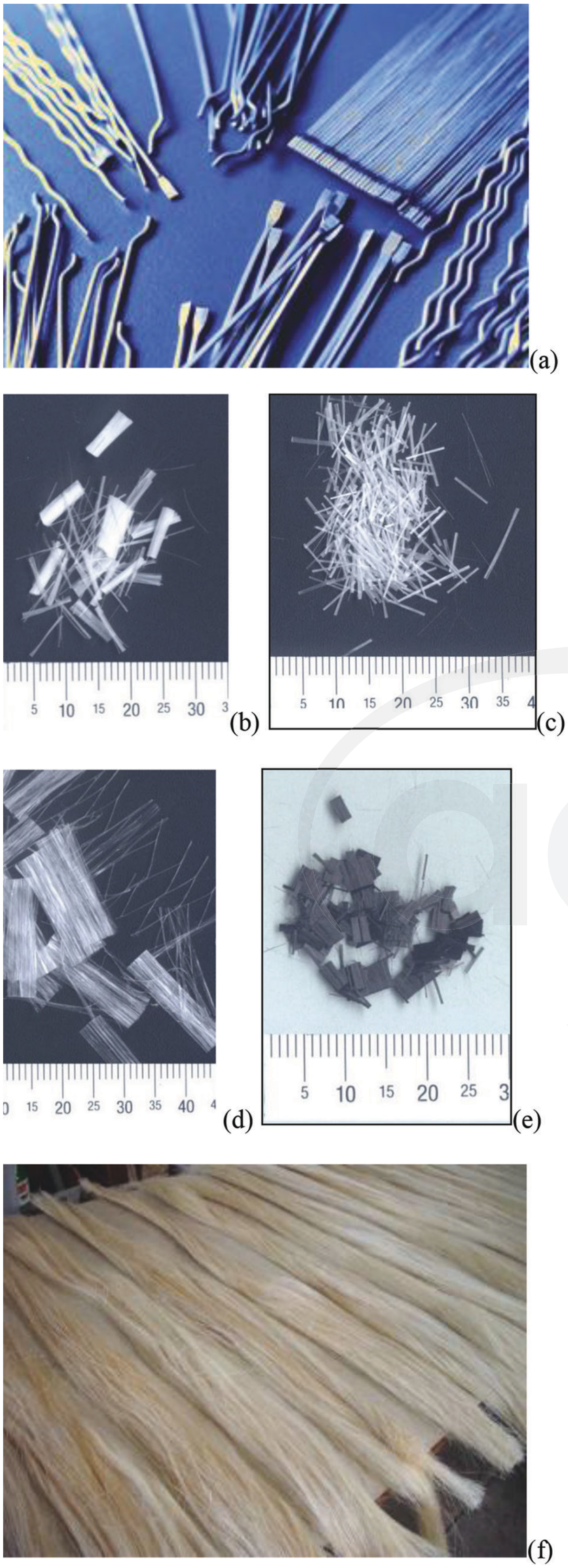

Fig. 1.2—Examples of different types of fibers used in FRC: (a) steel (with hooked ends, flattened ends, corrugated/undulated); (b) through (c) synthetic/polymeric microfibers; (d) glass; (e) carbon; and (f) natural; dimension scale where provided is in mm. (N

f_{150} = residual nominal bending strength corresponding to P_{150}, psi (MPa)
f_{600} = residual nominal bending strength corresponding to P_{600}, psi (MPa)
f_{eq} = equivalent nominal flexural strength, calculated with reference to predefined crack opening range, from nominal flexural stress versus crack opening curves obtained from flexural tests, psi (MPa)
f_p = peak nominal stress (as from results of flexural tests according to ASTM C1609/C1609M); may coincide with or be higher than f_1, psi (MPa)
f_R, f_{Rj} = residual nominal flexural strength, at a specified value of the crack mouth opening displacement, as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
f_{R1} = residual nominal flexural strength, at CMOD = 0.02 in. (0.5 mm), as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
f_{R1k} = characteristic value of f_{R1}
f_{R2} = residual nominal flexural strength, at CMOD = 0.06 in. (1.5 mm), as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
f_{R3} = residual nominal flexural strength, at CMOD = 0.10 in. (2.5 mm), as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
f_{R3k} = characteristic value of f_{R3}
f_{R4} = residual nominal flexural strength, at CMOD = 0.14 in. (3.5 mm), as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
h = specimen height, in. (mm)
L = length, span, in.-ft. (mm); also gauge length, in. (mm)
l_f = fiber length, in. (mm)
P = load, lbf (N)
P_1 = first cracking load (as from results of flexural tests according to ASTM C1609/C1609M), lbf (N)
P_{150} = residual load measured in flexural tests as per ASTM C1609/C1609M in correspondence of a midspan net deflection equal to 1/150 of the specimen length, lbf (N)
P_{600} = residual load measured in flexural tests as per ASTM C1609/C1609M in correspondence of a midspan net deflection equal to 1/600 of the specimen length, lbf (N)
P_p = peak load (as from results of flexural tests according to ASTM C1609/C1609M); may coincide with or be higher than P_1, kip (kN)
T_{150} = area under the load deflection curve obtained from flexural tests as per ASTM C1609/C1609M up to a value of the net deflection equal to 1/150 of the specimen length, in.-lb (J)
V_f = fiber volume fraction (generally expressed in percent)
δ = deflection, in. (mm)
θ = angle, deg

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology", http://

www.concrete.orgstoreproductdetails.aspx?ItemID=CT16. Definitions provided herein complement that resource.

aspect ratio—ratio of the length to the diameter of one single fiber or fiber filament. The diameter may be the actual or **equivalent diameter**, defined below.

crack—complete or incomplete separation of concrete in to two or more parts produced by breaking or fracturing.

equivalent diameter—for fibers with noncircular cross section, diameter of the equivalent circular cross section having the same area as the fiber cross section.

equivalent flexural residual strength—average flexural stress measured for an FRC beam based on the toughness, up to a specified deflection (or crack width).

fiber—slender and elongated solid material, generally with a length of at least 100 times its diameter; four primary types are defined generally by ASTM C1116/C1116M as follows: steel: ASTM A820/A820M; chopped polyolefin strand (synthetic or polymeric): ASTM D7508/D7508M; glass: ASTM C1666/C1666M; and cellulose/natural: ASTM D7357.

fiber volume fraction—total fiber volume in a unit volume of concrete (generally expressed as a percentage).

ligament—fracture cross section in a specimen, generally highlighted by the presence of one notch or two opposed notches, in prismatic specimens, or a circumferential notch, in cylinder specimens.

Mode I fracture—fracture mode where crack propagation occurs because of a uniaxial tensile stress state orthogonal to the crack plane.

residual flexural strength—flexural strength retained in a cracked fiber-reinforced concrete beam, typically measured at a certain deflection or crack width.

toughness—ability of fiber-reinforced concrete to sustain loads after cracking of the concrete, as described by its energy absorption capacity; in connection with fiber-reinforced concrete, the term "toughness" typically refers to flexural toughness or toughness in a bending test.

CHAPTER 3—SAMPLING AND SPECIMEN PREPARATION

3.1—General

In general, procedures outlined in ASTM C31/C31M, C42/C42M, C192/C192M, and C1609/C1609M as well as EN 12350-1, EN 12390-1, EN 12390-2, and EN 14651 should be followed for specimen preparation. Additional guidance for preparing fiber-reinforced shotcrete specimens is available in ACI 506.2. Test specimens should be prepared using external vibration whenever possible. Internal vibration is not desirable and rodding is not acceptable, as these methods of consolidation may produce preferential fiber alignment and nonuniform fiber distribution that may cause variance in the results. Although external vibration may produce some alignment of fibers, its influence is generally negligible because of the short duration of vibration required for consolidation of test specimens. The method, frequency, amplitude, and time of vibration should be recorded.

Consistent test specimen preparation and testing can reduce variance as consistently biased. Consistency helps to identify any influence by knowing what was done differently to produce bias in the results. Some test methods provide procedures for specimen preparation.

3.2—Test specimens

Test specimens should be cast in a single layer to avoid the reorientation of the fibers or fiber-free planes. Whenever a single dump method is not used to fill formwork, care should be used to avoid placing concrete in a manner that produces a lack of fiber continuity between successive placements. The preferred placement method is use of a wide shovel or scoop to place each concrete layer uniformly along the mold length. Any preferential fiber alignment by the mold surfaces can influence test results, particularly for small cross sections with long fibers. Generally, the smallest specimen dimension should be at least three times larger than the fiber length. Recommendations for selecting specimen size and preparing test specimens for flexural toughness tests are given in ASTM C1399/C1399M, ASTM C1609/C1609M, EN 14651, and EN 14889-2.

3.3—Sample size

Because statistical variation in the measured mechanical properties can be particularly high among samples with different fiber dispersion, fiber orientation, or both, more samples may be needed than for plain concrete for the same mechanical property and test to obtain a statistically representative set of results or lower variation on properties.

CHAPTER 4—COMPRESSIVE STRENGTH, MODULUS OF ELASTICITY, AND POISSON'S RATIO

4.1—General

Standard compressive strength testing procedures (ASTM C39/C39M; EN 12390-3) used for conventional concrete can be used for FRC as well. ASTM C469/C469M and EN 12390-13 tests for modulus of elasticity and Poisson's ratio are also applicable to FRC. The cylinders should be 6 x 12 in. (150 x 300 mm) or 4 x 8 in. (100 x 200 mm) (diameter x height) in size and made using external vibration. Smaller specimens are not recommended, specifically with macrofibers that are longer, stiffer, or both, because of likely induced preferred orientation.

The presence of fibers can alter the mode of failure of cylinders, and be helpful in avoiding spurious shear type failure in plain concrete, thus obtaining a failure mode characterized by finer cracks parallel to the applied stress (Fig. 4.1a). The higher the fiber factor $V_f l_f / d_f$, the more pronounced the change in a failure mode (Ou et al. 2012) that actually causes the concrete response to be less brittle. Significant post-peak strength can be retained with increasing deformation beyond the maximum load, as a function of fiber type, dosage, and aspect ratio (Fig. 4.1b). Because smaller cylinders give higher strengths for conventional concrete and promote preferential fiber alignment in FRC, small cylinders with long fibers could result in unrealistically high compressive strengths.