ACI 544.2R-17

Report on the Measurement of Fresh State Properties and Fiber Dispersion of Fiber-Reinforced Concrete

Reported by ACI Committee 544

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First Printing
May 2017
ISBN: 978-1-945487-64-4

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The committee would like to thank R. Lequense and M. Porter for their contributions to this report.

This report outlines existing procedures for testing and measuring fresh state performance and fiber dispersion in fiber-reinforced concrete (FRC). As for the former, test methods applicable to both ordinary vibrated FRC and fiber-reinforced self-consolidating concrete (FR-SCC) are reviewed. Methods for nondestructive monitoring of fiber dispersion and orientation in FRC materials and structures are also presented and their pros and cons addressed.

Keywords: fiber dispersion; fiber-reinforced concrete; fiber-reinforced self-consolidating concrete; fresh state performance; nondestructive testing.

CONTENTS

ACI 544.2R-17 supersedes ACI 544.2R-89 and was adopted and published May 2017.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The use of fiber-reinforced concrete (FRC) has evolved from experimental small-scale applications to routine factory and field applications involving the use of tens of millions of cubic yards (meters) each year globally. This has created a need to review existing test methods and, where necessary, develop new methods for determining the fresh and hardened properties of FRC that may be of interest for different engineering applications and may be required at different stages of the design, construction, and maintenance process. These methods are presented in an effort to standardize test procedures and equipment, and also to ensure that test results from different sources can be compared effectively. Whereas it is recognized that the use of procedures and equipment other than those discussed in this report may be employed because of past practices or availability of equipment, the use of standard tests facilitates the comparison of information, promotes the development or broadening of the data base needed to consistently quantify properties of the various types of FRC, and is preferable to nonstandard variants. Such data are also instrumental in developing consistent and internationally recognized design procedures that are based on standard measurements of relevant properties of the material, as well as in formulating reliable performance criteria to classify and accept the material.

Although most of the test methods described in this report were developed initially for steel FRC (SFRC), they are also applicable to concretes reinforced with glass, polymeric, and natural fibers, except when noted.

As the applications of FRC are being expanded and new fibers are introduced to the market, some existing test methods may be found insufficient or unable to provide meaningful data. Therefore, changes can be applied and, in these instances, care taken in consideration of the issues of repeatability and reproducibility of test results. Repeatability is defined as the variability among replicate test results obtained on the same material within a single laboratory or job site by one operator. Reproducibility refers to variability among test results obtained on the same material in different laboratories, job sites, or both. Regarding reproducibility, users are advised to carefully check the applicability of the test methods, both in lab conditions and in the field, as differences may exist between them.

1.2—Scope

This report applies to the measurement of fresh state and fiber-dispersion properties of both conventionally mixed and placed (vibrated) FRC and fiber-reinforced self-consolidating concrete (FR-SCC) using steel, glass, polymeric carbon, minerals (such as basalt), and natural fibers.

The test methods reported herein are also applicable to ultra-high-performance concrete (UHPC). It is worth remarking that, generally, UHPC does not contain coarse aggregates and is employed in combination with reduced or no amounts of conventional reinforcement. In view of this, care should be taken in assessing the significance of the results, as far as the consistency is concerned, of the volume of material employed in the tests with reference to the heterogeneity scale of the mixture (maximum aggregate size, maximum fiber length). Moreover, passing ability tests, such as the ones reviewed in 3.2.2, may also provide information of limited significance.

This report does not relate to thin glass FRC or mortar products produced by the spray-up process. The Prestressed Concrete Institute (1981), International Glassfibre Reinforced Concrete Association (2016a,b), and ASTM C1116/C1116M contain recommendations for test methods for these spray-up materials.

Measurement of the properties of fiber-reinforced shotcrete (FRS) that contain the aforementioned fiber types can be performed using the test methods described herein. Special procedures may be required to cast specimens or obtain them from existing structures, as well as to measure properties specific to shotcreting technology. Relevant provisions can be found in ACI 506.2.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

c = clear gap spacing in L-box test
d_f = fiber diameter, in. (mm)
d_{max} = maximum diameter of the flow spread in J-ring test, in. (mm)
d_{perp} = diameter measured perpendicular to the maximum diameter d_{max} in J-ring test, in. (mm)
l_f = fiber length, in. (mm)
R = electrical resistivity of fiber-reinforced concrete or fiber-reinforced cementitious composite, ohm
R_m = electrical resistivity of the parent plain concrete (matrix), ohm
T_{20} or T_{500} = time for the flow spread to reach a diameter of 20 in. (500 mm) in slump flow test, s (in European literature, it has been referenced as T_{50}, where 50 represents the threshold diameter in cm)
T_{final} = time for the flow spread to reach the final slump-flow diameter in slump flow test, s
T_V = V-funnel flow time, that is, time for the fluid concrete filling the funnel to completely come out once the nozzle of the funnel is opened, s
V_f = fiber volume fraction (generally expressed in percent)
γ = filling capacity in filling box test

$\dot{\gamma}$ = shear strain rate, applied to a fluid (in a rheometer test), s^{-1}

μ = plastic viscosity (in Bingham fluid model), that is, resistance of the fluid (concrete) to flow once the value of the yield stress has been overcome, psi·s (Pa·s)

σ = electrical conductivity of fiber-reinforced concrete or fiber-reinforced cementitious composite – inverse of R (Siemens)

$[\sigma_{fiber}]$ = intrinsic conductivity of fiber (Siemens)

σ_m = electrical resistivity of the parent plain concrete (matrix) – inverse of R_m

τ = shear stress applied to a fluid (in a rheometer test), psi (Pa)

τ_0 = yield stress, that is, value of the shear stress that has to be overcome for the fluid (concrete) to start flowing (in Bingham fluid model), psi (Pa)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," https://www.concrete.org/store/productdetail.aspx?ItemID=CT13. Definitions provided herein complement that source.

dynamic segregation—in a fluid concrete flow, separation of concrete constituents along the flow direction as a function of their specific gravity (heavier constituents tend to lag behind because of insufficient viscosity of the suspending phase to drag them ahead).

fiber aspect ratio—ratio of the length to the diameter of one single fiber or fiber filament.

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

fiber factor—product between the fiber volume fraction and the fiber aspect ratio.

specific surface area—total lateral surface area of a unit mass quantity of a given powder type/granular material or assortment of materials; it depends on the grain size distribution of the particles and on the specific gravity of the material.

static segregation—separation, in a fluid concrete mixture when at rest, of its constituents, as a function of their relative specific gravity (heavier constituents tend to settle because of insufficient yield stress of the suspending phase to hold them in suspension).

CHAPTER 3—FRESH STATE PROPERTIES

3.1—Sampling, unit weight, yield, and air content

To perform the tests described in this chapter to measure the fresh state properties of fiber-reinforced concrete (FRC), the sampling procedures outlined in ASTM C172/C172M and EN 12350-1 for conventional concrete should be applied.

Similarly, standard test equipment and procedures used for conventional concrete can be employed for determining the air content, yield, and unit weight of FRC (ASTM C138/C138M; ASTM C173/C173M; ASTM C231/C231M; EN 12350-6; EN 12350-7). Because of the alteration in fiber dispersion and orientation that may result from specimen preparation, the specimen molds should be filled in one lift. Consolidation may result in alteration in fiber dispersion and orientation. Because of this, samples should be consolidated, when applicable, using external or internal vibration as permitted by ASTM C31/C31M and ASTM C192/C192M only when the fiber orientation is not an issue, regarding the performance to be measured. Rodding should not be applied.

3.2—Workability and fresh state performance

3.2.1 *Workability tests for conventional vibrated FRC*—Workability is defined as that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogeneous condition. The presence of fibers can result in specific issues that require incorporation into the broad definition of workability, as stated previously and in related measuring techniques. This will be addressed more in this report. Workability is generally assessed using the following simple field tests.

3.2.1.1 *Slump test*—The slump test (ASTM C143/C143M; EN 12350-2) is a common, convenient, and inexpensive test, but it may not be a good indicator of workability for FRC. The addition of fibers hinders the flow behavior of fresh concrete, especially if no adjustment is made to the mixture composition (Bayasi and Soroushian 1992). An example is the rearrangement of coarse aggregate grading in consideration of the effects of fibers on the void ratio of the solid particle skeleton (Ferrara et al. 2007). Therefore, the addition of fibers can lead to a decrease in the measured slump with increasing the fiber factor, which is the product of the fiber volume fraction and the fiber aspect ratio. The rate of change in the measured slump with the fiber factor is directly related to the fiber type (Mangat and Swamy 1974; Swamy and Mangat 1974; Hughes and Fattuhi 1976; Bayasi and Soroushian 1992). In this respect, because slump is a simple visual measurement, the exact meaning of the measured slump may become questionable if merely compared to that of the mixture with no fibers. The real workability of a FRC can be better evaluated by measuring, for example, the mixing energy required to work the given FRC to the target casting condition (Chopin et al. 2004; Cazacliu and Roquet 2009). However, once it has been established by preliminary testing that a specific FRC mixture has satisfactory handling and placing characteristics at a given slump, with respect to the intended application, the slump test may be used as a quality control test to monitor the FRC consistency from batch to batch.

3.2.1.2 *Vebe test*—The Vebe consistometer test, described in EN 12350-3, measures the behavior of concrete subjected to external vibration and is acceptable for determining the workability of concrete placed using vibration, including FRC. It effectively evaluates the ability of FRC to flow under vibration, and helps to assess the ease with which entrapped air can be expelled.

The apparatus is placed on top of a vibrating table. The fresh concrete is compacted into a conical slump mold. The mold is removed and a clear plastic disc is placed on the top of the concrete. The vibrating table is started and the time taken for the transparent disc to be fully in contact with the concrete (the Vebe time), is measured. Similar to the slump test, the