

ACI 440.9R-15

Guide to Accelerated Conditioning Protocols for Durability Assessment of Internal and External Fiber-Reinforced Polymer (FRP) Reinforcement

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Guide to Accelerated Conditioning Protocols for Durability Assessment of Internal and External Fiber-Reinforced Polymer (FRP) Reinforcement

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Fiber-reinforced polymer (FRP) composites, when designed, fabricated, and installed, provide a sustainable and durable reinforcement system for concrete. This document presents guidance for assessing the durability performance of internal and external FRP composite reinforcement using accelerated conditioning protocols (ACPs) in combination with standard test methods for mechanical properties. The objective of ACPs is to enable manufacturers to characterize the durability of their FRP composite products and encourage researchers and testing laboratories to adopt common

test protocols to build a meaningful database of durability testing of FRP materials. Results of the tests conducted using the recommended ACPs are not intended to be used in the design of FRP composites as concrete reinforcement. In the future, however, when the relationship between field performance and ACPs is better understood, ACPs may be refined to allow use in quality control and design.

Keywords: accelerated conditioning; bond; durability; externally bonded; fiber-reinforced polymer composites; modulus of elasticity.

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CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Introduction**

This document is a guide to the assessment of the durability performance of internal and external fiber-reinforced polymer (FRP) composite reinforcement using accelerated conditioning protocols (ACPs) in combination with standard test methods for mechanical properties. The purpose of this guide is to document ACPs so that a standardized method can be created to gather data to eventually be used as a screening or acceptance tool.

FRP composites are increasingly being used in infrastructure applications as reinforcing bars and externally bonded reinforcement for strengthening reinforced concrete elements. The use of FRP composites is predicated on performance attributes linked to their light weight, high stiffness-to-weight and strength-to-weight ratios, ease of installation in the field, potential low system cost, and potentially high overall durability.

FRP composites are used by many industries, including automotive, marine, and aerospace. They have successfully been applied in pipelines, underground storage tanks, building façades, and as architectural components. The materials, loading conditions, and environments seen in many infrastructure applications, however, are unique. Anecdotal evidence provides substantial reason to believe that, if appropriately designed and fabricated, FRP composites can provide longer service life and lower maintenance costs than steel-reinforced structures.

FRP composites have been in use as concrete reinforcement since the 1980s. Consequently, long-term performance field data are limited, making it essential that potential vulnerabilities regarding FRP durability be identified and addressed early to ensure expected long-term service. One means to identify long-term vulnerability is through the use of accelerated conditioning. Few standard protocols for conducting durability testing exist, making it difficult to draw detailed conclusions from the present database of test results generated over the past two decades. Comparing tests conducted at different laboratories is often complicated by the large number of variables among tests.

FRP composite reinforcement embedded in concrete will experience different environmental influences than those experienced by externally bonded FRP composite reinforcement. Externally bonded FRP composite reinforcement is typically exposed directly to ambient environmental conditions where embedded reinforcement is not. In many applications, the bond of externally bonded FRP composite reinforcement is critical to the short- and long-term structural performance of the system. Due to the fundamental difference in exposure conditions of internal and external FRP composite reinforcement, different ACPs and mechanical testing for internal and external FRP composite reinforcement are necessary. In either case, durability, in the context of this guide, is defined as a measure of the retention of FRP physical and mechanical properties when exposed to the ACP environments for the prescribed duration.

An overview of the evaluation process includes the following four elements:

- 1) Specimen fabrication and preparation—Process used to fabricate the specimen and prepare it for exposure to the ACP.
- 2) Accelerated conditioning protocol—Sets out the parameters for the environment and stress, including duration, to which the specimen will be exposed (**Chapter 4**). Additional control specimens are stored in ambient laboratory conditions.
- 3) Mechanical testing—Tests the accelerated conditioned (AC) and control specimens following the exposure period. Testing is completed under unexposed conditions (**Chapters 5 and 6**).
- 4) Residual mechanical property determination—The method used to evaluate the effect of ACP on mechanical properties (**Chapters 5 and 6**).

1.2—Scope

This document provides guidance on using ACPs and associated standard mechanical test methods to assess the durability of FRP composite reinforcement for concrete with the objective to enable manufacturers to characterize the durability of their FRP products and to encourage researchers and testing laboratories to adopt common test protocols to build a meaningful database of durability test results for FRP materials. Results of the tests conducted using the recommended protocols are not intended for use directly in the design of FRP composites. They are meant to generate a database of consistent test results that can be

used in the future to refine the environmental factors recommended in ACI 440.1R, 440.2R, and 440.7R. Recommended environmental reduction factors used in the design of FRP composite reinforcement are provided in ACI 440.1R and 440.2R and are outside the scope of this guide.

The results of the conditioning and testing recommended in this guide are not intended to be useful in the prediction of service life. The use of these methods in conjunction with field evaluations of the performance of structures with FRP composite reinforcement in service conditions is encouraged. Future correlation of accelerated methods with field performance can help validate and improve confidence in their use.

Physicochemical tests that measure the changes in the physical and chemical properties of FRP materials can also be useful in assessing degradation of the material and its constituents after being subjected to the ACPs described in this guide.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

b	=	cross-sectional width of beam specimen
E_{L1}	=	average elastic modulus of unexposed control specimens, psi (MPa)
E_{L2}	=	average elastic modulus of accelerated conditioned specimens, psi (MPa)
f_u	=	ultimate tensile strength of fiber-reinforced polymer reinforcing bar, psi (MPa)
F_{p1}	=	average pull-off bond strength of unexposed control specimens, lbf (N)
F_{p2}	=	average pull-off bond strength of accelerated conditioned specimens, lbf (N)
F_{u1}	=	average tensile strength of unexposed control specimens, lbf (N)
F_{u2}	=	average tensile strength of accelerated conditioned specimens, lbf (N)
h	=	cross-sectional height of beam specimen
L	=	length of beam specimen
P_{b1}	=	average beam strength of unexposed control specimens, lbf (N)
P_{b2}	=	average beam strength of accelerated conditioned specimens, lbf (N)
R_{eb}	=	beam bond retention, percent
R_{em}	=	elastic modulus retention, percent
R_{ep}	=	pull-off bond retention, percent
R_{es}	=	ultimate strain retention, percent
R_{et}	=	tensile strength retention, percent
W_0	=	average unexposed specimen mass, g
W_1	=	average specimen mass of accelerated conditioned specimens, g
ϵ_{u1}	=	average ultimate strain of unexposed control specimens
ϵ_{u2}	=	average ultimate strain of accelerated conditioned specimens

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,”

<http://concrete.org/tools/concreteterminology.aspx>. Definitions provided herein complement that source.

aramid fiber—highly oriented organic fiber produced from an aromatic polyamide.

B-stage—intermediate stage in the reaction of certain thermosetting resins in which the material softens when heated and it is plastic and fusible but may not entirely dissolve or fuse; resin in an uncured prepreg is usually at this stage.

carbon fiber—fiber produced by heating organic precursor materials containing a substantial amount of carbon, such as rayon, polyacrylonitrile (PAN), or pitch, in an inert environment.

cure—inducing a reaction leading to cross linking in a thermosetting resin using chemical initiators, catalysts, radiation, heat, or pressure.

degradation—change in the mechanical or physical properties of a material that results in a detrimental effect on performance.

durability—measure of the retention of fiber-reinforced polymer physical and mechanical properties when exposed to the accelerated conditioning protocol environment for the prescribed duration.

E-glass—family of glass fibers with a calcium alumina borosilicate composition and a maximum alkali content of 2 percent.

fiber reinforced polymer bar—composite material formed into a long, slender, structural shape suitable for the internal reinforcement of concrete and consisting of primarily longitudinal unidirectional fibers bound and shaped by a rigid polymer resin material. The bar may have a cross section of variable shape, commonly circular or rectangular, and a deformed or roughened surface to enhance bonding with concrete.

fiber-reinforced polymer laminate—one or more layers of fiber reinforcements, such as glass, carbon, and aramid, arranged in one or more orientations—for example, 0, 90, +45, -45 degrees—and held together by a polymer matrix; FRP laminates come in the physical form of dry, prepreg, and precured materials.

glass fiber—fiber drawn from an inorganic fusion of silica (SiO₂) and other compounds that have cooled without crystallization.

impregnate—for fiber-reinforced polymer composites, to saturate the fibers with resin.

precured fiber-reinforced polymer—fully cured fiber-reinforced polymer composite material that is usually made in a factory and brought to the site as a rigid solid.

prepreg fiber-reinforced polymer—reinforcement fabrics for FRP laminates that have been preimpregnated with a resin that usually is cured to an intermediate stage (B-stage).

vinyl ester—thermosetting reaction product of epoxy resin with a polymerizable unsaturated acid that is then diluted with a reactive monomer.

wet layup—manufacturing process where dry fabric fiber reinforcement is impregnated on site with a saturating resin matrix and then cured in place.