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SI

International System of Units

Measuring Shrinkage, Creep, and Transport Properties of Fiber- Reinforced Concrete— Report

Reported by ACI Committee 544

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Measuring Shrinkage, Creep, and Transport Properties of Fiber-Reinforced Concrete—Report

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Measuring Shrinkage, Creep, and Transport Properties of Fiber-Reinforced Concrete—Report

Reported by ACI Committee 544

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Fiber-reinforced concrete (FRC) has become a viable choice for many designers and builders for the unique properties and advantages it provides. From slabs-on-ground to underground structures, the use of FRC has been expanding in concrete construction. This growth of applications has created the need to review the existing test methods for FRC and, where necessary, develop new ones. Two reports (ACI 544.2R and ACI 544.9R) have already been published regarding testing fresh properties and mechanical properties of FRC, respectively. This report is the third and final report on testing FRC for its durability properties, including shrinkage, creep, and permeability. Several standard and nonstandard test methods are presented in this report to represent some of the knowledge in this area.

Keywords: creep; durability; fiber-reinforced concrete; shrinkage; testing; transporting.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Some of the key properties of concrete structures vary as a function of time and the environment. These include, but are not limited to, shrinkage, creep, and transport properties such as permeability and diffusion. Fibers show a positive impact in improving the long-term durability (ACI 544.5R) and sustainability aspects of concrete (Cutright et al. 2013). As described in this report, fibers can help reduce and limit restrained shrinkage cracking, which may occur in concrete with a large, exposed surface such as slabs. These applications are susceptible to rapid changes in temperature and humidity, resulting in high water evaporation and higher potential for shrinkage cracking. Another example is the use of fibers in applications where sustained loads and creep stresses can be critical in the service life of the structure. Bridge deck overlays, environmental structures, and tunnel linings are some of the applications where fiber reinforce-

ment has been used successfully to enhance the long-term performance and durability of concrete (ACI 544.4R). To ensure structural integrity and proper serviceability, most building codes limit the allowable crack widths in the range of 0.006 to 0.015 in. (0.15 to 0.38 mm) for concrete structures exposed to weathering and fibers can be beneficial in maintaining such allowances (ACI 544.10). Fibers bridge cracks in a three-dimensional distributed manner because they are present throughout the body of concrete, whereas reinforcing bars control cracks more locally (Hubert et al 2015). Cracks may occur as a result of over-stressing or time-dependent stresses such as shrinkage and creep discussed in this report.

Fibers come in different material types, geometries, and sizes and typically range from 1/8 to 2.5 in. (3 to 65 mm) in length and are classified according to ASTM C1116/C1116M. These fiber material types include steel, glass, synthetic, and natural, as well as blended fibers. A sub-classification is often used based on the size and functionality of the fibers; hence, fibers can be classified as microfibers or macrofibers with the fiber diameter of 0.012 in. (0.3 mm) as the separating limit as defined by ASTM D7098/D7508M. Adding fibers to concrete can change its post-crack response from brittle to ductile under various types of loads, including compression, tension, flexure, and impact (ACI 544.4R). After cracking, fibers bridge the cracks and start to carry tensile stresses, commonly referred to as post-crack residual strength. More information on the mechanisms of FRC and related design guides can be found in ACI 544.4R. The presence of fibers will help with reducing and controlling the crack width and,

Table 1.1—Summary of the test methods presented in this report and their applicability to FRC

Property	Test	Description	Application to FRC
Shrinkage properties	Unrestrained, ASTM C157/C157M	Free (unrestrained) drying shrinkage of prismatic specimens	Not effective for studying macrofibers, as concrete does not crack*
	Restrained, ASTM C1579	Restrained plastic shrinkage of rectangular panels using stress risers	Effective in studying FRC for crack reduction in a comparative way. Quicker test.
	Restrained, ASTM C1581/C1581M	Restrained drying shrinkage of concrete cast around a steel ring	Effective in studying FRC for crack reduction and time of cracking in a comparative way. Longer test.
	Restrained, other	Restrained plastic shrinkage of square panels using a vacuum system	Effective in studying FRC for crack reduction in a comparative way.
Creep properties	Flexural: Beams	Precracking beams, followed by creep test at a specific percentage of residual stress (ASTM C1399/C1399M, C1609/C1609M, BS EN 14651)	Effective in studying FRC for cracked sections up to a known stress value. Test can take a long time.
	Flexural: Panels	Precracking round panels, followed by creep test at a specific percentage of residual stress (ASTM C1550)	Effective in studying FRC for cracked sections up to a known stress value. Test can take a long time.
	Direct tension	Direct tension test on precracked specimens (prismatic or cylindrical). Compression test. Fiber pullout test under creep load.	Useful in studying FRC if conducted correctly. Proper direct tension test is very difficult to perform for concrete.
Transport Properties	Chloride diffusion, ASTM C1202	Electrical indication of concrete’s ability to resist chloride ions ingress using cylinders.	Not effective for studying fibers, as concrete cannot be cracked.
	Chloride diffusion, ASTM C1556	Bulk chloride diffusion profile and coefficient using concrete cylinders. Can precrack cylinders using splitting tensile test.	Useful in studying FRC for precracked specimens and determining the role of fibers in reducing crack width and diffusion.
	Chloride diffusion, other	Bulk chloride diffusion profile and coefficient using concrete beams. Can precrack beams using FRC flexural tests.	Useful in studying FRC for precracked specimens and determining the role of fibers in reducing crack width and diffusion.
	Water permeability	Create water head (pressure) to flow water into a precracked concrete specimen (cylinder, beam, or panel).	Effective in studying FRC for precracked specimens and determining the role of fibers in reducing crack width and water flow rate and permeability.

*Synthetic microfibers may reduce bleeding and therefore can help reduce the plastic shrinkage of concrete. Refer to Section 3.2 for more information.

hence, improve the performance of concrete under shrinkage, creep, and environmentally induced stresses (ACI 544.5R). This report presents several standard and nonstandard test methods that have been used for determining and quantifying the effectiveness of fiber reinforcement in improving durability characteristics. A summary of the presented test methods in this report for measuring shrinkage, creep, and transport properties of FRC is shown in Table 1.1.

1.2—Scope

This is a report on the current knowledge on testing time-dependent properties of FRC, including shrinkage, creep behavior, and transport properties that affect the long-term durability. The objective of this report is to review some standard and nonstandard test methods available in the literature for better evaluating these properties. This document has summarized various published experiments; the results are presented to illustrate the test methodologies and should not be taken out of context or used for evaluating specific fibers. The results from the tests used in this document are not intended for direct use in design of FRC structures. The purpose of this document is to provide a better understanding of the many factors influencing test results for the determination of such properties. This report applies to shrinkage, creep, and transport properties of conventional FRC using fibers classified in ASTM C1116/C1116M. This report excludes test results for ultra-high-performance concrete (UHPC) or engineered cementitious composites (ECCs), both with elevated dosages of fibers. However, these tests may still be applicable to UHPC and ECC materials. The specific effects of concrete rheology and fiber orientation are also outside of the scope of this report; more information can be found elsewhere (Khayat et al. 2014; Kasim, and Khayat 2021).

CHAPTER 2—DEFINITIONS

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

diffusion—movement of species (ions, gas, or vapor) from an area of higher concentration to an area of lower concentration independent of the bulk motion of a fluid.

residual flexural strength—flexural strength retained in a cracked FRC beam, measured at a certain deflection or crack width.

CHAPTER 3—TESTING SHRINKAGE OF FRC

3.1—Shrinkage in concrete and FRC

Shrinkage of concrete is the reduction in volume caused by the loss of water or chemical reactions and can take place under various circumstances such as plastic shrinkage, autogenous shrinkage, carbonation shrinkage, and drying shrinkage (ACI 224R). When concrete is fresh (plastic), the tensile strength of the material is too low, and cracking can occur as a result of small shrinkage-induced stresses. More information on early-age cracking of concrete and its measurement techniques can be found in ACI 231R.

Typical strain value for hardened concrete in direct tension is in the range of 100 to 150×10^{-6} (Gopalaratnam and Shah 1985) and typical drying shrinkage strain of concrete is in the range of 300 to 600×10^{-6} (ACI 223R). These values can be reduced using shrinkage-reducing/compensating admixtures; however, cracking is expected in concrete when its strain limits are reached. Fibers can provide the additional strain and load-bearing capacity needed for resisting shrinkage stresses and controlling potential cracking (ACI 544.4R).

Concrete can contract under free (unrestrained) shrinkage without cracking; however, when concrete is restrained, it will go under shrinkage stresses and may experience cracking as shown schematically in Fig. 3.1a. This is important in measuring the cracking potential of concrete and the effectiveness of fibers in controlling shrinkage cracks. Fiber reinforcement will limit the extent of restrained shrinkage cracking by limiting the crack width in concrete elements (Shah and Weiss 2006). Synthetic microfibers and cellulose fibers can be beneficial for controlling plastic shrinkage cracks in concrete (ACI 266R). Macrofibers (synthetic or steel) can be used for controlling cracks from shrinkage or thermal stresses, as well as providing post-cracks load-bearing and strain capacity under applied service loads (ACI 544.4R).

There is some degree of uncertainty in predicting the shrinkage of concrete structures, as it depends on many parameters such as concrete composition, source of aggregates, ambient relative humidity, specimen geometry, and the ratio of the exposed surface to the volume of the structural element. If not controlled, drying shrinkage cracks can lead to serviceability and durability problems over time. Proper mixture design and construction practices can

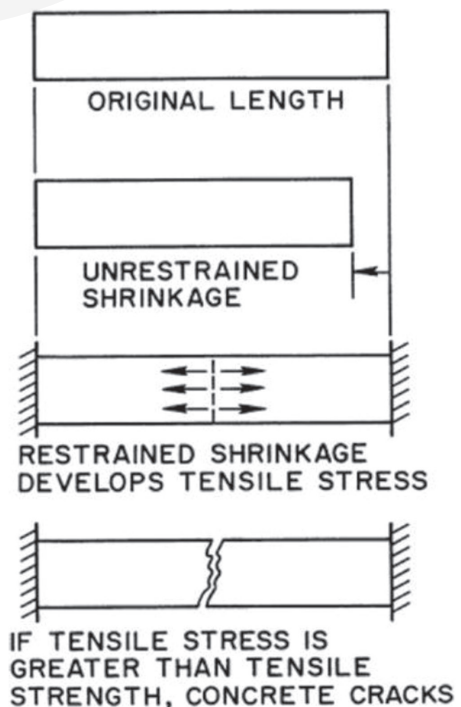


Fig. 3.1a—Cracking of concrete due to drying shrinkage (ACI 224R).