ACI 440.9R-15

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

Reported by ACI Committee 440

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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.

CONTENTS

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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 (SiO_2) 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.

CHAPTER 3—DURABILITY OF FIBER-REINFORCED POLYMER COMPOSITES

This chapter provides an introduction of reported factors that impact fiber-reinforced polymer (FRP) composite durability. FRP composite materials are formed through the physical combination of two or more constituent materials, of which at least one is a reinforcing material (for example, fiber) and a polymer matrix material (for example, resin). The matrix, which is typically a thermoset resin such as a vinyl ester or epoxy, binds the fibers together, allowing shear transfer between fibers; provides stability to the slender fibers; and serves as a protective barrier from environmental exposure. E-glass fibers offer high tensile strength and economical cost; however, they are susceptible to degradation due to moisture and alkalinity without the protection of an appropriate resin system. Similarly, aramid fibers are resistant to abrasion and impact, but show a propensity to creep, absorb moisture, and degrade under ultraviolet exposure. Carbon fibers are relatively inert to their environment. The arrangement of fibers in terms of their orientation typically results in FRP composites having anisotropic and heterogeneous material properties.

Durability of the resin system is dependent on several factors, including the resin components and proportions, as well as curing time and environmental exposure conditions. Resin systems available commercially are typically designed for specific end-use applications based on mechanical, physical, chemical, electrical, or other considerations associated with the intended operating environment; formulations are usually proprietary. Mechanical properties of the resins are typically published by manufacturers and are based on standard test methods. Typical properties of FRP composite materials used with concrete structures are found in ACI 440.1R and ACI 440.2R. While the important mechanical properties used for design and quality control are generally addressed within a project specification, durability properties are less so.

Currently, there is lack of consensus on standard test methods that evaluate the durability of resins and fibers. The more prominently investigated conditions affecting FRP durability include moisture (water and salt solution), other chemical solutions, alkaline environment, extreme temperature and thermal cycling, freezing and thawing, creep and relaxation, fatigue, and ultraviolet (UV) radiation. The influence of these conditions is not only dependent upon physical and environmental synergy, but also application. Internal reinforcement is likely to see a less varied environmental exposure than external reinforcement due to the protection provided by the concrete. For more-detailed discussion on FRP durability on both internal and external FRP systems, refer to ACI 440R.

CHAPTER 4—ACCELERATED CONDITIONING

Several environments presented in Chapter 3 adversely affect mechanical properties of fiber-reinforced polymer (FRP) composites over time. One of the inherent difficulties in durability testing is determining the time period required to impose changes in those properties. Ideally, to ensure that FRP composite reinforcement maintains its mechanical properties over the service life of the structure, the system should be built and observed in that environment for the specified time period—an obviously impractical approach. Consequently, as with durability testing of most materials, degradation of material properties is accelerated so that the exposure time is reasonable and practical.

4.1—Background

Bank et al. (1995) evaluated accelerated conditioning methods for determining the long-term performance of FRP composite reinforcement. They indicated that the degradation of fiber-reinforced polymer (FRP) composites could be accelerated with such environments as high or low temperature, moisture, chemicals, and gaseous mixtures, and that exposure to these environments would cause a change in mechanical or physical state. Further degradation could result by adding synergistic effects such as mechanical stress. In accelerated conditioning tests, the material is aged at a higher rate using an accelerating factor (generally temperature) according to the Arrhenius law, which assumes that the degradation process remains unchanged. The effect of temperature is more critical because the chemical degradation rate is not proportional but increases exponentially with the temperature (Robert et al. 2010).

Accelerating conditioning carries the risk that the accelerated process may also change the fundamental degradation mechanism or that the mechanism is not strictly chemical. In bonded FRP applications, the bond between FRP composite and concrete is a combination of hydrogen bonding and mechanical interlock. Consequently, the Arrhenius law is not strictly applicable to the overall degradation of the bond (Tatar et al. 2013). Because accelerated conditioning procedures are typically performed without a direct relation to the field conditions and time scale, accelerated conditions may vary from field conditions, resulting in either unconservative or overly conservative results.

Few standards are available that require evaluation of FRP composite reinforcement mechanical properties after being exposed to accelerated conditioning. AC125 specifies conditioning requirements, mechanical tests, and retention limits for resistance to moisture, saltwater, alkali, dry heat, ultraviolet (UV) light, and freezing and thawing. The specified conditioning protocols are to be applied over durations from 1000 to 10,000 hours. Many of the procedures in AC125 are similar to the accelerated conditioning protocols (ACPs) noted in this guide. One significant difference, however, is that AC125 uses an elevated temperature with water (100 ± 2°F [37.8 ± 1.1°C]) or laboratory temperature with an alkaline solution (73 ± 3°F [23.8 ± 1.7°C]). This guide suggests elevated temperature in conjunction with moisture or chemical solution to accelerate the degradation of the system.

4.2—Accelerated conditioning protocols

Although fiber rupture is a concern, the primary mechanism of degradation for fiber-reinforced polymer (FRP) reinforcing bars is the effect of alkalinity and moisture on the resin. For externally bonded FRP composites, the critical mechanism is considered to be the effect of moisture on the adhesion of FRP composite to concrete. The aim of conditioning specimens is to determine the effect of the environment on the mechanical properties. Sections 4.2.1 through 4.2.4 describe accelerated conditioning protocols (ACPs) designed to accelerate the degradation of mechanical properties. The ACP is a description of the environment and stress that the specimen should be exposed to during the conditioning period. Environment might include moisture by water or chemical solution, temperature, or a combination of them. In general, ACPs could be the environment, stress, or both, applied simultaneously. Although other exposures could be added in the future, this guide addresses environment and stress.

4.2.1 *Standard laboratory conditions*—For the purposes of comparison to accelerated conditioning (AC), standard laboratory temperature should be defined as 73.4 ± 5°F (23 ± 3°C) and standard laboratory humidity should be defined as 50 ± 10 percent relative humidity.

4.2.2 *ACP continuous immersion in water*—Continuous immersion in 122 ± 5°F (50 ± 3°C) potable water.

4.2.3 *ACP continuous exposure to humidity*—Continuous exposure to 100 percent relative humidity at 140 ± 5°F (60 ± 3°C).

4.2.4 *ACP continuous immersion in alkaline solution*—Continuous immersion in 140 ± 5°F (60 ± 3°C) alkaline solution in accordance with Section 11.3 of ASTM D7705/D7705M. Covering the alkaline solution before and during testing should prevent interaction with atmospheric CO_2 and prevent evaporation. Check the solution pH at the end of conditioning.

4.3—Mass change

The amount of moisture absorbed during exposure to the accelerated conditioning protocols (ACPs) may be important to the long-term performance of the fiber-reinforced polymer (FRP) system being tested. For many of the test procedures, mass change measurement can be performed in parallel with the ACP described in 4.2 and mechanical testing described in Chapters 5 and 6 for FRP bars and externally bonded FRP, respectively. If a measurement of the mass change is desired, measure the mass of the dry specimen according to Procedure D of ASTM D5229/D5229M (the initial mass W_0). Then, after immersion for the prescribed period of time, the specimen should be removed from the solution, quickly washed with deionized water, surface dried with tissue paper, and immediately weighed (this is the mass at Time 1, denoted as W_1).

In general, specimens are expected to absorb moisture during exposure. Consequently, a gain is expected over that of the control specimens. Mass loss would indicate a deleterious chemical reaction with the resin or fibers. Mass change should be calculated using Eq. (4.3) as follows

$$\Delta M = \frac{W_1 - W_0}{W_0} \times 100 \qquad (4.3)$$

where a positive sign indicates an increase in mass.

CHAPTER 5—FIBER-REINFORCED POLYMER REINFORCING BAR TESTS

Four test methods can be used individually or combined to determine the environmental effects on mechanical properties of fiber-reinforced polymer (FRP) reinforcing bars. Three of these methods are specified in ASTM D7705/D7705M: 1) unstressed conditioning followed by tension test; 2) conditioning with sustained tension, followed by tension test; and 3) conditioning with sustained tension inside concrete, followed by tension test. Section 5.1 presents the fourth method: the sustained bending stress test. As described in Chapter 3, durability of FRP composite reinforcement embedded in concrete can be affected by a number of environments. The primary concern, however, is the resistance of the FRP composite reinforcement to the alkaline environment caused by the surrounding concrete in combination with moisture.

5.1—Sustained bending stress test

The following procedures are intended to induce flexural stresses in fiber-reinforced polymer (FRP) reinforcing bars during conditioning. FRP bar segments are bent and secured in a curved strain jig in accordance with ASTM D543 to create a specified sustained flexural strain (Fig. 5.1). The recommended accelerated conditioning protocol (ACP) is immersion in a heated alkaline solution (Section 4.2.4) for a specified time period. The unexposed control specimens are associated with Section 4.2.1. Control parameters include solution temperature and sustained stress. Residual tensile strength, elastic modulus, and ultimate strain values are measured using ASTM D7205/D7205M and compared to those of unexposed control specimens. Final testing is conducted at room temperature rather than the elevated exposure temperature. At least five control specimens and five specimens exposed to the specified ACP should be tested.

5.1.1 *Specimen fabrication and preparation*—Specimens should be cut to a length sufficient to fit the strain jig and to be tested in accordance with ASTM D7205/D7205M.

5.1.2 *Accelerated conditioning protocol*—

(a) Accelerated conditioning—Immersion in alkaline solution as described in 4.2.4

(b) Duration—3000 hours

(c) Sustained stress—FRP specimens should be bent and secured in a curved stress jig in accordance with ASTM D543 to create a sustained flexural stress of 20 percent of the ultimate tensile strength f_u of the bar.

5.1.3 *Standard laboratory conditions*

Control specimens—Standard laboratory conditions as described in 4.2.1.

5.1.4 *Mechanical testing*—Following exposure to the specified ACP, the specimens should be carefully removed from the jig, thoroughly rinsed with water, and post-conditioned according to Procedure B of ASTM D618. Grips should be applied and accelerated conditioning specimens and control specimens should be tested in accordance with ASTM D7205/D7205M within 24 hours following completion of post-conditioning.

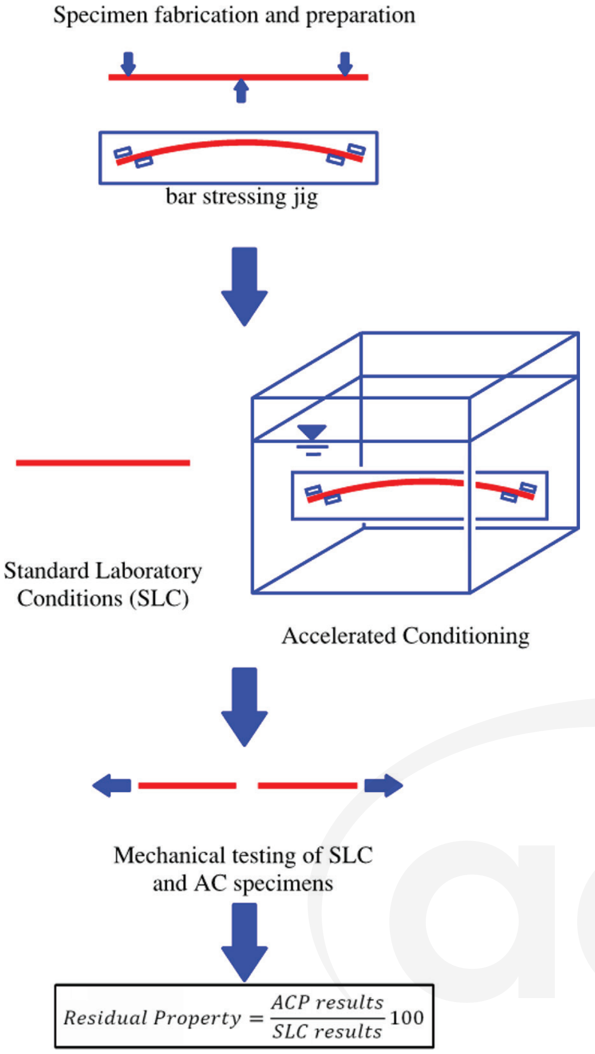

Fig. 5.1—Example procedure for combining accelerated conditioning and mechanical testing for determining residual mechanical properties for reinforcing bars.

5.1.5 *Residual mechanical properties*—The tensile strength retention should be calculated using Eq. (5.1.4a) with a precision of two significant figures.

$$R_{et} = \frac{F_{u2}}{F_{u1}} \times 100 \tag{5.1.4a}$$

The elastic modulus retention should be calculated using Eq. (5.1.4b) with a precision of three significant figures. Elastic modulus should be calculated as directed in ASTM D7205/D7205M.

$$R_{em} = \frac{E_{L2}}{E_{L1}} \times 100 \tag{5.1.4b}$$

The ultimate strain retention should be calculated using Eq. (5.1.4c) with a precision of three significant figures. The ultimate strain capacity of the specimen, ε_u, should be calculated as directed in ASTM D7205/D7205M.

$$R_{es} = \frac{\varepsilon_{u2}}{\varepsilon_{u1}} \times 100 \tag{5.1.4c}$$

CHAPTER 6—EXTERNALLY BONDED FIBER-REINFORCED POLYMER TESTS

Durability of fiber-reinforced polymer (FRP) composite reinforcement externally bonded to concrete can be affected by a number of environments. This chapter presents tests that are used to determine the effect that an accelerated conditioning protocol (ACP) will have on important mechanical properties of the FRP-to-concrete bond.

The recommended ACP involves immersion in heated water. Three test procedures and the ACPs described pertain to tensile behavior of FRP laminate and bond of the FRP system to concrete for both cured-in-place and precured systems. A cured-in-place system might include fabric, saturant, primer, and putty. A precured system might include laminate, adhesive, and putty. Section 6.1 addresses specimen fabrication for the three procedures. Sections 6.2 and 6.3 address FRP externally bonded onto concrete, which is schematically outlined in Fig. 6. Section 6.4 addresses procedures for testing the FRP system alone.

6.1—Specimen fabrication and preparation

6.1.1 *Specimen fabrication and preparation for beam bond test*—Concrete described in 6.1.4 should be used to construct plain concrete beams, as shown in Fig. 6.1.1. The recommended dimensions for the beam are 4 in. (100 mm) square with a block length of 14 in. (350 mm) and a clear span of 12 in. (300 mm).

The specimen should be saw cut on a form-finished face at midspan to a depth of $h/2$. The width (kerf) of the saw cut may be cut with a composite or diamond blade. The same blade width should be used throughout a particular series of tests to allow for greater repeatability in testing. Saw cutting should be performed in a manner that minimizes spalling, microcracking, and other near-surface deterioration adjacent to the saw cut. As an alternate to saw cutting, the required weakened plane can be created by inserting a thin shim into the formwork. The notch gap width should be approximately 0.04 to 0.125 in. (1 to 3 mm). The average slot width should be reported.

Application of the externally bonded fiber-reinforced polymer (FRP) composite reinforcement should be in accordance with the manufacturer's recommendations. Surface preparation should be in accordance with 6.4.2.1 of ACI 440.2R-08. FRP composites should be cured for 7 days at standard laboratory conditions as noted in 4.2.1 before exposure to accelerated conditioning protocols (ACPs). Control specimens should be stored at standard laboratory conditions.

The FRP reinforcement should be a single layer with a minimum width of 1 in. (25 mm). Fabric reinforcement should be 0.123 lb/ft^2 (600 gsm). If a larger beam size is required to obtain an adhesive failure mode—for example, a 6 x 6 in. (150 x 150 mm)—then the length of the FRP composite reinforcement may be adjusted. In this case, a

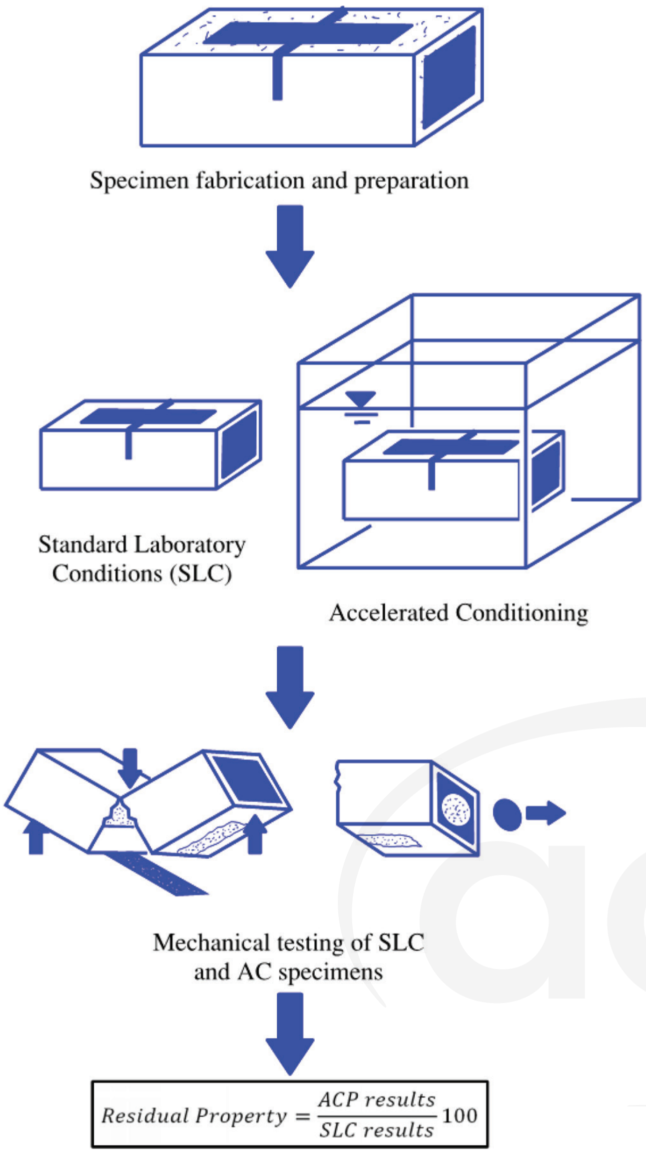

Fig. 6—Example procedure for combining accelerated conditioning and mechanical testing to determine residual mechanical properties for externally bonded reinforcement. Beam (Section 6.2) and pull-off (Section 6.3) test procedures are shown.

pilot study should be conducted without ACP to determine the FRP composite reinforcement width *w* and concrete strength required to give an adhesive failure mode in the control specimens. Excessive FRP composite reinforcement will generally lead to a shear failure of the concrete prism, which is an invalid failure mode for this test.

6.1.2 *Specimen fabrication and preparation for pull-off bond test*—If a direct tension pull-off test is to be conducted in conjunction with the beam test, then a test patch for this purpose should be applied to the end of the beam specimen as shown in Fig. 6.1.1. Concrete described in 6.1.4 should be used to construct control and ACP specimens.

Application of the externally bonded FRP composite should be in accordance with the manufacturer's recommendations. Surface preparation should be in accordance with 6.4.2.1 of ACI 440.2R-08. FRP composites should be cured for 7 days at standard laboratory conditions before exposure to ACP. Control specimens should be stored at standard laboratory conditions as instructed in 4.2.1. The circular saw cut and the circular loading fixture for the pull-off test should be applied after ACP exposure.

6.1.3 *Specimen fabrication and preparation for tensile stress test*—Companion tension coupons (6.4) should be fabricated at the same time as beam and pull-off bond specimens. Coupons should be fabricated to allow testing in accordance with ASTM D7565/D7565M for wet layup and ASTM D3039/D3039M for pultruded plate with the exception of conditioning according to Procedure A of ASTM D618.

6.1.4 *SLC and ACP concrete mixture*—Concrete used for accelerated conditioning tests described in 6.2 and 6.3 should be formulated as follows:

6.1.4.1 *Aggregates*—Aggregates should conform to ASTM C33/C33M, and the maximum aggregate size should be 1/2 in. (12.7 mm) for a 4 in. (100 mm) beam width.

6.1.4.2 *Cement*—Type I/II portland cement conforming to ASTM C150/C150M should be used. The concrete mixture should not include any other supplementary cementitious or pozzolonic materials, such as slag, fly ash, silica fume, and limestone powder; or chemical admixtures, such as air-entraining agents, water reducers, high-range water reducers, shrinkage-compensating admixtures, corrosion inhibitors, set retarders, or set accelerators.

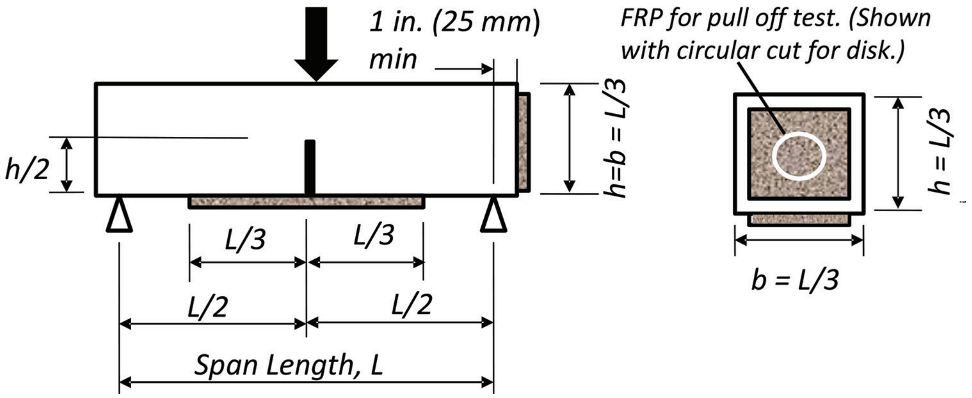

Fig. 6.1.1—Beam bond test specimen configuration.

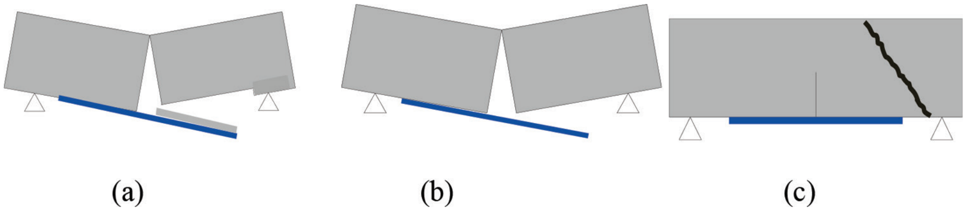

Fig. 6.2—FRP concrete failure modes: (a) cohesive failure mode; (b) adhesive failure mode; and (c) shear failure of concrete block.

6.1.4.3 *Curing*—Specimens should be cured for 28 days in a moist environment in accordance with ASTM C511. Cylinders should undergo the same curing regime. After curing, specimens should be dry prior to applying FRP.

6.1.4.4 *Concrete strength*—The 28-day compressive strength of the cylinders should be between 6500 and 8500 psi (46 and 60 MPa). Cylinders should be cast and tested in accordance with ASTM C31/C31M and ASTM C39/C39M.

6.2—Beam bond test

The beam bond test consists of loading small concrete beams reinforced in flexure with externally bonded fiber-reinforced polymer (FRP) reinforcement; specimens are loaded in three-point bending to failure. Residual load capacities of beams with bond failures are measured and compared to those of the unexposed control specimens. The test procedure, which was developed by Gartner et al. (2011), is similar in specimen configuration and testing procedures to those used to determine modulus of rupture of concrete (ASTM C78/C78M). For each test, at least five control specimens (standard laboratory conditions [SLCs]) and five specimens exposed to the specified accelerated conditioning protocols (ACPs) should be tested.

In bonded FRP reinforcement design, a cohesive bond failure mode is typically assumed, which is where the fracture surface passes entirely through the concrete substrate and some concrete remains adhered to the FRP (Fig. 6.2(a)). Durability of this failure mode, however, is mainly dependent on the durability of the concrete through which the fracture surface passes. The intent of the combined ACP and bond tests recommended in this section is not to test the concrete durability, but rather to test the durability of the adhesive strength of the FRP system being applied to the surface of the concrete (Fig. 6.2(b)). The failure mode of accelerated conditioning (AC) specimens should be primarily adhesive to provide any notable information on the durability of the bond of the system. If both control and AC specimens exhibit adhesive failure modes, the true degradation of the adhesive bond is determined. A mode change from cohesive in the control specimens to adhesive in the AC specimens also provides an indication of changes in the bond of the system associated to its durability and should be noted in the final data. A third failure mode, which is shear cracking of the concrete beam as indicated in Fig. 6.2(c), is considered an invalid test result. Shear failure is avoided by using concrete blocks with sufficiently high concrete compressive strength, as described in 6.1.4.

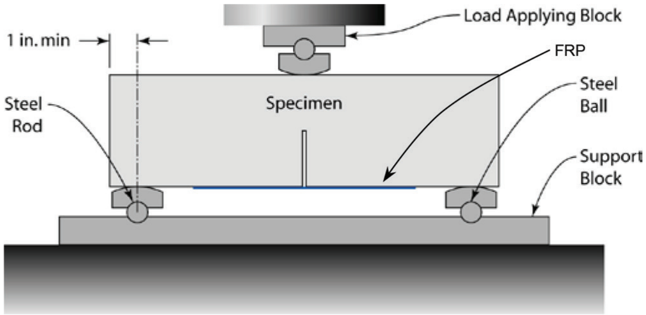

Fig. 6.2.3—Schematic view of a suitable apparatus for flexure test of concrete by three-point loading method.

6.2.1 *Accelerated conditioning protocol*—

(a) Accelerated conditioning—Immersion in water as described in 4.2.2

(b) Duration—3000 hours

(c) Sustained stress—None.

6.2.2 *Standard laboratory conditions*

Control specimens–Standard laboratory conditions as described in 4.2.1.

6.2.3 *Mechanical testing*—SLC and AC specimens should be post-conditioned for 24 hours in 100 percent relative humidity at a temperature of 73.4 ± 3.6°F (23 ± 2°C). The beam test should be conducted within 2 to 5 hours following the post conditioning. Companion direct tension pull-off tests as described in 6.3 should be conducted with the beam test. Following exposure to the specified ACP, both SLC and AC beams should be tested using ASTM C78/C78M procedures with the setup adjusted as shown in Fig. 6.2.3. Testing is conducted at room temperature rather than at the elevated exposure temperature to which some AC specimens are subjected. Concrete compressive strength, failure mode, and beam specimen ultimate load (P_b) should be reported for each test. When possible, force-displacement behavior and the concrete mixture design used should be reported. The initial fabric or laminate type, width, and thickness should be reported to ensure consistency between laboratory-prepared specimens. A final composite thickness should be reported after testing.

6.2.4 *Residual mechanical properties*—The beam bond retention should be calculated with a precision of three significant figures using Eq. (6.2.4) as follows

$$R_{eb} = \frac{P_{b2}}{P_{b1}} \times 100 \qquad (6.2.4)$$

The standard deviation, coefficient of variation, or both, should be reported with the average beam strength.

6.3—Pull-off bond test

The direct tension, pull-off test is performed in accordance with ASTM D7522/D7522M by pulling a small circular patch of externally bonded fiber-reinforced polymer (FRP) concrete composites off the concrete substrate. Residual bond strength and failure mode of the accelerated conditioning (AC) specimens are measured and compared to those of unexposed control specimens. The failure mode is also noted and may be used to characterize bond. For each test, at least five control specimens and five specimens exposed to the specified accelerated conditioned protocol (ACP) should be tested.

6.3.1 *Accelerated conditioning protocol—*

(a) Accelerated conditioning—Continuous immersion in water as described in 4.2.2

(b) Duration—3000 hours

(c) Sustained stress—None.

6.3.2 *Standard laboratory conditions—*

Control specimens—Standard laboratory conditions as described in 4.2.1.

6.3.3 *Mechanical testing*—Pull-off tests should be conducted according to ASTM D7522/D7522M. Cutting the core should occur immediately after removing the specimen from the water bath prior to post-conditioning. Specimens should be post-conditioned for 24 hours in 100 percent relative humidity at a temperature of 73.4 ± 3.6°F (23 ± 2°C). The direct tension pull-off test should be conducted between 2 and 5 hours following the post-conditioning. Testing is conducted at room temperature rather than at the elevated AC exposure temperature. Reference cylinders (ASTM C39/C39M) should be tested concurrent with control specimens to establish the concrete compressive strength. The initial fabric or laminate type along with the width and thickness should be reported to ensure consistency between laboratory-prepared specimens.

6.3.4 *Residual mechanical properties*—Pull-off bond retention should be calculated with a precision of three significant figures using Eq. (6.3.4) as follows

$$R_{ep} = \frac{F_{p2}}{F_{p1}} \times 100 \qquad (6.3.4)$$

6.4—Tensile test of fiber-reinforced polymer

This test evaluates the tensile capacity of the fiber-reinforced polymer (FRP) fabric or laminate under standard laboratory conditions (SLC) and accelerated conditioning (AC). Specimen mass, residual tensile strength, elastic modulus, and ultimate strain values should be measured and compared to those of unexposed control specimens (refer to 6.1.1 and 6.1.2). The recommended accelerated conditioning protocol (ACP) parameters are water temperature and immersion time. These specimens may serve as companion specimens to either the beam and pull-off test (refer to 6.2 and 6.3).

6.4.1 *Accelerated conditioning protocol—*

Accelerated conditioning—Continuous immersion in water as described in 4.2.2

Duration—3000 hours

Sustained stress—None.

6.4.2 *Standard laboratory conditions—*

Control specimens—Standard laboratory conditions as described in 4.2.1.

6.4.3 *Mechanical testing*—Following exposure to the specified ACP, the specimens should be rinsed thoroughly with water and post-conditioned according to Procedure A of ASTM D618. Tabs should be applied and both AC and control specimens should be tested in accordance with ASTM D7565/D7565M or ASTM D3039/D3039M as appropriate. The initial fabric or laminate and final thickness of the FRP composite material should be reported to ensure consistency between laboratory-prepared specimens.

Residual mechanical properties R_{et}, R_{em}, and R_{es} should be calculated and reported as described in 5.1.4.

CHAPTER 7—FUTURE WORK AND RECOMMENDATIONS

Test methods and conditioning protocols presented in this document can be used to test fiber-reinforced polymer (FRP) composite reinforcement for durability performance when exposed to moisture and high-alkaline environments. Results of these tests can be used by manufacturers to improve product components and manufacturing processes and by researchers and testing laboratories to adopt common test protocols to build a meaningful database of results from durability testing of FRP materials. Although the use of these test protocols does not duplicate service life conditions, the data acquired will yield an improved understanding of FRP durability performance and allow accelerated conditioning protocol (ACP) test calibration between conditioned and unconditioned systems. As these tests are used more broadly and long-term field data become available, correlations between results from ACP and field observations can be studied to provide information regarding service life. As a future work, acceptable limits on the residual mechanical properties should be developed for ACP test results.

The ACP protocols do not provide recommended laminate thicknesses or bar diameters to be used for durability testing. Experience in the aerospace industry has shown that, for a given exposure environment, the moisture absorption profile for a laminate cross section is highly dependent on the laminate thickness, exposure time, and diffusion properties of the laminate (Campbell 2010). Future work should investigate the applicability of Fick's law of diffusion on the moisture absorption profile through the specimen thickness/diameter and provide recommendations regarding the specimen thickness or diameter to be used with the ACP. In addition, real-world fluctuations in temperature, humidity, and sustained stress should be considered in the expected long-term moisture profile. Effects of post-cure, including temperature and length of cure time on the composite, should be evaluated between the control and conditioned specimens.

Physicochemical tests, such as thermogravimetric analysis (with or without evolved gas analysis and Fourier transform infared spectroscopy), differential scanning calorimetry, dynamic mechanical analysis, thermomechanical analysis, X-ray diffraction, scanning electron microscopy, and transmission electron microscopy that measure the changes in the physical and chemical properties of FRP materials, are needed to fully characterize degradation of the FRP material and its constituents after subjection to ACPs described in this guide. Future research will be directed to this area to enable complete understanding of the degradation mechanisms under ACP with an emphasis toward a more scientific determination of C_E factors for related ACI 440 design guide documents (ACI 440.1R, ACI 440.2R, and ACI 440.7R).

Results of the tests conducted using the recommended ACP are not intended for use in the design of FRP composites as concrete reinforcement. In the future, however, when the relationship between field performance and accelerated conditioning is better understood and characterized, the ACPs are envisioned to be adjusted to allow for use in design. Sufficient data, however, are not yet available to calibrate ACP test results to either a particular service life or the environmental (C_E) factor used in ACI 440.1R and 440.2R.

CHAPTER 8—REFERENCES

ACI committee documents and documents published by other organizations are listed first by document number, full title, and year of publication followed by authored documents listed alphabetically.

American Concrete Institute

440R-07—Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures

440.1R-06—Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars.

440.2R-08—Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.

440.7R-10—Guide for the Design and Construction of Externally Bonded Fiber-Reinforced Polymer Systems for Strengthening Unreinforced Masonry Structures.

ASTM International

C31/C31M-12—Standard Practice for Making and Curing Concrete Test Specimens in the Field

C33/C33M-13—Standard Specification for Concrete Aggregates

C39/C39M-14—Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

C78/C78M-10—Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

C150/C150M-12—Standard Specification for Portland Cement

C511-13—Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the testing of Hydraulic Cements and Concrete

D543-14—Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents

D618-13—Standard Practice for Conditioning Plastics for Testing

D3039/D3039M-14—Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

D5229/D5229M-14—Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

D7205/D7205M-06(2011)—Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars

D7522/D7522M-09—Standard Test Method for Pull-Off Strength for FRP Bonded to Concrete Substrate

D7565/D7565M-10—Standard Test Method for Determining Tensile Properties of Fiber Reinforced Polymer Matrix Composites Used for Strengthening of Civil Structures

D7705/D7705M-12—Standard Test Method of Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction

International Code Council

AC125-12—Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber-Reinforced Polymer (FRP) Composite Systems

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Bank, L. C.; Gentry, T. R.; and Barkatt, A., 1995, “Accelerated Test Methods to Determine the Long-Term Behavior of FRP Composites: Environmental Effects,” *Journal of Reinforced Plastics and Composites*, V. 14, Jan, pp. 559-587.

Campbell, F. C., 2010, “Structural Composite Materials,” ASM International, Society for Materials Scientists and Engineers, Materials Park, OH, 612 pp.

Gartner, A.; Douglas, E. P.; Dolan, C. W.; and Hamilton, H. R., 2011, “Small Beam Bond Test Method for CFRP Composites Applied to Concrete,” *Journal of Composites for Construction*, V. 15, No. 1, Jan-Feb., pp. 52-61. doi: 10.1061/(ASCE)CC.1943-5614.0000151

Robert, M.; Wang, P.; Cousin, P.; and Benmokrane, B., 2010, “Temperature as an Accelerating Factor for Long-Term Durability Testing of FRPs: Should There Be Any Limitations?” *Journal of Composites for Construction*, V. 14, No. 4, Aug., pp. 361-367. doi: 10.1061/(ASCE)CC.1943-5614.0000102

Tatar, J.; Weston, C.; Blackburn, P.; and Hamilton, H. R., 2013, “Direct Shear Adhesive Bond Test,” FRPRCS-11: 11th International Symposium on Fiber Reinforced Polymer for Reinforced Concrete Structures, 2013, 10 pp.

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