Feasibility of Epoxy Bond Enhancement on High-Strength Concrete

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Feasibility of Epoxy Bond Enhancement on High-Strength Concrete

by

Amanda A. Lewis

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering
Department of Civil and Environmental Engineering
College of Engineering
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Surface preparation, Vacuum exposure, Pull-off testing

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Dedication

For every girl and woman who has ever been asked to dim their light.
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Table of Contents

List of Tables iii
List of Figures v
Abstract xvi

Chapter 1: Introduction 1
  1.1 Overview 1
  1.2 Objective Statement 2
  1.3 Thesis Organization 2

Chapter 2: Literature Review 4
  2.1 Fiber-Reinforced Polymers 4
  2.2 Fiber-Reinforced Polymers as a Repair Material 5
    2.2.1 Fibers 6
    2.2.2 Polymers 7
    2.2.3 Repair Process 8
  2.3 Quality Control 9
    2.3.1 Nondestructive Techniques 9
    2.3.2 Destructive Techniques 11
  2.4 Recently Performed Research 12
  2.5 Chapter Summary 14

Chapter 3: Specimen Fabrication, Surface Preparation, and Repair 15
  3.1 Formwork 15
  3.2 Specimen Materials and Fabrication 16
  3.3 Specimen Surface Preparation 17
  3.4 Repair Materials 21
  3.5 Vacuum Chamber 23
  3.6 Repair Procedure 25

Chapter 4: Testing Procedures 29
  4.1 Nondestructive Testing 29
  4.2 Destructive Testing 32
List of Tables

Table 3.1  28-day compression test results  17
Table 3.2  Carbon fiber mesh typical dry fiber mechanical properties  22
Table 3.3  High-viscosity epoxy resin mechanical properties  22
Table 3.4  Cured laminate mechanical properties  22
Table 3.5  Medium-viscosity epoxy resin mechanical properties  23
Table 3.6  Low-viscosity epoxy resin mechanical properties  23
Table 3.7  Summary of repair specifics on the 8744-psi mix specimens  26
Table 3.8  Summary of repair specifics on the 9427-psi mix specimens  27
Table 5.1  Specimen 1 pull-off testing results  43
Table 5.2  Specimen 2 pull-off testing results  44
Table 5.3  Specimen 3 pull-off testing results  44
Table 5.4  Specimen 4 pull-off testing results  44
Table 5.5  Specimen 5 pull-off testing results  45
Table 5.6  Specimen 6 pull-off testing results  45
Table 5.7  Specimen 7 pull-off testing results  45
Table 5.8  Specimen 8 pull-off testing results  46
Table 5.9  Specimen 9 pull-off testing results  46
Table 5.10  Specimen 10 pull-off testing results  46
Table 5.11  Specimen 11 pull-off testing results  47
| Table 6.1 | Average maximum pull-off strength per 8744-psi mix slab specimen | 64 |
| Table 6.2 | Average maximum pull-off strength per 9427-psi mix slab specimen | 65 |
List of Figures

Figure 2.1  Test sample matrix described in the 2019 study by Al Azzawi, Mullins, et. al. 14
Figure 3.1  Twelve fabricated concrete specimen forms 15
Figure 3.2  Casting concrete specimens and cylinders at both pour locations 16
Figure 3.3  Pressure washer used for wet jetting 18
Figure 3.4  Wet jetting slab specimens 18
Figure 3.5  Wet-jetted surface characterization 19
Figure 3.6  3D surface characterization scans of unprepared repair surface (top) and wet jetted surface (bottom) 20
Figure 3.7  Batch of slab specimens set up for oven drying 21
Figure 3.8  Annotated vacuum chamber diagram 24
Figure 3.9  Vacuum chamber connected to vacuum pump 25
Figure 3.10  Photo illustrating the crimped ¼-inch polyethylene tubing to be submerged in epoxy 27
Figure 3.11  Epoxy flowing into sealed vacuum chamber 28
Figure 3.12  Epoxy flooding repair surface in sealed vacuum chamber 28
Figure 4.1  Annotated diagram of heat-lamp-on-stand assembly 30
Figure 4.2  Test setup with slab specimen ready for active pulse thermography testing 31
Figure 4.3  Example mid-test video still of active pulse thermography test pass 31
Figure 4.4  Overhead (plan) view diagram of the test box top plate showing the dolly access opening

Figure 4.5  Simplified diagram (elevation view) of the test box

Figure 4.6  MTS Test System pull-off testing set up

Figure 4.7  Loading dollies adhered to repaired slab specimen cubes

Figure 4.8  Scoring the repair surface of a test cube around the adhered loading dolly

Figure 4.9  Vacuuming scored repair surface to reveal score depth

Figure 5.1  Visual inspection photograph (left) and active thermography still (right) for Specimen 1: f’c 8744-psi mix; medium-viscosity polymer; no vacuum exposure

Figure 5.2  Visual inspection photograph (left) and active thermography still (right) for Specimen 2: f’c 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure

Figure 5.3  Visual inspection photograph (left) and active thermography still (right) for Specimen 3: f’c 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure

Figure 5.4  Visual inspection photograph (left) and active thermography still (right) for Specimen 4: f’c 8744-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure

Figure 5.5  Visual inspection photograph (left) and active thermography still (right) for Specimen 5: f’c 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure

Figure 5.6  Visual inspection photograph (left) and active thermography still (right) for Specimen 6: f’c 8744-psi mix; high-viscosity polymer; no vacuum exposure

Figure 5.7  Visual inspection photograph (left) and active thermography still (right) for Specimen 7: f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure

Figure 5.8  Visual inspection photograph (left) and active thermography still (right) for Specimen 8: f’c 9427-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure
Figure 5.9  Visual inspection photograph (left) and active thermography still (right) for Specimen 9: f’c 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure 41

Figure 5.10  Visual inspection photograph (left) and active thermography still (right) for Specimen 10: f’c 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure 42

Figure 5.11  Visual inspection photograph (left) and active thermography still (right) for Specimen 11: f’c 9427-psi mix; high-viscosity polymer; no vacuum exposure 42

Figure 5.12  Specimen 1 photo summary of pull-off failures 47
Figure 5.13  Specimen 2 photo summary of pull-off failures 48
Figure 5.14  Specimen 3 photo summary of pull-off failures 48
Figure 5.15  Specimen 4 photo summary of pull-off failures 48
Figure 5.16  Specimen 5 photo summary of pull-off failures 49
Figure 5.17  Specimen 6 photo summary of pull-off failures 49
Figure 5.18  Specimen 7 photo summary of pull-off failures 49
Figure 5.19  Specimen 8 photo summary of pull-off failures 50
Figure 5.20  Specimen 9 photo summary of pull-off failures 50
Figure 5.21  Specimen 10 photo summary of pull-off failures 50
Figure 5.22  Specimen 11 photo summary of pull-off failures 51

Figure 6.1  Overlay image with marked anomalies for Specimen 1: f’c 8744-psi mix; medium-viscosity polymer; no vacuum exposure 52

Figure 6.2  Overlay image with marked anomalies for Specimen 2: f’c 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure 53

Figure 6.3  Overlay image with marked anomalies for Specimen 3: f’c 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure 53
Figure 6.4  Overlay image with marked anomalies for Specimen 4:  
$f'c$ 8744-psi mix; low-viscosity polymer with turmeric;  
24-hour vacuum exposure  
54

Figure 6.5  Overlay image with marked anomalies for Specimen 5:  
$f'c$ 8744-psi mix; low-viscosity polymer with turmeric;  
no vacuum exposure  
54

Figure 6.6  Overlay image with marked anomalies for Specimen 6:  
$f'c$ 8744-psi mix; high-viscosity polymer; no vacuum exposure  
55

Figure 6.7  Overlay image with marked anomalies for Specimen 7:  
$f'c$ 9427-psi mix; medium-viscosity polymer; no vacuum exposure  
55

Figure 6.8  Overlay image with marked anomalies for Specimen 8:  
$f'c$ 9427-psi mix; low-viscosity polymer with turmeric-water solution;  
no vacuum exposure  
56

Figure 6.9  Overlay image with zero marked anomalies (none visible) for  
Specimen 9:  $f'c$ 9427-psi mix; low-viscosity polymer with turmeric;  
24-hour vacuum exposure  
56

Figure 6.10  Overlay image with marked anomalies for Specimen 10:  
$f'c$ 9427-psi mix; low-viscosity polymer with turmeric;  
no vacuum exposure  
57

Figure 6.11  Overlay image with marked anomalies for Specimen 11:  
$f'c$ 9427-psi mix; high-viscosity polymer; no vacuum exposure  
57

Figure 6.12  Results summary diagram for Specimen 1  
58

Figure 6.13  Results summary diagram for Specimen 2  
59

Figure 6.14  Results summary diagram for Specimen 3  
59

Figure 6.15  Results summary diagram for Specimen 4  
60

Figure 6.16  Results summary diagram for Specimen 5  
60

Figure 6.17  Results summary diagram for Specimen 6  
61

Figure 6.18  Results summary diagram for Specimen 7  
61

Figure 6.19  Results summary diagram for Specimen 8  
62
Figure 6.20  Results summary diagram for Specimen 9 62
Figure 6.21  Results summary diagram for Specimen 10 63
Figure 6.22  Results summary diagram for Specimen 11 63
Figure 6.23  Comparison of average pull-off strengths of like repair strategy specifics per each concrete mix 65
Figure 6.24  Comparison of average pull-off-strength-to-$f_r$ ratio of like repair strategy specifics per each concrete mix 67
Figure 6.25  Graphical representation of all pull-off test results in relation to $f_r$, comparison study pull-off strengths, and the tensile pull-off strength requirement as defined by ACI 440.2R 67
Figure 6.26  Graphical representation of all pull-off-to-$f_r$ ratios for each pull-off test and comparison study values 69
Figure A.1  Mix ticket for SCP concrete pour 74
Figure A.2  Mix ticket for Coreslab concrete pour 75
Figure B.1  Vacuum chamber setup 76
Figure B.2  Cut carbon fiber fabric with epoxy mixing bucket and roller 77
Figure B.3  Vacuuming slab specimen repair surfaces 77
Figure B.4  Wiping down slab specimen repair surfaces with acetone 78
Figure B.5  Staged CF fabric sheets and specimens ready for repair 78
Figure B.6  Low-viscosity epoxy parts staged for measuring and mixing 79
Figure B.7  Pouring measured low-viscosity epoxy parts into mixing bucket 79
Figure B.8  Mixing low-viscosity epoxy parts after coloring addition 80
Figure B.9  Portioning out mixed low-viscosity epoxy for CF fabric impregnation 80
Figure B.10  Impregnating CF fabric and rolling low-viscosity primer epoxy layer onto repair surfaces 81
Figure B.11  Smoothing low-viscosity CFRP repair after applying impregnated CF fabric 81
Figure B.12  Vacuum chamber with crimped ¼-inch polyethylene tubing to be submerged in epoxy 82
Figure B.13  Low-viscosity epoxy entering sealed vacuum chamber 82
Figure B.14  Epoxy flooding slab specimen repair surface in sealed vacuum chamber 83
Figure B.15  Flooded repair surface in sealed vacuum chamber 83
Figure B.16  Flooded repair surface after breaking vacuum seal 84
Figure B.17  Removal of slab edge barrier on vacuum-exposed slab specimen 84
Figure B.18  Rolling low-viscosity primer epoxy layer on vacuum-saturated repair surface 85
Figure B.19  Smoothing low-viscosity CFRP repair after applying impregnated CF fabric 85
Figure B.20  Mixing medium-viscosity epoxy 86
Figure B.21  Rolling medium-viscosity primer epoxy layer onto repair surfaces 86
Figure B.22  Impregnating CF fabric with medium-viscosity epoxy 87
Figure B.23  Overhead photo showing medium-viscosity primer epoxy layer application and CF fabric impregnation 87
Figure B.24  Smoothing medium-viscosity CFRP repair after applying impregnated CF fabric 88
Figure B.25  Mixing high-viscosity epoxy 88
Figure B.26  Curing slab specimens and staged slab specimens for final application of low-viscosity CFRP 89
Figure B.27  Mixing low-viscosity epoxy with coloring addition 89
Figure B.28  Rolling low-viscosity primer epoxy layer onto repair surfaces 90
Figure B.29  Impregnating CF fabric with low-viscosity epoxy 90
Figure B.30  Completed low-viscosity CFRP repair on non-vacuum-exposed slab specimens 91

Figure B.31  Flooding vacuum-exposed repair surface with low-viscosity epoxy 91

Figure B.32  Flooded repair surface in sealed vacuum chamber 92

Figure B.33  Removing edge barrier on vacuum-exposed slab specimen 92

Figure B.34  Rolling low-viscosity primer epoxy layer on vacuum-saturated repair surface 93

Figure B.35  Smoothing low-viscosity CFRP repair to remove any bubbles or voids 93

Figure C.1  Specimen 1 Cube 1 pull-off testing failure photograph: fʿc 8744-psi mix; medium-viscosity polymer; no vacuum exposure 94

Figure C.2  Specimen 1 Cube 2 pull-off testing failure photograph: fʿc 8744-psi mix; medium-viscosity polymer; no vacuum exposure 94

Figure C.3  Specimen 1 Cube 3 pull-off testing failure photograph: fʿc 8744-psi mix; medium-viscosity polymer; no vacuum exposure 95

Figure C.4  Specimen 1 Cube 4 pull-off testing failure photograph: fʿc 8744-psi mix; medium-viscosity polymer; no vacuum exposure 95

Figure C.5  Specimen 1 Cube 5 pull-off testing failure photograph: fʿc 8744-psi mix; medium-viscosity polymer; no vacuum exposure 95

Figure C.6  Specimen 1 Cube 7 pull-off testing failure photograph: fʿc 8744-psi mix; medium-viscosity polymer; no vacuum exposure 96

Figure C.7  Specimen 2 Cube 1 pull-off testing failure photograph: fʿc 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure 96

Figure C.8  Specimen 2 Cube 4 pull-off testing failure photograph: fʿc 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure 96

Figure C.9  Specimen 2 Cube 6 pull-off testing failure photograph: fʿc 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure 97
Figure C.10  Specimen 2 Cube 7 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure

Figure C.11  Specimen 3 Cube 1 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure

Figure C.12  Specimen 3 Cube 3 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure

Figure C.13  Specimen 3 Cube 4 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure

Figure C.14  Specimen 3 Cube 6 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure

Figure C.15  Specimen 3 Cube 7 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure

Figure C.16  Specimen 4 Cube 2 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure

Figure C.17  Specimen 4 Cube 6 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure

Figure C.18  Specimen 5 Cube 1 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure

Figure C.19  Specimen 5 Cube 3 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure

Figure C.20  Specimen 5 Cube 5 pull-off testing failure photograph:
  \( f'c \) 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure
Figure C.21  Specimen 5 Cube 6 pull-off testing failure photograph: 
f’c 8744-psi mix; low-viscosity polymer with turmeric; 
no vacuum exposure 101

Figure C.22  Specimen 6 Cube 2 pull-off testing failure photograph: 
f’c 8744-psi mix; high-viscosity polymer; no vacuum exposure 101

Figure C.23  Specimen 6 Cube 6 pull-off testing failure photograph: 
f’c 8744-psi mix; high-viscosity polymer; no vacuum exposure 101

Figure C.24  Specimen 6 Cube 8 pull-off testing failure photograph: 
f’c 8744-psi mix; high-viscosity polymer; no vacuum exposure 102

Figure C.25  Specimen 7 Cube 1 pull-off testing failure photograph: 
f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure 102

Figure C.26  Specimen 7 Cube 4 pull-off testing failure photograph: 
f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure 102

Figure C.27  Specimen 7 Cube 5 pull-off testing failure photograph: 
f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure 103

Figure C.28  Specimen 7 Cube 7 pull-off testing failure photograph: 
f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure 103

Figure C.29  Specimen 7 Cube 8 pull-off testing failure photograph: 
f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure 103

Figure C.30  Specimen 8 Cube 5 pull-off testing failure photograph: 
f’c 9427 psi mix; low-viscosity polymer with turmeric-water solution; 
no vacuum exposure 104

Figure C.31  Specimen 8 Cube 6 pull-off testing failure photograph: 
f’c 9427 psi mix; low-viscosity polymer with turmeric-water solution; 
no vacuum exposure 104

Figure C.32  Specimen 8 Cube 8 pull-off testing failure photograph: 
f’c 9427 psi mix; low-viscosity polymer with turmeric-water solution; 
no vacuum exposure 104

Figure C.33  Specimen 9 Cube 1 pull-off testing failure photograph: 
f’c 9427-psi mix; low-viscosity polymer with turmeric; 
24-hour vacuum exposure 105
Figure C.34  Specimen 9 Cube 2 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure 105

Figure C.35  Specimen 9 Cube 3 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure 105

Figure C.36  Specimen 9 Cube 4 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure 106

Figure C.37  Specimen 9 Cube 5 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure 106

Figure C.38  Specimen 9 Cube 6 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure 106

Figure C.39  Specimen 9 Cube 8 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure 107

Figure C.40  Specimen 10 Cube 2 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure 107

Figure C.41  Specimen 10 Cube 3 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure 107

Figure C.42  Specimen 10 Cube 6 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure 108

Figure C.43  Specimen 10 Cube 7 pull-off testing failure photograph:
f'c 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure 108

Figure C.44  Specimen 11 Cube 2 pull-off testing failure photograph:
f'c 9427-psi mix; high-viscosity polymer; no vacuum exposure 108

Figure C.45  Specimen 11 Cube 4 pull-off testing failure photograph:
f'c 9427-psi mix; high-viscosity polymer; no vacuum exposure 109
Figure C.46 Specimen 11 Cube 8 pull-off testing failure photograph:
f’c 9427-psi mix; high-viscosity polymer; no vacuum exposure
Abstract

While fiber-reinforced polymer materials have many applications in various industries, when used structurally, many cases, such as flexural and shear strengthening, are considered bond critical. Interfacial bond quality between a fiber-reinforced polymer system and the substrate is dependent on two mechanisms: chemical bonding and mechanical interlock, with mechanical interlock having the greater effect on bond quality. Mechanical interlock describes the type of bond that occurs as a result of surface roughness and substrate porosity and can be significantly affected by surface preparation methods and surface moisture.

This study aims to explore the possibility of enhancing bond quality between carbon-fiber-reinforced polymers and a high-strength concrete substrate through the implementation of three strategies: surface preparation by wet jetting, employing lower viscosity epoxies, and applying the lowest viscosity epoxy under vacuum conditions. Bond quality was evaluated through both nondestructive and destructive test methods; more specifically, visual inspection, active pulse thermography, and tensile pull-off testing was performed. Results indicate that lower-viscosity epoxies and vacuum exposure does not increase bond strength, and surface preparation by wet jetting may improve bond quality as compared to preparation by sand blasting, however future work may be needed here.
Chapter 1: Introduction

1.1 Overview

Fiber-reinforced polymers are composite materials consisting of two components: fibers typically produced from either glass or carbon fiber and polymer resins. While these materials have many applications in various industries, in construction, fiber-reinforced polymers are used both architecturally and structurally. Structural applications include both new construction and structural strengthening retrofits or repair of existing structures; examples include repair of damaged concrete bridges from either vehicle collision or earthquake, restoration of capacity lost to corrosion damage, increase of structural capacity, and provision of relief to embedded reinforcement steel. In the cases of flexural and shear strengthening, application of fiber-reinforced polymers is considered bond critical, or dependent on the quality of interfacial bond between a fiber-reinforced polymer system and the substrate, with tensile pull-off or bond strength requirements defined by the American Concrete Institute.

Interfacial bond quality between a fiber-reinforced polymer system and the substrate is dependent on two mechanisms: chemical bonding and mechanical interlock, with mechanical interlock having the greater influence on quality of bond. Mechanical interlock is achieved through both the surface roughness and porosity of the substrate and can be significantly affected by surface preparation and surface moisture. In 2019, a paper was published on an investigation into the role of concrete porosity on carbon fiber-reinforced polymer-concrete bond, which was performed at the University of South Florida. It was found that the depth of epoxy penetration into a concrete
substrate was markedly greater for the high-porosity concrete mixture as compared to the middle-
and low-porosity mixtures.

1.2 Objective Statement

The objective of this study is to explore potential feasibility of epoxy bond enhancement in
fiber-reinforced polymer repairs on high-strength concrete slab specimens. Three strategies are
applied: surface preparation by wet jetting, employing lower viscosity epoxies, and applying the
lowest viscosity epoxy under vacuum conditions. Slab specimens are then tested using both
nondestructive and destructive methods; more specifically, visual inspection, active pulse
thermography, and tensile pull-off testing is performed. Results will be grouped by slab specimen
repair strategy specifics in order to identify any correlations between repair strategy, surface
anomalies, thermal anomalies, and pull-off strength.

1.3 Thesis Organization

The organization of this thesis is arranged into the seven chapters described below.

Chapter 2 discusses fiber-reinforced polymer (FRP) composite materials, their use as a
structural repair material, the individual components of these composites, as well as the process of
repair using FRP materials and quality control methods to ensure a sound repair. This chapter also
provides a brief overview of the study published in 2019 that focused on FRP mechanical bond as
it relates to concrete porosity. Chapter 3 details the process of fabricating the concrete slab
specimens used in this study and the materials used, such as concrete mix, epoxy materials, and
fiber mesh fabric. Additionally, repair surface preparation and repair procedures are also outlined
in Chapter 3. Chapter 4 outlines both nondestructive and destructive testing procedures used to
evaluate bond quality for each repaired slab specimen. Chapter 5 reports full results from the
testing protocol outlined in Chapter 4. Chapter 6 provides a discussion and summary of the results
presented in Chapter 5. Lastly, Chapter 7 provides a concise listing of conclusions based on the results and analysis of this study.
Chapter 2: Literature Review

This chapter provides a brief discussion on fiber-reinforced polymers (FRP), fiber-reinforced polymers as a repair material, quality control methods, and recently performed research related to the role of concrete porosity in epoxy penetration depth in externally bonded FRP applications.

2.1 Fiber-Reinforced Polymers

Composite materials, which fiber-reinforced polymers are considered, have been used as building materials for thousands of years. Early composites were composed of simply soil, water, and straw or grass, which resulted in a stronger material when combined (ACI Committee 440, 2007). The concept of something being “greater than the sum of its parts” is recognized throughout many of the composite materials developed over the years (ACMA, 2020). It was not until after the advent of plastics in the beginning of the 20th century, however, that FRP technology was developed (ACI Committee 440, 2007). Since this technological advancement, modern composite materials are often comprised of a polymeric resin matrix that surrounds fiber reinforcements. In addition to building materials, fiber-reinforced polymers have been known to be used in countless other applications including marine vehicles, road motor vehicles, cycling, professional motorsports, aerospace, as well as other manufacturing and infrastructure applications, where traditional materials like steel, aluminum, timber, or even concrete would have otherwise been used. Fiber-reinforced polymers are typically preferred when considerations such as strength-to-weight ratios, corrosion resistance, durability, and/or design flexibility are necessary (ACMA, 2020).
Fiber-reinforced polymers can be processed for manufacturing two ways: open molding or closed molding. The open molding process can be broken down into more specific methods, which include hand lay-up, spray-up, and filament winding; what they all have in common, however, is being exposed to air during the curing process. Hand lay-up involves placing fiber reinforcements by hand and applying the polymer portion of the composite with a brush or roller. The spray-up method involves short fiber reinforcements premixed into a polymer and, using specialized equipment, spraying the composite material onto a molding surface. Finally, filament winding involves uninterrupted lengths of fiber reinforcement strands pre-saturated with polymer that are wound around a revolving mold. Conversely, closed molding involves placing and allowing FRP components to cure in a mold closed off from the surrounding environment, such as two-sided molds, injection molding, or vacuum molding (ACMA, 2020).

2.2 Fiber-Reinforced Polymers as a Repair Materials

Fiber-reinforced polymers have been used in various capacities as a building construction material for decades. These capacities include both architectural and structural applications. Architectural applications include decorative elements to structures such as cupolas, domes, cornices, columns, and façade details (ACMA, 2020). Structural applications include the construction of entire bridge decks, reinforcing materials such as FRP reinforcing bars embedded in concrete, or materials used in the structural repair or retrofitting of existing structures (ACI Committee 440, 2007; ACMA, 2020).

When fiber-reinforced polymers are prescribed in structural repair or retrofitting applications, FRP is often seen applied to concrete structures. According to the National Highway Institute (2020), damaged concrete bridges from either vehicle collision or earthquake make excellent candidates for FRP repair. It is also possible to restore capacity lost to corrosion damage,
increase structural capacity, as well as provide relief to embedded reinforcement steel through FRP applications.

2.2.1 Fibers

The fiber component of fiber-reinforced polymers can be satisfied by a number of materials; however, three specific types are most often used in FRP repair applications: glass, carbon, and aramid (ACMA, 2020; National Highway Institute, 2020). Each of these fibers have their own benefits, which contribute to optimizing the performance of the repair.

Glass fibers can be broken down into three classes – C-glass, E-glass, and S-glass – although, E-glass, manufactured from easily-acquired lime-alumina-borosilicate, prevails in structural applications. E-glass is known to be highly electrically insulating, highly corrosion resistant, as well as having low sensitivity to moisture. Possible issues in structural applications include its higher density compared to carbon or aramid, lower modulus, creep factor, and temperature sensitivity (ACMA, 2020; National Highway Institute, 2020).

Carbon fibers can be further broken down by material, as they can be polyacrylonitrile-based (PAN-based), rayon-based, or pitch-based. Although relatively expensive, these fibers – specifically PAN-based – are preferred for bridge repair due to its high strength, high stiffness, high fatigue resistance, and lower thermal expansion coefficients compared to glass or aramid. Possible issues in structural applications include electrically conductive properties causing galvanic corrosion if used on metal, however this can be avoided by including a break material in the design, such as glass and resin (ACMA, 2020; National Highway Institute, 2020).

Aramid fibers, better known as Kevlar®, are synthetic fibers known for being high strength (six times stronger than steel), low density, and both thermally and electrically insulating. Although better known for its ballistic and blast protection applications, Kevlar has been used in
structural applications – more specifically, Kevlar 29 and 49 – as it does have high fatigue, creep, and impact resistance (ACMA, 2020; National Highway Institute, 2020).

In addition to material selection, fiber architecture can also be manipulated to suit specific needs. Fibers can be provided as multi-end and single-end rovings; mats of chopped strands; or woven, stitched, or braided fabrics. These variations in fiber architecture allow for the detailing of unidirectional or multidirectional reinforcement (ACI Committee 440, 2007).

2.2.2 Polymers

The polymer component of fiber-reinforced polymers is satisfied by two primary types of resins: thermosets and thermoplastics. Thermosets include polyester, epoxy, vinyl ester, phenolic, and polyurethane materials; whereas thermoplastics include acrylonitrile butadiene styrene (ABS), polycarbonate, polyethylene, polystyrene, and polyvinyl chloride (PVC) materials. Thermosets typically start out as low-melting point solids or liquid and are then permanently cured through heat, a catalyst, or by combining the two, which cross-links or polymerizes the molecule network (ACI Committee 440, 2007; ACMA, 2020; National Highway Institute, 2020). If heated after curing, thermosets may soften and lose hardness but will not melt and flow as they did in their initial form (ACI Committee 440, 2007). Conversely, thermoplastics are solid at room temperature, have the ability to soften to a semifluid state when heated, and may be molded in this state. Once cooled, thermoplastics harden, however the molecule network does not cross link and is therefore not a permanent cure. This allows these materials to be endlessly softened, melted, molded, and remolded (ACI Committee 440, 2007; ACMA, 2020; National Highway Institute, 2020). Because thermoplastics do not cure permanently, their use in structural capacities is less suitable (National Highway Institute, 2020). In addition to the general differences between thermosets and
thermoplastics, the individual resins within these two subsets can also vary in viscosity allowing for further customization in the application design.

2.2.3 Repair Process

Although the various combinations of an externally bonded FRP reinforcing system are seemingly endless, the repair process can be summarized in a few steps. Beginning with surface preparation, much of the quality and durability of an externally bonded FRP reinforcing system is dependent upon a sound and properly prepared substrate (ACI Committee 440, 2017). According to the International Concrete Repair Institute (2013), surface preparation is defined as, “the removal of laitance, dirt, oil, films, paint, coatings, sound, and unsound concrete, and other materials that will interfere with the adhesion or penetration of a sealer, coating, polymer overlay, or repair material,” the goal of which is to ensure the substrate pore structure is open in order to accept the application of the specified repair system. Ensuring the substrate pore structure is open is primarily achieved through surface roughening. The required roughening profile is specified in ACI 440.2R-17 Section 6.4.2.1 which states, “concrete surface should be prepared to a surface profile not less than CSP 3, as defined by ICRI 310.2R.” In the event the concrete substrate is not competent enough for the specified repair system, the substrate itself must first be repaired (ACI Committee 440, 2017). Once the repair surface is properly prepared, the specified resin or resins should be mixed and the subsequent application of the FRP repair system to follow in accordance with manufacturer’s procedures. The repair should then be allowed to cure per the manufacturer’s specifications, paying particular attention to time and temperature requirements, as curing is dependent on these two factors.

In bond-critical FRP applications, structural strengthening is reliant on the interfacial bond between the FRP system and the concrete substrate. Examples of these applications include
flexural and shear strengthening. Typically, this type of strengthening is performed on beams and slabs (ACI Committee 440, 2007). The interfacial bond quality between an FRP system and concrete substrate is a function of primarily two mechanisms: chemical bonding and mechanical interlock, with mechanical interlock having a larger effect on bond quality. Mechanical interlock between an FRP system and concrete substrate occurs when the repair material penetrates into and hardens within open cavities or pores and general surface roughness of the concrete substrate; therefore, bond quality can be significantly affected by the surface preparation and surface moisture of the concrete substrate, as well as concrete porosity (Bissonnette, Courard, Garbacz, Vaysburd, & Fay, 2017).

2.3 Quality Control

Quality control of FRP repairs is typically carried out by both nondestructive and destructive testing techniques. Nondestructive techniques are testing methods that do not cause any “structurally significant damage,” as defined by ACI 228.2R-98, or do not destroy “the serviceability of the part or system,” as defined by the American Society for Nondestructive Testing (ASNT). Nondestructive methods are better suited for detecting anomalies in materials as compared to destructive testing methods, which are more often used to establish physical and strength properties of a material (ACI Committee 228, 1998; American Society for Nondestructive Testing, 2019).

2.3.1 Nondestructive Techniques

In addition to visual inspection, the most common nondestructive method, there are many nondestructive testing methods available. Often named for their penetration mechanism or required equipment, the ASNT recognizes 13 additional nondestructive test methods. These methods include:
1. Acoustic emission testing
2. Electromagnetic testing
3. Guided wave testing
4. Infrared and thermal testing
5. Laser testing
6. Leak testing
7. Liquid penetrant testing
8. Magnetic flux leakage
9. Magnetic particle testing
10. Neutron radiographic testing
11. Radiographic testing
12. Ultrasonic testing
13. Vibration analysis

ACI Committee 228 specifies nondestructive test methods suitable for evaluation of concrete structures in ACI 228.2R. Each of these methods falls under one of the categories defined by ASNT. Again, in addition to visual inspection, these techniques include: ultrasonic pulse velocity, ultrasonic echo, impact echo, spectral analysis of surface waves, sonic echo, impulse response, impedance logging, crosshole sonic logging, parallel seismic, direct transmission radiometry, backscatter radiometry, radiography, gamma-gamma logging, covermeter, half-cell potential, polarization methods, penetrability methods, infrared thermography, and radar (ACI Committee 228, 1998). When it comes to identifying undesirable conditions such as delaminations, disbonds, or voids, infrared thermography can be used when applied properly (American Society for Nondestructive Testing, 2019).
Infrared thermography does not directly measure surface temperature but rather surface radiance; therefore, the imaging produced by this method illustrates the variation in surface radiance. Emitted radiation wavelengths, however, are dependent on temperature, with higher temperatures corresponding to shorter wavelengths eventually entering the visible spectrum at suitably high temperatures (ACI Committee 228, 1998).

When applied to concrete structures, infrared thermography relies on two principles: first that the surface can emit electromagnetic radiation energy and the second being that anomalies such as delaminations, disbonds, or voids disrupt or affect the flow of heat (ACI Committee 228, 1998). This heat flow can be a result of natural heating processes (passive) as is seen with solar gain throughout the day or artificially through means such as heat lamps (active). When considering the active approach, pulse thermography is a common thermal stimulation method. This method involves exposing a testing surface or specimen to heat temporarily, then observing the temperature decay. Any anomalies would appear as an area higher in temperature as compared to the surrounding area; this is due to a reduction of the diffusion rate as a result of the subsurface anomaly (Maldague, 2002).

2.3.2 Destructive Techniques

Unlike nondestructive testing, destructive methods test a material to failure, which establishes the physical and/or strength properties. Depending on the material and its application, this can be achieved through compression testing, tensile testing, shear testing, flexural testing, torsion testing, or impact testing. For FRP laminates bonded to concrete, ACI Committee 440 has provided a test method recommendation guide for this specific condition, which includes the method for direct tension pull off testing (ACI Committee 440, 2012). In the most recent version of the guide, it is recommended that ASTM 7522 be followed for this test. Generally, this test
method involves scoring through the FRP laminate to the concrete substrate with a core drill having an interior diameter equal to the circular loading fixture, bonding the circular loading fixture to the scored portion of the FRP laminate, connecting the loading fixture to the pull-off testing apparatus, and applying increasing load until failure. The test method also includes descriptions of seven failure modes ranging from bonding adhesive failure at the loading fixture to cohesive failure in the concrete substrate.

2.4 Recently Performed Research

In 2019, an investigation into the role of concrete porosity on carbon fiber-reinforced polymer-concrete bond was published by the American Concrete Institute in the ACI Structural Journal (Al Azzawi, Mullins, & Sen, 2019). This study was performed at the University of South Florida, and the objective of which was to test the bond strength between carbon fiber-reinforced polymers (CFRP) and concrete for both high-porosity, low-strength concrete as well as low-porosity, high-strength concrete under identical moisture exposure conditions in order to show any effects of epoxy penetration of voids within concrete on CFRP bond quality and durability (Al Azzawi, 2018). Testing program elements included slab sample specimens fabricated from three distinct concrete mixtures, each with differing concrete strengths, two commercially available, unidirectional CFRP systems, and three exposure categories (control, wet, and dry). Bond quality was evaluated through pull-off testing.

A total of twenty-four (24) 9-inch square slab sample specimens, with thicknesses of 2.5 inches, were fabricated using three different concrete batches for differing concrete strengths. The measured 28-day strengths for each batch were:

- 2325 psi – referred to as Group 15
- 4206 psi – referred to as Group 35
- 7040 psi – referred to as Group 50

Porosity for each batch was also quantified through mercury intrusion porosimetry (MIP). This testing gave the following results for each batch group:

- Group 15 – 0.1085 cm³/g (0.00174 ft³/lb)
- Group 35 – 0.0922 cm³/g (0.00145 ft³/lb)
- Group 50 – 0.0731 cm³/g (0.00117 ft³/lb)

All of which conform to the inverse relationship assumption of lower-strength concretes exhibiting higher porosity and higher-strength concretes exhibiting lower porosity.

Surface preparation for the CFRP repair was performed in accordance with ACI-440.2R-17, aiming to achieve a Concrete Surface Profile (CSP) 3. This was accomplished through light sandblasting. In addition to repair surface preparation, the slab specimens were oven dried for 48 hours at 230°F per ASTM C642 (Standard Test Method for Density, Absorption, and Voids in Hardened Concrete). Three slab sample specimens were then subsequently repaired using both CFRP systems (two systems total) for Concrete Batch Groups 15, 35, and 50, giving a total of 18 repaired slab sample specimens. A visual representation of this breakdown can be seen in Figure 2.1 below.

With respect to epoxy penetration between each concrete mixture, results of this study showed that the depth of penetration was markedly greater for the high-porosity mixture. In the representative cross-sectional images provided in the study, depth of penetration in the high-porosity sample ranged from approximately 4 to 9 millimeters, whereas in the low-porosity sample, depth of penetration was at approximately 1.5 millimeters consistently across the cross section.
Figure 2.1 Test sample matrix described in the 2019 study by Al Azzawi, Mullins et. al.

2.5 Chapter Summary

Aside from a detailed overview of polymers and fiber-reinforced polymers, this chapter introduced the concept of, and selected results associated with, mechanical bond stemming from concrete porosity. This study focuses on epoxy bond enhancement of epoxies used in carbon-fiber-reinforced polymer systems on relatively low-porosity, high-strength concrete mixes. The two concrete mixes used in this study are both approved by the Florida Department of Transportation. Three strategies for epoxy bond enhancement are applied: surface preparation through wet jetting, employing lower viscosity epoxies, and applying the lowest viscosity epoxy under vacuum conditions.
Chapter 3: Specimen Fabrication, Surface Preparation, and Repair

This chapter discusses the materials and methods used to fabricate the concrete slab specimens used for this study, surface preparation methods, and the CFRP materials and methods used to repair the concrete slab specimens.

3.1 Formwork

A total of twelve (12) specimen forms were fabricated using 8-foot whitewood 2x4 studs. The studs were cut into a total of forty-eight (48) 10.5-inch lengths in order to create square forms with inner dimensions of 9 in. x 9 in. x 3.5 in. The bottom of each form was made from 10.5-inch squares of ½-inch plywood. Each form was fastened together using a total of eight standard 3.5-inch deck screws – one on each side and four around the bottom. Finally, the interiors of the forms were caulked along the seams and sprayed with WD-40 to aid in demolding. The completed forms can be seen below in Figure 3.1.

![Figure 3.1 Twelve fabricated concrete specimen forms.](image)
3.2 Specimen Materials and Fabrication

A total of twenty-four (24) 9-inch x 9-inch x 2.5-inch slab specimens and thirty (30) concrete cylinders were cast over two separate concrete pours (Figure 3.2); the first on March 11, 2019, at Standard Concrete Products in Tampa, Florida, and the second on April 30, 2019 at Coreslab in Tampa, Florida. Mix tickets for each pour can be found in Appendix A. Twelve (12) slab specimens and eighteen (18) cylinders were cast on 3/11/19. Twelve (12) slab specimens and twelve (12) cylinders were cast on 4/30/19. Both pours were added onto previously scheduled pours each using Florida Department of Transportation mix designs.

![Figure 3.2 Casting concrete specimens and cylinders at both pour locations.](image)

Slab specimens and cylinders were cured in open air in the conditioned space of the Soils Laboratory. The thermostat temperature was consistently set to 72° F during this time. Cylinders remained in their molds while the slab specimens were demolded after 7 days. At 28 days post pour,
cylinders were tested to determine the 28-day strength of each mix, the results of which may be found in Table 3.1 below. The average 28-day compressive strength for Mix A was 8744 psi, and Mix B average 28-day compressive strength was 9427 psi.

**Table 3.1 28-day compression test results.**

<table>
<thead>
<tr>
<th>Cylinder #</th>
<th>Maximum Load (kips)</th>
<th>Fracture Type</th>
<th>Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>109.72</td>
<td>2</td>
<td>8731.22</td>
</tr>
<tr>
<td>2</td>
<td>110.03</td>
<td>2</td>
<td>8756.08</td>
</tr>
<tr>
<td>Mix B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>117.80</td>
<td>2</td>
<td>9374.56</td>
</tr>
<tr>
<td>2</td>
<td>119.12</td>
<td>2</td>
<td>9478.87</td>
</tr>
</tbody>
</table>

### 3.3 Specimen Surface Preparation

The repair surface of each slab specimen was first prepared by wet jetting in order to develop a Concrete Surface Profile of CSP3 as per ACI 440.2R-17. Wet jetting was accomplished with a Simpson 3100 psi 2.5 GPM (gallon per minute) Premium Pressure Washer fit with Kränzle rotary nozzle (Figure 3.3). Slab specimens were lined up against an exterior wall of the ENG building and wet jetted (see Figure 3.4) by holding the nozzle 3 to 4 inches away from the concrete surface moving in a horizontal back-and-forth pattern across the slab, a vertical back-and-forth pattern across the slab, as well as diagonally back-and-forth across the slab; this ensured the repair surfaces were wet jetted as evenly as possible.

One of the wet-jetted slab specimens was set aside for surface characterization using a Keyance VR-5000 3D Measurement System (Figure 3.5). This allowed for a scanned and measured 3D surface profile of the specimen. The specimen was scanned per the manufacturer’s specifications. Surface characterization scans of both the unprepared and wet jetted surfaces can be seen in Figure 3.6, which shows both an increase in surface variation and amplitude exceeding the Concrete Surface Profile illustrated in CSP3 as per ACI 440.2R-17.
Just prior to repair, the remaining specimens were oven dried in batches (see Figure 3.7) for 48 hours at 230°F in order to evaporate any moisture that might have otherwise interfered with CFRP adhesion or penetration.

*Figure 3.3 Pressure washer used for wet jetting.*

*Figure 3.4 Wet jetting slab specimens.*
Figure 3.5 Wet-jetted surface characterization.
Figure 3.6 3D surface characterization scans of unprepared repair surface (top) and wet jetted surface (bottom).
3.4 Repair Materials

The materials used for this study included one commercially available, unidirectional carbon fiber (CF) mesh fabric and three distinct, commercially available two-part epoxy resins. The control epoxy resin is an impregnating resin, and when paired with the CF mesh, is considered a structural strengthening system by the manufacturer. The remaining two epoxy resins are lower in viscosity compared to the control and are considered to be crack healers by the manufacturer, however, for this study they were used as impregnating resins. For purposes of this thesis, the three epoxy resins will be identified by their relative viscosities and referred to as high viscosity (the control), medium viscosity, and low viscosity. Manufacturer specifications for the CF mesh fabric and each epoxy resin can be found in Tables 3.2, 3.3, 3.5, and 3.6, respectively, below. Additionally,
the cured laminate system properties for the CF mesh paired with the high-viscosity, control epoxy resin can be found in Table 3.4.

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>550 ksi (3,793 MPa)</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>34 msi (234.5 GPa)</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>1.5%</td>
</tr>
<tr>
<td>Areal Weight</td>
<td>18 oz/yd² (611 g/m²)</td>
</tr>
<tr>
<td>Density</td>
<td>0.065 lb/in³ (1.8 g/cc)</td>
</tr>
<tr>
<td>Nominal Fiber Thickness</td>
<td>0.0135 in (0.34 mm)</td>
</tr>
<tr>
<td>Fiber Direction</td>
<td>Unidirectional</td>
</tr>
</tbody>
</table>

Table 3.3 High-viscosity epoxy resin mechanical properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (ASTM D-638)</td>
<td>8 ksi (55 MPa)</td>
</tr>
<tr>
<td>Tensile Modulus (ASTM D638)</td>
<td>2.5 x 10⁵ psi (1,724 MPa)</td>
</tr>
<tr>
<td>Elongation at Break (ASTM D-638)</td>
<td>3%</td>
</tr>
<tr>
<td>Flexural Strength (ASTM D-790)</td>
<td>11.5 ksi (79 MPa)</td>
</tr>
<tr>
<td>Flexural Modulus (ASTM D-790)</td>
<td>5 x 10⁵ psi (3,450 MPa)</td>
</tr>
<tr>
<td>Mixed Viscosity</td>
<td>approx. 500 cps</td>
</tr>
</tbody>
</table>

Table 3.4 Cured laminate mechanical properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>160.9 ksi (1,110 MPa)</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>10.39 msi (71.7 GPa)</td>
</tr>
<tr>
<td>Tensile % Elongation</td>
<td>1.45%</td>
</tr>
<tr>
<td>Nominal Laminate Thickness</td>
<td>0.04 in (1.0 mm)</td>
</tr>
<tr>
<td>Tensile Strength per unit width</td>
<td>6.4 kips/in/ply</td>
</tr>
<tr>
<td>Stiffness per unit width</td>
<td>416 kips/in/ply</td>
</tr>
</tbody>
</table>
Table 3.5 Medium-viscosity epoxy resin mechanical properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (14 day)</td>
<td>7.9 ksi (54 MPa)</td>
</tr>
<tr>
<td>Modulus of Elasticity (14 day)</td>
<td>$2.0 \times 10^5$ psi (1,400 MPa)</td>
</tr>
<tr>
<td>Elongation at Break (14 day)</td>
<td>3.1%</td>
</tr>
<tr>
<td>Flexural Strength (14 day)</td>
<td>5.4 ksi (37.2 MPa)</td>
</tr>
<tr>
<td>Tangent Modulus in Bending (14 day)</td>
<td>$3.8 \times 10^5$ psi (2,620 MPa)</td>
</tr>
<tr>
<td>Shear Strength (14 day)</td>
<td>4.3 ksi (29.6 MPa)</td>
</tr>
<tr>
<td>Mixed Viscosity</td>
<td>approx. 200 cps</td>
</tr>
</tbody>
</table>

Table 3.6 Low-viscosity epoxy resin mechanical properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (14 day)</td>
<td>7.1 ksi (48.9 MPa)</td>
</tr>
<tr>
<td>Modulus of Elasticity (14 day)</td>
<td>Not Reported</td>
</tr>
<tr>
<td>Elongation at Break (14 day)</td>
<td>10%</td>
</tr>
<tr>
<td>Flexural Strength (14 day)</td>
<td>8.5 ksi (58.6 MPa)</td>
</tr>
<tr>
<td>Tangent Modulus in Bending (14 day)</td>
<td>$3.2 \times 10^5$ psi (2,206 MPa)</td>
</tr>
<tr>
<td>Shear Strength (14 day)</td>
<td>5.8 ksi (40.0 MPa)</td>
</tr>
<tr>
<td>Mixed Viscosity</td>
<td>approx. 105 cps</td>
</tr>
</tbody>
</table>

3.5 Vacuum Chamber

Three slab specimens were exposed to vacuum conditions for 24 hours prior to repair and during primer epoxy coat application. The purpose of the vacuum exposure was to evacuate any air from near-surface pores in the concrete. After the 24-hour exposure, a primer epoxy coat was flooded onto the slab repair surface while still under vacuum. The vacuum was then released, and the epoxy was subsequently pulled into the previously evacuated near-surface pores. Additional procedure details for this process will be outlined in Section 3.6.
The vacuum chamber was fabricated using 12-inch diameter PVC pipe, closed-cell foam seal stripping, 1-inch-thick acrylic sheeting, vacuum tubing, a quick connect hose coupling, release valve, brass compression fitting, and ¼-inch polyethylene tubing. An annotated diagram of the assembly can be seen below in Figure 3.8. During use, the chamber was connected to a Rietschle Thomas vacuum pump via the quick connect hose coupling, as seen in Figure 3.9.

Figure 3.8 Annotated vacuum chamber diagram.
(1: one-inch-thick acrylic plate, 2: 12-inch diameter PVC pipe, 3: brass compression fitting for ¼-inch polyethylene tubing, 4: closed-cell foam seal stripping, 5: release valve, 6: release valve connected to vacuum tubing with quick connect hose coupling)
3.6 Repair Procedure

A total of eleven (11) slab specimens were repaired with CFRP for this study, six specimens from the 8744-psi mix and five specimens from the 9427-psi mix. Two specimens from the 8744-psi mix and one specimen from the 9427-psi mix were exposed to vacuum prior to the repair. Prior to placement in the vacuum chamber, each vacuum-exposed slab specimen was fit with a foil edge barrier affixed with caulk. Additionally, all slab specimen repair surfaces were vacuumed and wiped with acetone prior to any repair steps. Further breakdown of repair specifics for specimens of each mix can be found in Tables 3.7 and 3.8, respectively. Both epoxy mixing and CFRP repairs
were performed in laboratory conditions. Laboratory temperature was consistent throughout the application and curing process at around 73º F.

The carbon fiber fabric was cut to approximately 9-inch squares. Each epoxy component for each epoxy type was measured and mixed per the manufacturer’s specifications. Mixing was performed in a metal mixing bucket using a power drill with a small paddle mixing attachment. For the vacuum-exposed specimens, the exterior end of a crimped ¼-inch polyethylene tubing (Figure 3.10) was submerged in a mixing cup of epoxy. The ¼-inch polyethylene tubing was then uncrimped allowing the epoxy to flow through the tubing into the still-sealed chamber and flood the repair surface of the slab (Figures 3.11 and 3.12). Once the full repair surface was flooded, the vacuum was released, and the slab specimen was removed from the chamber. For all other specimens, epoxy was poured onto each repair surface. The applied epoxy on both the vacuum-exposed slab specimens and all other specimens was then rolled on the repair surface as a primer layer. The carbon fiber fabric was impregnated with the epoxy and applied to the primed repair surface, then subsequently rolled to smooth and remove any bubbles or voids. The repaired slabs were then allowed to cure for 28 days in laboratory conditions. A full photo sequence of epoxy mixing and repair application can be found in Appendix B.

Table 3.7 Summary of repair specifics on the 8744-psi mix specimens.

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Epoxy Viscosity</th>
<th>Coloring Additions</th>
<th>Vacuum Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Medium</td>
<td>N/A</td>
<td>No Vacuum</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Turmeric-Water Solution</td>
<td>24-hour Vacuum</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>Turmeric-Water Solution</td>
<td>No Vacuum</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>Turmeric</td>
<td>24-hour Vacuum</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>Turmeric</td>
<td>No Vacuum</td>
</tr>
<tr>
<td>6</td>
<td>High</td>
<td>N/A</td>
<td>No Vacuum</td>
</tr>
</tbody>
</table>
Table 3.8 Summary of repair specifics on the 9427-psi mix specimens.

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Epoxy Viscosity</th>
<th>Coloring Additions</th>
<th>Vacuum Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Medium</td>
<td>N/A</td>
<td>No Vacuum</td>
</tr>
<tr>
<td>8</td>
<td>Low</td>
<td>Turmeric-Water Solution</td>
<td>No Vacuum</td>
</tr>
<tr>
<td>9</td>
<td>Low</td>
<td>Turmeric</td>
<td>24-hour Vacuum</td>
</tr>
<tr>
<td>10</td>
<td>Low</td>
<td>Turmeric</td>
<td>No Vacuum</td>
</tr>
<tr>
<td>11</td>
<td>High</td>
<td>N/A</td>
<td>No Vacuum</td>
</tr>
</tbody>
</table>

Figure 3.10 Photo illustrating the crimped ⅛-inch polyethylene tubing to be submerged in epoxy.
Figure 3.11 Epoxy flowing into sealed vacuum chamber.

Figure 3.12 Epoxy flooding repair surface in sealed vacuum chamber.
Chapter 4: Testing Procedures

This chapter defines and outlines the testing procedures used to evaluate and characterize the quality of the CFRP repair applied to the concrete slab specimens.

4.1 Nondestructive Testing

Nondestructive testing included two testing methods: 1) visual inspection and 2) active pulse infrared (IR) thermography. Per ACI 228.2R-98, the intent of visual inspection is to “observe, classify, and document the appearance of distress on exposed surfaces,” (ACI Committee 228, 1998). After 28 days of curing, repair surfaces of each slab specimen were photographed and visually inspected for any exterior surface anomalies.

Active pulse thermography was performed using a strip-style heat lamp as an artificial heat source and a Flir Tau 320 Infrared Camera. Test setup included configuration of the infrared camera and arrangement of the heat source on a stand capable of being pulled over top and across the repair surface of each slab specimen. The heat lamp was situated on a stand in order to maintain a consistent distance of 3 inches between the repair surface and heat source for each test pass. A diagram of this assembly can be seen in Figure 4.1. The infrared camera was securely fixed directly over the testing surface pointed straight down in order to capture a full overhead view of each test pass. Prior to testing, the infrared camera thermal scale algorithm settings were calibrated using the built-in “Once Bright” configuration setting within the Flir Tau Camera Controller software. Use of an analog-to-digital video converter allowed for a thermal video recording of each test pass. A photo presenting the test setup with a slab specimen ready for testing can be seen in Figure 4.2.
The steps outlined below were followed for the active pulse thermography testing of each repaired slab specimen:

1. Turn on heat source and allow to reach full temperature.
2. Begin thermal video recording.
3. Pull heat source over top and across the repair surface of the slab specimen at a rate of approximately 0.5 to 0.75 inches per second.
4. Observe video output until repaired slab surface has returned to thermal equilibrium.
5. Stop thermal video recording.

An example mid-test video still illustrating a test pass can be seen in Figure 4.3.

Analysis of each video recording consisted of visually observing the surface gradient temperature decay of each test pass. Recordings were inspected frame by frame and any temperature anomalies were documented.

Figure 4.1 Annotated diagram of heat-lamp-on-stand assembly.
(1: strip-style heat lamp; 2: 4x4 post base; 3: 2x4 whitewood stud)
Figure 4.2 Test setup with slab specimen ready for active pulse thermography testing.

Figure 4.3 Example mid-test video still of active pulse thermography test pass.
4.2 Destructive Testing

The final testing method performed on the repaired slab specimens was tensile pull-off testing and was performed in accordance with ASTM D7522-15, the Standard Test Method for Pull-Off Strength for FRP Laminate Systems Bonded to Concrete Substrate. A 220-kip MTS Hydraulic Test System paired with a specialized test box and tensile loading device (loading dolly) grip was used for this testing. A simplified diagram of the specialized test box and loading device grip is illustrated in Figures 4.4 (plan view) and 4.5 (elevation view). The tensile loading devices used were circular dollies 1.25 inches in diameter. A photograph illustrating this test system setup can be seen in Figure 4.6. Load and displacement data were collected digitally via the accompanying MTS FlexTest Controller software and Station Manager application.

Due to the size restrictions of the specialized test box, each repair slab specimen was cut down into 8 individual test cubes prior to the attachment of the loading dollies. This resulted in a total of eighty-eight (88) test cubes. The attachment surfaces of all loading dollies were sandblasted in order to maximize adherence for load testing. Once cut down, each test cube and loading dolly adhering surface was wiped with acetone, and one loading dolly was affixed to each test cube using 3M Scotch-Weld DP420. An example of this completed process for one repaired slab specimen can be seen in Figure 4.7. The loading dolly adhesive was allowed to cure for seven days. Once cured, the repaired slab specimen surface was scored around the adhered dolly using a diamond hole saw with an inner diameter of 1.25 inches and a drill press, as shown in Figure 4.8. Scoring consisted of drilling completely through the CFRP laminate and just into the concrete substrate, as shown in Figure 4.9.

Once all specimen cubes were prepared for testing, as defined above, the MTS Test System was configured for tensile pull-off testing with an absolute end level of 5 kips and a test rate of 20
lb/sec. Prior to testing, it was helpful to determine an optimal starting position of the force transducer for quick and efficient setup of each specimen cube, then setting that displacement position as the datum (zero). This allowed for the force transducer to be quickly “reset” prior to setting up the next cube for testing. The steps outlined below were followed for the tensile pull-off testing of each specimen cube:

1. Bring the force transducer to the predetermined zero displacement position.

2. Place the specimen cube into the test box ensuring that the loading dolly clears the access opening of the test box top plate and is securely inserted into the grip.

3. Secure the top plate of the test box.

4. Using the MTS remote set to Displacement mode, fine tune the position of force transducer such that there is approximately 1/8 inch spacing between the top of the specimen cube and the underside of the test box top.

5. Switch the MTS mode to Force.

6. Begin the preconfigured test and data recording (simultaneously).

7. End test once pull-off failure has occurred.

8. Record the nature of the failure plane.

Figure 4.4 Overhead (plan) view diagram of the test box top plate showing the dolly access opening.
Figure 4.5 Simplified diagram (elevation view) of the test box. (Test box attached to loading piston of MTS and loading device grip attached to force transducer of MTS; 1: loading device grip; 2: test box top plate; 3: screws for securing test box top plate)

Figure 4.6 MTS Test System pull-off testing set up.
Figure 4.7 Loading dollies adhered to repaired slab specimen cubes.

Figure 4.8 Scoring the repair surface of a test cube around the adhered loading dolly.
Figure 4.9 Vacuuming scored repair surface to reveal score depth.
Chapter 5: Results

This chapter presents the documented observations related to the visual inspections performed on the repaired slab specimens and results of the testing outlined in Chapter 4, which includes nondestructive active pulse thermography and destructive pull-off tensile testing.

5.1 Visual Inspection Observations and Nondestructive Testing Results

Visual inspection photographs and thermal video stills can be found in Figures 5.1 through 5.11 below. Video stills of selected instants of each temperature decay were captured after a frame-by-frame analysis of the recorded temperature decay of each repair surface.

Figure 5.1 Visual inspection photograph (left) and active thermography still (right) for Specimen 1: f′c 8744-psi mix; medium-viscosity polymer; no vacuum exposure.
Figure 5.2 Visual inspection photograph (left) and active thermography still (right) for Specimen 2: $f'_c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure.

Figure 5.3 Visual inspection photograph (left) and active thermography still (right) for Specimen 3: $f'_c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.
Figure 5.4 Visual inspection photograph (left) and active thermography still (right) for Specimen 4: f’c 8744-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.

Figure 5.5 Visual inspection photograph (left) and active thermography still (right) for Specimen 5: f’c 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.
Figure 5.6 Visual inspection photograph (left) and active thermography still (right) for Specimen 6: $f'_c$ 8744-psi mix; high-viscosity polymer; no vacuum exposure.

Figure 5.7 Visual inspection photograph (left) and active thermography still (right) for Specimen 7: $f'_c$ 9427-psi mix; medium-viscosity polymer; no vacuum exposure.
Figure 5.8 Visual inspection photograph (left) and active thermography still (right) for Specimen 8: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.

Figure 5.9 Visual inspection photograph (left) and active thermography still (right) for Specimen 9: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.
Figure 5.10 Visual inspection photograph (left) and active thermography still (right) for Specimen 10: $f_c$ 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.

Figure 5.11 Visual inspection photograph (left) and active thermography still (right) for Specimen 11: $f_c$ 9427-psi mix; high-viscosity polymer; no vacuum exposure.
5.2 Destructive Testing Results

Tensile pull-off testing results for each slab specimen are presented below in Tables 5.1 through 5.11. Results include both pull-off strength values in pounds per square inch (psi) and characterized failure modes per ASTM D7522-15. Full photographs of each test cube resulting in failures other than Failure Mode A can be found in Appendix C. Photo summaries of pull-off failures other than Failure Mode A for each slab specimen are presented in Figures 5.12 through 5.22 below. Definitions for each failure mode characterization per ASTM D7522-15 are as follows:

- A: bonding adhesive failure at loading fixture
- B: cohesive failure in FRP laminate
- C: adhesive failure at FRP/adhesive interface
- D: cohesive failure in adhesive
- E: adhesive failure at FRP/concrete interface
- F: mixed modes E and G
- G: cohesive failure in concrete substrate

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<th>Failure Mode</th>
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</thead>
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<td>G</td>
</tr>
<tr>
<td>3</td>
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<td>F</td>
</tr>
<tr>
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Table 5.2 Specimen 2 pull-off testing results.

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</tr>
<tr>
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Table 5.3 Specimen 3 pull-off testing results.

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<td>4</td>
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Table 5.4 Specimen 4 pull-off testing results.

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Table 5.5 Specimen 5 pull-off testing results.

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Table 5.6 Specimen 6 pull-off testing results.

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Table 5.7 Specimen 7 pull-off testing results.

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Table 5.8 Specimen 8 pull-off testing results.

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Table 5.9 Specimen 9 pull-off testing results.

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Table 5.10 Specimen 10 pull-off testing results.

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Table 5.11 Specimen 11 pull-off testing results.

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Figure 5.12 Specimen 1 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)
Figure 5.13 Specimen 2 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)

Figure 5.14 Specimen 3 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)

Figure 5.15 Specimen 4 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)
Figure 5.16 Specimen 5 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)

Figure 5.17 Specimen 6 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)

Figure 5.18 Specimen 7 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)
Figure 5.19 Specimen 8 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)

Figure 5.20 Specimen 9 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)

Figure 5.21 Specimen 10 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)
Figure 5.22 Specimen 11 photo summary of pull-off failures. (excludes cubes resulting in Failure Mode A)
Chapter 6: Analysis and Discussion

Visual inspection of the repaired slab specimens yielded no significant surface anomalies. Prior to tensile pull-off testing, the thermal video stills presented in Chapter 5 were overlayed onto the repaired slab photographs and analyzed in an image digitizer. Using the overall slab dimensions to establish a cartesian coordinate system, x-y coordinates for thermal anomalies on each slab specimen were identified. Each digitized thermal overlay composite image is presented below in Figures 6.1 to 6.11.

Figure 6.1 Overlay image with marked anomalies for Specimen 1: \( f'c \) 8744-psi mix; medium-viscosity polymer; no vacuum exposure.
Figure 6.2 Overlay image with marked anomalies for Specimen 2: f’c 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure.

Figure 6.3 Overlay image with marked anomalies for Specimen 3: f’c 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.
Figure 6.4 Overlay image with marked anomalies for Specimen 4: $f'_c$ 8744-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.

Figure 6.5 Overlay image with marked anomalies for Specimen 5: $f'_c$ 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.
Figure 6.6 Overlay image with marked anomalies for Specimen 6: $f_c$ 8744-psi mix; high-viscosity polymer; no vacuum exposure.

Figure 6.7 Overlay image with marked anomalies for Specimen 7: $f_c$ 9427-psi mix; medium-viscosity polymer; no vacuum exposure.
Figure 6.8 Overlay image with marked anomalies for Specimen 8: f’c 9427-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.

Figure 6.9 Overlay image with zero marked anomalies (none visible) for Specimen 9: f’c 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.
Based on these image digitizations, it can be seen that the medium- and low-viscosity systems resulted in fewer thermal anomalies as compared to the high-viscosity system for the 8744-psi concrete mixture. There were no correlations between thermal anomalies and vacuum exposure versus no vacuum exposure for the 8744-psi concrete mixture. Results were less straightforward for the 9427-psi concrete mixture with no clear correlation between thermal anomalies and epoxy.
viscosity. The 9427-psi mixture did show fewer thermal anomalies on the vacuum exposed specimen as compared to the non-vacuum exposed specimens, however.

Diagrams of each slab specimen were created which include maximum pull-off strengths (in psi) at their approximate testing locations on each slab specimen with distinctions between Failure Mode A and all other failure modes, as well as marked approximate locations of thermal anomalies based on the digitized locations previously discussed. Approximate locations of thermal anomalies are marked with a red X and testing locations resulting in Failure Mode A are outlined in a dashed line border. It should also be noted that the pull-off testing values are highlighted based on a relative conditional scale across all slab specimens. Highlight colors range from red (lower strengths) to yellow (middle strengths) to green (higher strengths). These diagrams can be seen below in Figures 6.12 to 6.22.

![Figure 6.12 Results summary diagram for Specimen 1.](image)
Figure 6.13 Results summary diagram for Specimen 2.

Figure 6.14 Results summary diagram for Specimen 3.
Figure 6.15 Results summary diagram for Specimen 4.

Figure 6.16 Results summary diagram for Specimen 5.
Figure 6.17 Results summary diagram for Specimen 6.

Figure 6.18 Results summary diagram for Specimen 7.
Figure 6.19 Results summary diagram for Specimen 8.

Figure 6.20 Results summary diagram for Specimen 9.
Figure 6.21 Results summary diagram for Specimen 10.

Figure 6.22 Results summary diagram for Specimen 11.
Based on the marked thermal anomaly locations, individual pull-off strength values, and relative values across all slab specimens, there doesn’t appear to be any correlation between pull-off strengths and number of thermal anomalies present. In fact, the slab specimen that exhibited the highest number of thermal anomalies resulted in the highest average pull-off strength (Specimen 6). This was not consistent across the different concrete mixes, however. Moreover, the locations of thermal anomalies did not always correlate to the individual locations with the lowest pull-off strengths on each slab specimen. Maximum pull-off strength averages were calculated for each slab specimen and are included below in Tables 6.1 and 6.2. A plot comparing average pull-off strengths of like repair specifics per each concrete mix can also be seen below in Figure 6.23. Figure 6.23 shows that the high-viscosity (control) epoxy results in the highest average pull-off strengths followed by (in order of greatest to least) those specimens with low-viscosity epoxy applied without vacuum exposure, specimens with low-viscosity applied with vacuum exposure, and finally, specimens with medium-viscosity epoxy applied (without vacuum). Because the specimens colored with powdered turmeric resulted in higher pull-off strengths as compared to the specimens colored with wet turmeric (turmeric-water solution), these are the specimens that are used for comparison against the high- and medium-viscosity epoxies.

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Average Maximum Pull-off Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>573.3</td>
</tr>
<tr>
<td>2</td>
<td>554.7</td>
</tr>
<tr>
<td>3</td>
<td>596.9</td>
</tr>
<tr>
<td>4</td>
<td>643.1</td>
</tr>
<tr>
<td>5</td>
<td>648.8</td>
</tr>
<tr>
<td>6</td>
<td>695.2</td>
</tr>
</tbody>
</table>

Table 6.1 Average maximum pull-off strength per 8744-psi mix slab specimen.
Table 6.2 Average maximum pull-off strength per 9427-psi mix slab specimen.

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Average Maximum Pull-off Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>559.8</td>
</tr>
<tr>
<td>8</td>
<td>529.5</td>
</tr>
<tr>
<td>9</td>
<td>571.2</td>
</tr>
<tr>
<td>10</td>
<td>612.7</td>
</tr>
<tr>
<td>11</td>
<td>628.1</td>
</tr>
</tbody>
</table>

Figure 6.23 Comparison of average pull-off strengths of like repair strategy specifics per each concrete mix. [Med: Specimens 1 & 7, Low w/ Vac (TW): Specimen 2, Low w/o Vac (TW): Specimens 3 & 8, Low w/ Vac (T): Specimens 4 & 9, Low w/o Vac (T): Specimens 5 & 10, High: Specimens 6 & 11]

Based on ACI 318-14, the tensile strength ($f_t$) was calculated for each concrete mix using the compressive strengths evaluated at the time of pull-off testing (several months after the 28-day...
strengths were evaluated). These compressive strengths were 9,485 psi and 12,506 psi, respectively. ACI 318-14 Section 14.5.2.1 gives the tensile strength to be:

\[ f_t = 5\sqrt{f'_c} \]

Using the above-referenced compressive strengths, the tensile strength for each concrete mix was calculated to be:

- 8744-psi Mix: 487 psi
- 9427-psi Mix: 559 psi

Not only can these tensile values be used to compare against pull-off strengths, but they can also be used in conjunction with the average pull-off strengths to calculate pull-off/f_t ratios, which are better suited for comparison to determine the percentage of tensile capacity of the concrete substrate that is captured. A similar comparison to Figure 6.23 using these pull-off/f_t ratios can be seen in Figure 6.24 below. Figure 6.24 shows that less tensile capacity is captured across the board for the 9427-psi concrete mix as compared to the 8744-psi mix.

While there were pull-off test failures that resulted in bonding adhesive failures at the loading fixture, overall, the pull-off strength values for this failure mode were distributed fairly evenly across all specimens. In other words, these values did not overwhelmingly represent either the lower or higher ends of pull-off strengths. This is clearer in Figure 6.25 below, where the solid data markers represent tests resulting in Failure Modes B through G and empty data markers represent tests resulting in Failure Mode A. It should be noted, however, that the tests resulting in Failure Mode A may result in higher pull-off strengths if retested to result in a Failure Mode B through G, which would increase the averages per specimen.
Figure 6.24 Comparison of average-pull-off-strength-to-$f_t$ ratio of like repair strategy specifics per each concrete mix.

Figure 6.25 Graphical representation of all pull-off test results in relation to $f_t$, comparison study pull-off strengths, and the tensile pull-off strength requirement as defined by ACI 440.2R.
Concrete tensile values for each concrete mix are marked. Line values at the centers of each pull-off test distribution for each specimen represent the pull-off averages per specimen. The comparison study pull-off strengths were obtained from the pull-off averages reported for the highest-strength concrete mix control specimens in the 2019 Al Azzawi, et al. study discussed in Chapter 2. As there were two control specimens in this study, these values were reported as 376 psi and 379 psi, respectively. Finally, the tensile pull-off strength requirement as defined by ACI 440.2R is also included, which is stated as 200 psi. Here, it is shown that all specimens resulted in an increase in pull-off strength as compared to the comparison study values. Furthermore, all pull-off results far exceeded the ACI 440.2R requirement, which provides significant allowance for any strength loss that may occur as a result of long-term exposure conditions, such as daily weather or marine conditions.

The pull-off/f\text{t}\text{c} ratio was also calculated for each individual pull-off test performed and the comparison study average pull-off strengths. The comparison study calculations used the provided 28-day compressive strength for the highest-strength concrete mix, which likely yielded a higher ratio as compared to a ratio calculated using the compressive strength at time of pull-off testing. These ratios are also represented graphically in Figure 6.26 below, similar to Figure 6.25. Here, it is shown that all average pull-off/f\text{t}\text{c} ratios increased in relation to the comparison study, suggesting that using wet jetting for surface preparation may improve bond quality as compared to surface preparation by sand blasting, the method used in the comparison study. Most notably, an increase in the high-viscosity (control) epoxy values, which was likewise used in the comparison study. It should also be pointed out that concrete strengths used in this study were higher than the highest-strength mix used in the comparison study, which may suggest that the specimens used in this study were also lower porosity compared to those in the comparison study. The final item of note
is that the scoring method used in the comparison study differed from that in this study. More specifically, the specimens were scored deeper into the concrete substrate in the comparison study. This may have had an overall effect on pull-off strengths. It is worth calling attention to the numerous individual pull-off tests from all specimens resulting in strengths that exceeded the theoretical tensile capacity as defined by ACI 318-14, as seen in Figure 6.25. Future work that includes a finite element analysis of each scoring method may be beneficial.

*Figure 6.26* Graphical representation of all pull-off-to-$f_t$ ratios for each pull-off test and comparison study values.
Chapter 7: Conclusions

- The medium- and low-viscosity systems resulted in fewer thermal anomalies as compared to the high-viscosity system for the 8744-psi concrete mixture; however, this was not the trend for the 9427-psi mixture, which showed no clear correlation between thermal anomalies and epoxy viscosity.

- There doesn’t appear to be any correlation between pull-off strengths and number of thermal anomalies present, nor did the locations of thermal anomalies correlate to the individual locations with the lowest pull-off strengths on each slab specimen. This shows that thermal imaging may need to register a larger differential than what was configured for this testing before there is a bond quality issue.

- Specimens repaired with the low-viscosity system without vacuum exposure resulted in higher overall pull-off strengths in relation to those repaired with the low-viscosity system with 24-hour vacuum exposure, however, this trend falls apart when only the tests resulting in Failure Modes B through G are considered. This implies that there is no evidence of any benefit to vacuum exposure prior to epoxy application.

- All pull-off results far exceeded the ACI 440.2R requirement, which provides significant allowance for any strength loss that may occur as a result of long-term exposure conditions.

- All average pull-off/f′_c ratios increased in relation to the comparison study, suggesting that using wet jetting for surface preparation may result in improved bond quality. The scoring
method used in the comparison study differed from that of this study, which may have had an overall effect on pull-off strengths. It is worth noting that several individual pull-off tests resulted in strengths that exceeded the theoretical tensile capacity as defined by ACI 318-14. Further investigation through a finite element analysis of each scoring method may be beneficial.

- The highest average pull-off strengths occurred on slab specimens repaired with the high-viscosity (control) system, indicating that a lower viscosity epoxy does not improve bond quality.
References


Appendix A: Concrete Mix Tickets

Figure A.1 Mix ticket for SCP concrete pour.
Figure A.2 Mix ticket for Coreslab concrete pour.

<table>
<thead>
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<th>Company:</th>
<th>Coreslab</th>
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<tr>
<td>Date/rev'd</td>
<td>4/11/19</td>
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<tr>
<td>Trial:</td>
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**MIX DESIGN**

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<th>Lbs.</th>
<th>Type</th>
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<th>Trial Weights</th>
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**Theo Unit Weight**

|             | Total | 26.99 |

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**Add. Water Al.:**

|             | Spng | 4.3 |

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<th>Concrete Temp.</th>
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</table>

| Sand/Agg Ratio | 0.469 |
| W/Cm           | 0.369 |
| Total Cementitious | 800.00 |
| % Fly Ash       | 34.3  |
| Total Mass      | 3792  |
Appendix B: Repair Procedure Photo Sequence

Figure B.1 Vacuum chamber setup.
Figure B.2 Cut carbon fiber fabric with epoxy mixing bucket and roller.

Figure B.3 Vacuuming slab specimen repair surfaces.
Figure B.4 Wiping down slab specimen repair surfaces with acetone.

Figure B.5 Staged CF fabric sheets and specimens ready for repair.
Figure B.6 Low-viscosity epoxy parts staged for measuring and mixing.

Figure B.7 Pouring measured low-viscosity epoxy parts into mixing bucket.
Figure B.8 Mixing low-viscosity epoxy parts after coloring addition. (turmeric-water solution; see summary tables of repair specifics)

Figure B.9 Portioning out mixed low-viscosity epoxy for CF fabric impregnation.
Figure B.10 Impregnating CF fabric and rolling low-viscosity primer epoxy layer onto repair surfaces.

Figure B.11 Smoothing low-viscosity CFRP repair after applying impregnated CF fabric.
Figure B.12 Vacuum chamber with crimped $\frac{3}{4}$-inch polyethylene tubing to be submerged in epoxy.

Figure B.13 Low-viscosity epoxy entering sealed vacuum chamber.
Figure B.14 Epoxy flooding slab specimen repair surface in sealed vacuum chamber.

Figure B.15 Flooded repair surface in sealed vacuum chamber.
Figure B.16 Flooded repair surface after breaking vacuum seal.

Figure B.17 Removal of slab edge barrier on vacuum-exposed slab specimen.
Figure B.18 Rolling low-viscosity primer epoxy layer on vacuum-saturated repair surface.

Figure B.19 Smoothing low-viscosity CFRP repair after applying impregnated CF fabric.
Figure B.20 Mixing medium-viscosity epoxy.

Figure B.21 Rolling medium-viscosity primer epoxy layer onto repair surfaces.
Figure B.22 Impregnating CF fabric with medium-viscosity epoxy.

Figure B.23 Overhead photo showing medium-viscosity primer epoxy layer application and CF fabric impregnation.
Figure B.24 Smoothing medium-viscosity CFRP repair after applying impregnated CF fabric.

Figure B.25 Mixing high-viscosity epoxy.
Figure B.26 Curing slab specimens and staged slab specimens for final application of low-viscosity CFRP.

Figure B.27 Mixing low-viscosity epoxy with coloring addition. (turmeric powder)
Figure B.28 Rolling low-viscosity primer epoxy layer onto repair surfaces.

Figure B.29 Impregnating CF fabric with low-viscosity epoxy.
Figure B.30 Completed low-viscosity CFRP repair on non-vacuum-exposed slab specimens.

Figure B.31 Flooding vacuum-exposed repair surface with low-viscosity epoxy.
Figure B.32 Flooded repair surface in sealed vacuum chamber.

Figure B.33 Removing edge barrier on vacuum-exposed slab specimen.
Figure B.34 Rolling low-viscosity primer epoxy layer on vacuum-saturated repair surface.

Figure B.35 Smoothing low-viscosity CFRP repair to remove any bubbles or voids.
Appendix C: Tensile Pull-Off Testing Failure Photographs

Figure C.1 Specimen 1 Cube 1 pull-off testing failure photograph: $f_c$ 8744-psi mix; medium-viscosity polymer; no vacuum exposure.

Figure C.2 Specimen 1 Cube 2 pull-off testing failure photograph: $f_c$ 8744-psi mix; medium-viscosity polymer; no vacuum exposure.
Figure C.3 Specimen 1 Cube 3 pull-off testing failure photograph: $f'c$ 8744-psi mix; medium-viscosity polymer; no vacuum exposure.

Figure C.4 Specimen 1 Cube 4 pull-off testing failure photograph: $f'c$ 8744-psi mix; medium-viscosity polymer; no vacuum exposure.

Figure C.5 Specimen 1 Cube 5 pull-off testing failure photograph: $f'c$ 8744-psi mix; medium-viscosity polymer; no vacuum exposure.
Figure C.6 Specimen 1 Cube 7 pull-off testing failure photograph: $f\text{'c}$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure.

Figure C.7 Specimen 2 Cube 1 pull-off testing failure photograph: $f\text{'c}$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure.

Figure C.8 Specimen 2 Cube 4 pull-off testing failure photograph: $f\text{'c}$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure.
Figure C.9 Specimen 2 Cube 6 pull-off testing failure photograph: $f'c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure.

Figure C.10 Specimen 2 Cube 7 pull-off testing failure photograph: $f'c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; 24-hour vacuum exposure.

Figure C.11 Specimen 3 Cube 1 pull-off testing failure photograph: $f'c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.
Figure C.12 Specimen 3 Cube 3 pull-off testing failure photograph: $f'c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.

Figure C.13 Specimen 3 Cube 4 pull-off testing failure photograph: $f'c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.

Figure C.14 Specimen 3 Cube 6 pull-off testing failure photograph: $f'c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.
Figure C.15 Specimen 3 Cube 7 pull-off testing failure photograph: $f'_c$ 8744-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.

Figure C.16 Specimen 4 Cube 2 pull-off testing failure photograph: $f'_c$ 8744 psi-mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.

Figure C.17 Specimen 4 Cube 6 pull-off testing failure photograph: $f'_c$ 8744-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.
Figure C.18 Specimen 5 Cube 1 pull-off testing failure photograph: $f'$c 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.

Figure C.19 Specimen 5 Cube 3 pull-off testing failure photograph: $f'$c 874-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.

Figure C.20 Specimen 5 Cube 5 pull-off testing failure photograph: $f'$c 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.
Figure C.21 Specimen 5 Cube 6 pull-off testing failure photograph: $f'c$ 8744-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.

Figure C.22 Specimen 6 Cube 2 pull-off testing failure photograph: $f'c$ 8744-psi mix; high-viscosity polymer; no vacuum exposure.

Figure C.23 Specimen 6 Cube 6 pull-off testing failure photograph: $f'c$ 8744-psi mix; high-viscosity polymer; no vacuum exposure.
Figure C.24 Specimen 6 Cube 8 pull-off testing failure photograph: $f'c$ 8744-psi mix; high-viscosity polymer; no vacuum exposure.

Figure C.25 Specimen 7 Cube 1 pull-off testing failure photograph: $f'c$ 9427-psi mix; medium-viscosity polymer; no vacuum exposure.

Figure C.26 Specimen 7 Cube 4 pull-off testing failure photograph: $f'c$ 9427-psi mix; medium-viscosity polymer; no vacuum exposure.
Figure C.27 Specimen 7 Cube 5 pull-off testing failure photograph: f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure.

Figure C.28 Specimen 7 Cube 7 pull-off testing failure photograph: f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure.

Figure C.29 Specimen 7 Cube 8 pull-off testing failure photograph: f’c 9427-psi mix; medium-viscosity polymer; no vacuum exposure.
Figure C.30 Specimen 8 Cube 5 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.

Figure C.31 Specimen 8 Cube 6 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.

Figure C.32 Specimen 8 Cube 8 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric-water solution; no vacuum exposure.
Figure C.33 Specimen 9 Cube 1 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.

Figure C.34 Specimen 9 Cube 2 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.

Figure C.35 Specimen 9 Cube 3 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.
Figure C.36 Specimen 9 Cube 4 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.

Figure C.37 Specimen 9 Cube 5 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.

Figure C.38 Specimen 9 Cube 6 pull-off testing failure photograph: $f'c$ 9427-psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.
Figure C.39 Specimen 9 Cube 8 pull-off testing failure photograph: $f'_c$ 9427 psi mix; low-viscosity polymer with turmeric; 24-hour vacuum exposure.

Figure C.40 Specimen 10 Cube 2 pull-off testing failure photograph: $f'_c$ 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.

Figure C.41 Specimen 10 Cube 3 pull-off testing failure photograph: $f'_c$ 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.
Figure C.42 Specimen 10 Cube 6 pull-off testing failure photograph: $f_c$ 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.

Figure C.43 Specimen 10 Cube 7 pull-off testing failure photograph: $f_c$ 9427-psi mix; low-viscosity polymer with turmeric; no vacuum exposure.

Figure C.44 Specimen 11 Cube 2 pull-off testing failure photograph: $f_c$ 9427-psi mix; high-viscosity polymer; no vacuum exposure.
Figure C.45 Specimen 11 Cube 4 pull-off testing failure photograph: $f'c$ 9427-psi mix; high-viscosity polymer; no vacuum exposure.

Figure C.46 Specimen 11 Cube 8 pull-off testing failure photograph: $f'c$ 9427-psi mix; high-viscosity polymer; no vacuum exposure.