August
2017

Performance of Adhesive and Cementitious Anchoring Systems

Charles D. Baker, *Governor*

Karyn E. Polito, *Lieutenant Governor*

Stephanie Pollack, *MassDOT Secretary & CEO*

U.S. Department of Transportation
Federal Highway Administration

massDOT
Massachusetts Department of Transportation

Technical Report Document Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
n/a	n/a	n/a

4. Title and Subtitle	5. Report Date
Performance of Adhesive and Cementitious Anchoring Systems	August 2017
	6. Performing Organization Code n/a
7. Author(s) Dr. Scott Civjan, Mirna Mendoza, Douglas Droesch, and Rachel Wang	8. Performing Organization Report No. UMTC 17-5
9. Performing Organization Name and Address University of Massachusetts Amherst College of Engineering 130 Natural Resources Road Amherst MA 01003	10. Work Unit No. (TRAIS) n/a 11. Contract or Grant No. n/a
12. Sponsoring Agency Name and Address Massachusetts Department of Transportation Office of Transportation Planning Ten Park Plaza, Suite 4150, Boston, MA 02116	13. Type of Report and Period Covered Final Report: September 2014–May 2017 14. Sponsoring Agency Code n/a

15. Supplementary Notes
n/a

16. Abstract
This research project evaluated the behavior of adhesive and cementitious bonded anchoring systems per the approach found in the provisional standard AASHTO TP-84, in order to provide recommendations pertaining to the test method. Additional parameters studied included installation direction and extreme in-service temperatures. Polymer characterization testing of adhesive products was also conducted in order to comment on technique usefulness for quality assurance and quality control of field-installed bonded anchor materials. While AASHTO TP-84 is a promising test method, adoption is not recommended unless it is adopted nationally. Recommendations are provided to improve the method, and the test method is not applicable to materials with higher variability in static test results, as measured by coefficient of variation in results. Some concerns still persist regarding physical aging on bonding materials. Based on a small sample of tests, there is concern regarding material performance in tension should the temperature drop below the manufacturer recommended installation temperature during the life of the anchor. Polymer characterization testing is expected to be a useful tool for quality assurance and quality control of anchor materials. A proposed implementation plan is included to allow anchor approval; however, the prohibition on sustained pure tension load should remain in place.

17. Key Word	18. Distribution Statement
Adhesive anchor, post-installed anchor, creep, pullout test, test methods, sustained tension	n/a

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
unclassified	unclassified	132	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

This page left blank intentionally.

Performance of Adhesive and Cementitious Anchoring Systems

Final Report

Prepared by:

Dr. Scott Civjan
Principal Investigator

Mirna Mendoza
Research Assistant

Douglas Droesch
Research Assistant

Rachel Wang
Research Assistant

130 Natural Resources Road
Amherst, MA 01003

Prepared for:

Massachusetts Department of Transportation
10 Park Plaza Suite 41602
Boston, MA 02116

August 2017

This page left blank intentionally.

Acknowledgements

Prepared in cooperation with the Massachusetts Department of Transportation, Office of Transportation Planning and the United States Department of Transportation, Federal Highway Administration.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view of policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

This page left blank intentionally.

Executive Summary

This study of Performance of Adhesive and Cementitious Anchoring Systems was undertaken as part of the Massachusetts Department of Transportation Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

Post-installed anchoring systems are advantageous to Massachusetts Department of Transportation (MassDOT) projects, due to their ease of attachment to existing structures. However, recommendations on materials from various manufacturers are currently lacking for certain situations such as long-term tension loading. The purpose of the investigation presented in this report is to provide guidance to MassDOT on the use of anchoring systems. This research project evaluated the behavior of adhesive and cementitious bonded anchoring systems per the Stress-versus-Time-to-Failure (SvTTF) approach found in the provisional standard AASHTO TP-84, in order to provide recommendations pertaining to the test method. Supplemental short-term anchor pullout tests were conducted using the best-performing materials as evaluated by AASHTO TP-84, to study the effects of certain in-service and installation parameters on bond strength. The parameters studied included installation direction and extreme in-service temperatures. Polymer characterization testing of adhesive products was also conducted in order to comment on technique usefulness for quality assurance/quality control of field-installed bonded anchor materials.

Results of the project support the continuation of MassDOT Engineering Directive E-10-001. An implementation plan is recommended to provide a method for acceptance on MassDOT's Qualified Construction Materials List for uses allowed under that directive. Acceptance criteria include some testing and materials characterizations beyond ICC-ES AC308 criteria to address recommended limitations on coefficient of variation (COV) and performance at decreased temperatures that may be experienced under field conditions. Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (DSC) data are also required.

The following observations and recommendations can be concluded from this research.

AASHTO TP-84 Materials

- The SvTTF approach of AASHTO TP-84 [4] is very promising, though restrictions are recommended.
- The SvTTF approach can overestimate the long-term capacity of a material with large variation in results of short-term tests. Therefore, a maximum COV of 10% for short-term tests is recommended in order to proceed with the full SvTTF procedure.
- The extrapolation of four months of long-term data to a design life of 100 years should be further justified due to the inherent variability in material behavior and the unknown effect of physical aging on bonding materials. Pending further study, a more

conservative approach or required inspection of anchors at ages beyond ten times the four-month test protocol is recommended.

- Based on the limited bonding materials studied for this research project, epoxy materials presented the most reliable long-term load performance. The methyl methacrylate, ester-based, and cementitious materials did not perform well; however, further research is needed to study a larger sampling of these material types.
- The test method has a slight inconsistency in how short-term data is reported. It is recommended that short-term tests be included in the SvTTF trend lines and they be plotted at actual time zero to be consistent with the reporting of long-term data. It is noted that the plotting at time zero makes minimal difference in results for materials meeting the maximum COV of 10% for short-term tests.
- Specific criteria should be provided when data can be excluded from results, such as specimens that fail while being loaded to their percentage of MSL (%MSL) for long-term testing and specimens that are noted to have incomplete curing.
- It is expected that new products will be developed with higher bond strengths than are now typical. The test procedure many not be able to ensure bond failures without violating the minimum embedment depths specified. Reducing embedment depths further may result in tests that are dominated by bond performance at the top and bottom of the anchor, which may not be representative of a typical embedment depth for an installed anchor.
- A precision and bias have not been established for this test method.

Installation Direction Testing

- It was found that horizontal installations resulted in a loss of capacity on the order of 10% of downward installed specimens for these materials and specimens.

Extreme Temperature Testing

- Material 7, a product recommended for use in cold temperature, exhibited excellent performance in extreme cold temperature testing, while both Material 1B and Material 2, materials recommended for typical installation temperatures, had severely reduced capacities when tested at temperatures lower than their recommended installation temperatures, even though they were installed and cured within the recommended range.
- Materials 1B, 2, and 7 were influenced not just by temperature occurring during the installation, but through the service life of the anchor. Therefore, it is important to consider the service life temperature of post-installed adhesive anchors as well as the installation temperature.

Polymer Characterization Testing

- FTIR is expected to be a useful tool for quality assurance and quality control of adhesive anchor materials. The method can be used to verify that the adhesive was properly mixed at the site and verify consistency of a product from batch to batch.

- It is recommended that samples to be used for FTIR testing be cast as thin disks approximately 1.5 inches (38.1 mm) in diameter and 0.03 inch to 0.05 inch (0.762 mm to 1.27 mm) thick. It is recommended best practice to apply a single cure temperature and cure time to all sample disks for consistency. The research team recommends a curing temperature of 74°F (23°C) and cure time of seven days.
- DSC testing is most useful at determining the glass transition temperature of a material. This can be useful in assessing materials that may have lower performance at elevated temperatures that may occur in the field.

Implementation

- Current prohibition of structural applications for adhesive anchors per MassDOT Engineering Directive E-10-001 "Guideline for the use of Adhesive Anchors" shall be continued.
- Approval of anchors materials shall require ICC-ES AC308 certification with additional requirements to address recommended limitations on COV and performance at decreased temperatures that may be experienced under field conditions. DSC and FTIR data shall be provided.
- Installation shall be performed by certified personnel.

This page left blank intentionally.

Table of Contents

This page left blank intentionally.

List of Tables

This page left blank intentionally.

List of Figures

This page left blank intentionally.

List of Acronyms

Acronym	Expansion
AASHTO	American Association of State Highway Transportation Officials
ACI	American Concrete Institute
ASTM	American Society of Testing Materials
CCD	Concrete Capacity Design
COV	Coefficient of Variation
DSC	Differential Scanning Calorimetry
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FTIR	Fourier Transform Infrared Spectroscopy
ICC-ES	International Code Council-Evaluation Services
LRFD	Load and Resistance Factor Design
MassDOT	Massachusetts Department of Transportation
MSDS	Manufacturer Safety Data Sheet
MSL	Mean Static Load
NCHRP	National Cooperative Highway Research Program
NTSB	National Transportation Safety Board
PTFE	Polytetrafluoroethylene
SvTTF	Stress-versus-Time-to-Failure

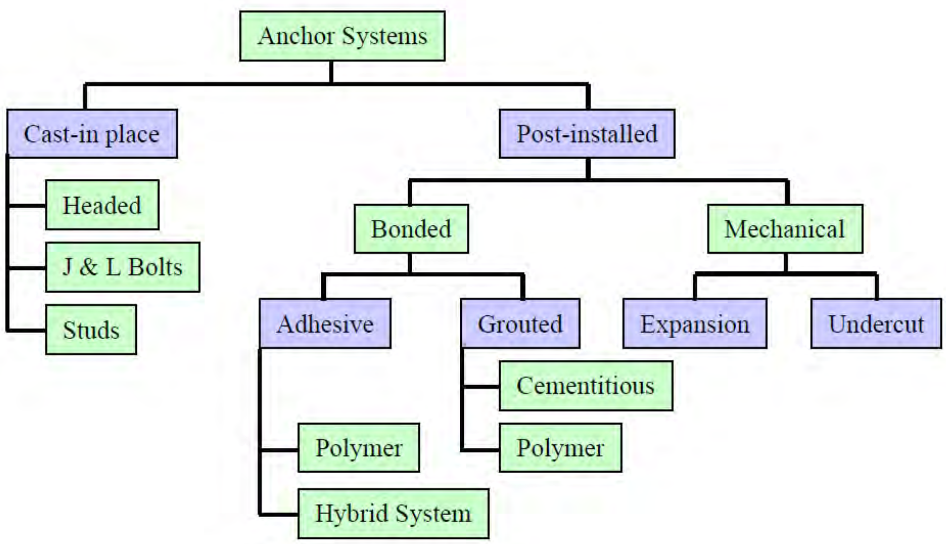
This page left blank intentionally.

1.0 Introduction

This study of Performance of Cementitious and Adhesive Anchorage Systems was undertaken as part of the Massachusetts Department of Transportation Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

1.1 Overview

Adhesive and cementitious anchoring systems have widespread use in transportation structures. Typical applications for these systems include bridge widening, concrete repair, and rehabilitation and mounting of structural or architectural features to concrete. Anchorage systems of this type can be characterized as cast-in-place or post-installed, as defined in Figure 1.1.



Source: Cook and Burtz, 2003 [14]

Figure 1.1: **Types of anchor systems**

Cast-in-place anchors are placed in the wet concrete before it sets. These are generally the strongest type of fasteners and exhibit reliable behavior. However, casting is difficult and requires great accuracy in placement to ensure proper alignment. Post-installed anchors are installed in a pre-drilled hole in the base material and use proprietary methods to attach to the hardened concrete. These anchoring systems can offer more freedom in placement to ensure more accurate alignment and provide time-saving advantages during construction. However, their behavior is more variable than cast-in-place anchors, and they are susceptible to installation and in-service conditions.

Post-installed anchorage systems commonly consist of a steel rod or reinforcing bar that is installed into a pre-dilled hole in the hardened concrete and rely on either mechanical interlock or a bonding material to transfer load from the anchor to the concrete. Post-installed bonded anchors can be further divided into adhesive or grouted systems. Adhesive anchors are defined as having a hole diameter less than or equal to 1.5 times the anchor diameter and typically use a polymer material to bond the anchor rod to concrete [1, 2]. ACI 355.4 [1] provides the following definition for adhesives used in adhesive anchor systems:

> Any adhesive comprised of chemical components that cure when blended together. Adhesives are formulated from organic polymers, or a combination of organic polymers and inorganic materials. Organic polymers used in adhesives can include, but are not limited to, epoxies, polyurethanes, polyesters, methyl methacrylates and vinyl esters [1].

Grouted anchors are defined as having a hole diameter greater than 1.5 times the anchor diameter and generally use cementitious materials as a bonding agent [2]. Adhesive and grouted anchors generally have similar installation procedures. First, a hole is drilled in the base concrete using a rotary impact hammer and then cleaned with a wire brush, compressed air, and/or a water jet. The bonding material is then delivered into the hole, and the anchor rod is inserted per the manufacturer recommendations. The anchor is then required to cure undisturbed for the time period prescribed by the manufacturer's recommendations before load can be applied to the system.

Post-installed anchors are often preferred to cast-in-place anchors because they provide a simple and economical system for attaching fixtures to hardened concrete. However, their behavior can be less consistent and more susceptible to changes in environmental conditions. Also, post-installed adhesive and grouted anchors can exhibit displacement over time when subjected to sustained tensile load, which can result in excessive displacement or complete failure of the anchor. This behavior, defined as creep or long-term tension load, can lead to catastrophic accidents in transportation structures. Long-term tension load can cause failure in adhesive anchors at loads lower than their short-term, or static, capacity.

Adhesive anchor research has recently been summarized in two National Cooperative Highway Research Program (NCHRP) reports, NCHRP 757 [2] and NCHRP Report 639 [3]. These reports specifically focused on the creep characteristics of adhesive anchors, where [3] proposed a new American Association of State Highway Transportation Officials (AASHTO) provisional standard developed to assess the creep performance of post-installed bonded anchoring systems, AASHTO TP-84(2010c) [4]. This test method differs from the long-term test procedure of ACI 355.4 [1] in that it uses a Stress versus Time-to-Failure (SvTTF) graph to predict the life of an adhesive anchoring system under a specific long-term tension load, instead of pass/fail criteria based on extrapolating displacement data. Revisions to ACI 355.4 [1] to include similar testing have also been proposed. The succeeding report, [2], expanded on the research by investigating additional environmental parameters that can affect bond strength.

1.2 Motivation for the Study

Post-installed systems are advantageous to MassDOT projects, due to their ease of attachment to existing structures. However, recommendations on materials from various manufacturers are currently lacking for certain situations such as creep. The 2006 Boston, Massachusetts, I-90 connector tunnel ceiling failure collapse is a fatal example of an incident caused by the long-term tension failure of epoxy adhesive anchors. The anchor failure caused precast ceiling units to drop onto the roadway, causing one fatality and one person with minor injuries. After the accident, inspections were conducted on the remaining anchors, and it was found that a significant number of them had displaced significantly since their installation. Displacement of these anchors ranged from less than 0.10 inches (2.54 mm) to more than 1.00 inch (25.40 cm) [5]. State and local authorities chose to close the tunnel while inspections and corrective actions occurred.

The National Transportation Safety Board (NTSB) determined that the probable cause of the ceiling collapse was the use of an epoxy adhesive anchor system that was reported to have poor long-term load characteristics [5]. In response to the failure, NTSB recommended to the FHWA to prohibit the use of adhesive anchors under long-term loading conditions until test standards were established, and this recommendation was adopted by MassDOT. This tragic accident, shown in Figure 1.2 (from NTSB, p. 1), revealed an insufficiency in the understanding of the behavior of bonded anchoring systems and a need to conduct further research to improve the acceptance criteria for post-installed bonded anchoring systems under long-term load applications in order to ensure maximum safety where these systems are used.

Source: NTSB, 2007 [5]

Figure 1.2: I-90 Tunnel ceiling collapse due to adhesive anchor failure

1.3 Research Objectives

The purpose of this investigation was to provide guidance to MassDOT on the use of anchoring systems. This investigation evaluated the behavior of adhesive and cementitious bonded anchoring systems to concrete in order to develop design recommendations and acceptance criteria for anchoring systems to be listed as a "Qualified Construction Material" on MassDOT projects. This project assessed the performance of anchor materials per the provisional standard, AASHTO-TP 84[4], in order to provide recommendations and background pertaining to the test method and also evaluate the effect of certain installation and in-service factors on the bond strength of adhesive anchors. Furthermore, polymer characterization testing of epoxy adhesives was conducted in order to comment on supplemental methods that could be useful in field quality assurance and quality control of anchor materials used in sustained tensile load applications.

1.4 Scope of Work

The University of Massachusetts, Amherst (UMass) developed the necessary testing capabilities to meet AASHTO TP-84 criterion. In order to develop recommendations pertaining to the provisional standard, six bonding materials from various manufacturers and chemistries were tested per AASHTO TP-84 [4] to observe test variability between the different materials. The testing of each product involved a minimum of five short-term anchor pullout tests to determine the mean static load (MSL), and a series of ten long-term tests using stress levels that range from 60%-80% of the MSL. To study the effects of certain in-service and installation parameters on bond strength, additional anchor pullout tests were conducted using the best-performing materials as evaluated by AASHTO TP-84 [4]. The parameters tested included installation direction and extreme in-service temperatures.

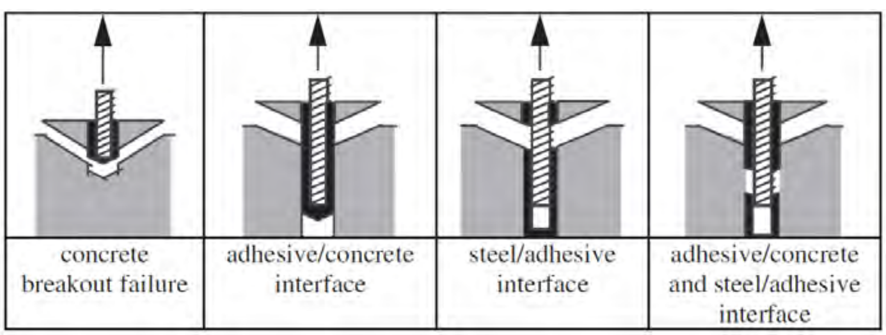
Polymer characterization testing of six adhesive products was also conducted in order to comment on technique usefulness for field quality assurance and quality control of field-installed bonded anchor materials. The methods tested included Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (DSC). FTIR has been frequently used for the chemical analysis of cured epoxy samples, as it provides a fast and efficient way of determining their approximate chemical composition. FTIR tests were conducted over a range of curing temperatures and curing times for each material. The purpose was to determine if material variability can be identified when a material is modified and to verify that proper mixing was accomplished at the site. DSC testing has also proven effective in determining the glass transition temperature of epoxy adhesives, an important property of an epoxy that can be linked to many performance parameters.

2.0 Background

This chapter presents an overview of the background of existing behavior models and design of bonded anchoring systems, as well as the current test standards applicable to post-installed bonded anchor systems.

2.1 Behavior Models and Failure Modes of Bonded Anchors

Failure modes of bonded anchors can occur in any of the elements: base concrete, steel anchor rod, or bonding material. Figure 2.1 shows typical failure modes exhibited by bonded anchors. These failure modes include: concrete breakout failure; adhesive (or grout)/concrete interface bond failure; adhesive (or grout)/steel interface bond failure; and a combination of adhesive (or grout)/concrete and adhesive (or grout)/steel interface failure. Failure of the steel anchor rod is an additional failure mode to be considered, particularly in bonded anchors with high bond stress capacity, and would be the failure mode of an ideal anchor system that develops the full capacity of the anchor. Concrete breakout failures are addressed in ACI 318-14 Chapter 17 [6] and are predicted using the Concrete Capacity Design (CCD) Model. The three bond failure modes are predicted using a uniform bond stress model. The anchor capacity is defined by the tensile capacity of the steel anchor rod. The CCD model was developed for cast-in-place and mechanical anchors, but is applicable to grouted anchors that fail with a full concrete breakout cone. The three bond failure modes are exclusive to bonded anchors.



Source: Zamora et al., 2003 [10]. Authorized reprint from *ACI Structural Journal*, Vol. 100, No. 2.

Figure 2.1: Potential failure modes of bonded anchors

2.1.1 Concrete Capacity Design Model

The CCD model was developed by Eligenhausen (1987) [7] and was first compared with existing American Concrete Institute (ACI) standards by Fuchs (1995) [8]. The underlying assumption of the model is that the base concrete fails in tension and a 35° full cone is formed from the end of the embedded head to the concrete surface, as is shown in Figure 2.2. This design method was validated for headed cast-in-place anchors and post-installed mechanical anchors and has been the model used by ACI for headed anchors that fail in tension or shear (cast-in-place or mechanical), but is also applicable to post-installed anchors that preclude bond failure modes. Equation 1 is the related design equation from ACI 318-14 [6].

$$\boldsymbol{N}_{\mathbf{b}} = \mathbf{k}\sqrt{\boldsymbol{f'}_{c}}\mathbf{h}_{\mathbf{ef}}^{\mathbf{1.5}} \qquad \text{Eq. 1}$$

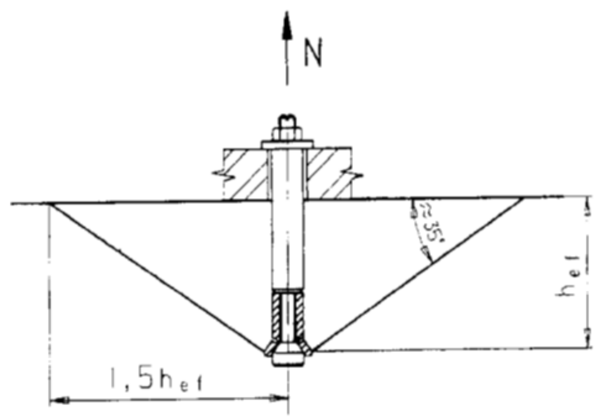
Where,

N_b = Basic concrete breakout strength in tension of a single anchor in cracked concrete, lbs.

K = Coefficient for basic concrete breakout strength in tension (24 for cast-in-place anchors, 16 for mechanical post-installed anchors)

f'_c = Specified compressive strength of concrete, psi

h_{ef} = Effective anchor embedment depth, in.

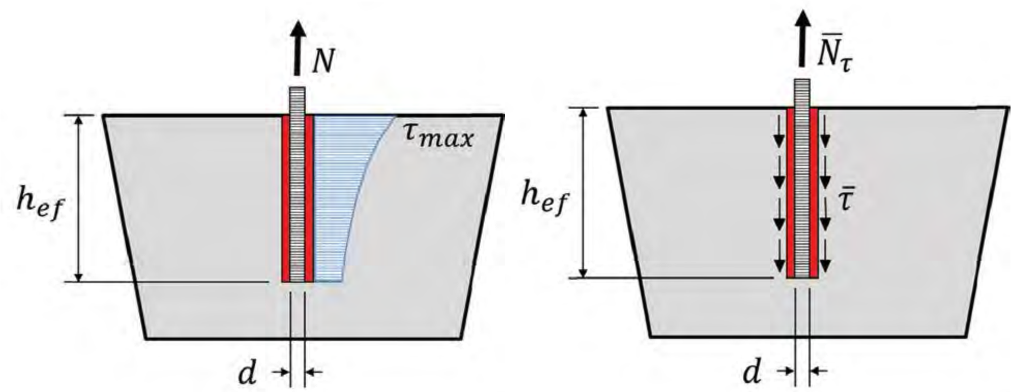


Source: Fuchs et al., 1995 [8]. Authorized reprint from *ACI Structural Journal* ,Vol. 92, No. 1.

Figure 2.2: Full concrete breakout cone as predicted by CCD

2.1.2 Uniform Bond Stress Model

The uniform bond stress model was first recommended as the standard design model by Cook et al. (1998) [9] and is summarized by Zamora et al. (2003) [10] and Cook et al. (2013) [2]. It was found that adhesive anchors in the elastic range exhibit a hyperbolic tangent stress distribution along the length of the anchor, as is shown in Figure 2.3(a). It can be observed from this figure that that smallest stresses are found at the embedded end of the anchor and the highest stresses are concentrated where the anchor rod exits the concrete. Above 30% of MSL, the upper portions of the adhesive become plastic and load begins redistributing further into the hole. At approximately 70% MSL, the entire length of adhesive reaches the plastic range and a uniform stress is achieved throughout, as seen in Figure 2.3(b). Therefore, the uniform bond stress model has been found to be a valid behavioral model for predicting the maximum load capacity of an anchor.



(a) (b)

Source: Cook et al., 2013 [2]. Authorized reprint from the Transportation Research Board.

Figure 2.3: (a) Hyperbolic tangent stress distribution; (b) uniform bond stress distribution

This model is defined per Equation 2.

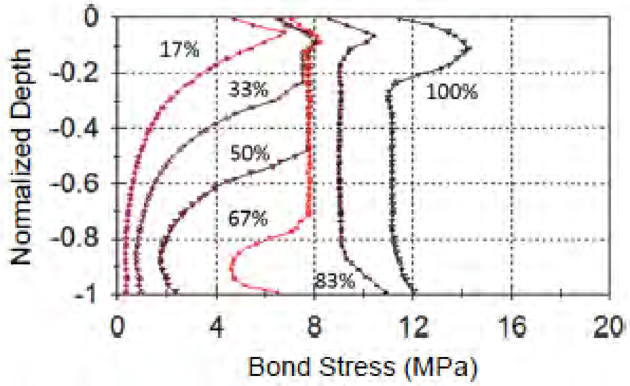
$$\bar{N}_\tau = \bar{\tau}\pi d h_{ef} \quad \text{Eq. 2}$$

Where,

$\bar{N}\tau$ = mean failure load, lbs.
$\bar{\tau}$ = mean bond strength, psi
d = anchor diameter, in.
h_{ef} = embedment depth, in.

Figure 2.4 includes the stress distribution along the length of an adhesive anchor under various percentages of MSL. It can be seen that at low load levels, the stress distribution generally followed the hyperbolic tangent curve. However, at higher load levels, the stress at the bottom and top of the anchor did not precisely follow the uniform bond stress distribution model, showing that this model should be taken as an approximation. Moreover, the uniform bond stress model is only applicable when the following conditions are met [2]:

- Adhesive bonded anchors where the hole diameter does not exceed 1.5 times the anchor diameter.
- Embedment depth to anchor diameter ratio does not exceed 20.



Source: Cook et al., 2013 [2]. Authorized reprint from the American Society of Civil Engineers (ASCE).

Figure 2.4: Stress distribution along length of adhesive anchor for h_{ef}/d_o=8.0

For design, the nominal bond strength of adhesive bonded anchors is dependent upon the mean bond strength of anchors installed in accordance with the manufacturer's instructions and the product's sensitivity to installation and in-service factors. Equation 3 provides the design relationship for Load and Resistance Factor Design (LRFD).

$$N_u \leq \varphi N_{bond} \qquad \text{Eq. 3}$$

Where,

N_u= factored tension load, lbs.
φ= capacity reduction factor
N_{bond}= $\tau' \pi d h_{ef}$
τ'= nominal bond stress, psi
d= anchor diameter, in.
h_{ef}= embedment depth, in.

The nominal bond strength (τ') is the 5% lower fractile of mean bond strength modified by a series of reduction factors (α) that account for the loss of capacity due to adverse installation and in-service conditions as defined in Equation 4. The nominal bond strength is generally determined through confined laboratory tests as these tests force bond failure. ACI 355.4 prescribes a reduction factor of 0.75 to be applied when bond shear stress is determined through confined testing.

$$\tau' = \tau_k \alpha_1 \alpha_2 \alpha_3 \qquad \text{Eq. 4}$$

Where,

τ'= 5% lower fractile of mean bond strength
$\alpha_1 \alpha_2 \alpha_3$= reduction factors determined from comparing the bond strength under different installation and in-service conditions to the baseline bond strength

Zamora et al. (2003) [10] presented validated models of grouted anchor behavior in tension. Non-headed grouted anchors generally exhibit the same failure modes as adhesive anchors.

However, grouted anchors have a bond stress of (τ) for the grout/steel interface failure mode and a bond stress of (τ_o) for the grout/concrete interface failure mode. The uniform bond stress model for adhesive anchors applies to grouted anchors, with the modifications defined in Equation 5. The lower value calculated from Equation 2 or Equation 5 is used to predict the mean failure load or mean static load of non-headed grouted anchors for the two different bond failures.

Headed grouted anchors will not experience a grout/steel failure mode due to the presence of the head, but can experience a bond failure at the grout/concrete interface or a full concrete breakout cone. Failure of the bond at the grout/concrete interface can be predicted by Equation 5 [10]. Failure of the grout is not mentioned in the literature; however, it is a possible failure mode that should be further investigated.

$$\bar{N}_\tau = \tau_o \pi_o h_{ef} \qquad \text{Eq. 5}$$

Where,

- $\bar{N}\tau$= mean failure load, lbs.
- $\bar{\tau}_o$= mean bond strength, psi
- d anchor diameter, in.
- h_{ef}= embedment depth, in.

2.2 Current Test Standards for Anchoring to Concrete

This section discusses current test standards and methods for bonded anchors. Test standards are published from multiple agencies, including: American Society of Testing Materials (ASTM), ACI, International Code Council-Evaluation Services (ICC-ES), and AASHTO.

2.2.1 ASTM E488 (2010): Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements

This standard test method covers the procedures for determining short-term, seismic, fatigue and shock, tensile, and shear strengths of concrete and masonry anchorage systems (post-installed and cast-in-place). It is a widely accepted test method used for determining the short-term capacity of anchors that has been fully or partially adopted by most governing agencies. AASHTO TP-84 [4] references the short-term pullout test procedure described in this standard to calculate the MSL of a test series. The short-term test subjects an anchor to tensile load that is applied at a continuous load rate such that the anchor fails within 2 ± 1 minute. Load and displacement must be monitored and recorded throughout the test at a minimum sampling rate of one reading per second to capture the peak load at the time of failure. ASTM E488 (2010) [11] and AASHTO TP-84 [4] require a minimum of five anchors to be tested and their results averaged in order to determine the MSL.

2.2.2 ASTM E1512 (2007): Standard Test Methods for Testing Bond Performance of Bonded Anchors

ASTM E1512 (2007) [12] provides testing procedures for assessing the effects of bond strength under factors such as elevated temperature, fire, moisture, and freeze/thaw cycles. This standard is similar to ASTM E488 (2010) [11], but is exclusively for the testing of bonded anchors and has the addition of long-term (creep) testing. The long-term test qualifies adhesive anchors by testing an anchor at 40% MSL for 42 days 110°F (43°C). The criterion of 40% MSL was chosen based on an ASD factor of safety of 4 and a multiplier of 1.6 for maximum expected long-term load. A database study showed that most anchor failures occurred within 21 days; therefore, a total of 42 days of testing was conservatively chosen [2]. The testing temperature of 110°F (43°C) was selected based on results of a study conducted on a bridge located in the California desert, which showed that the average maximum peak temperature of the bridge was 110°F (43°C) [2].

The last 20 days (20 data points) from the test are used to construct a logarithmic trend line using a least squares fit. This trend line is extrapolated out to 600 days, and the 600-day displacement is compared with short-term test displacement. The 600-day requirement is based on monitoring of a bridge in California that experienced temperatures between 110°F (43°C) and 115°F (46°C) during 10% of a typical summer day. Summer was assumed to last four months; therefore, a bridge with a lifespan of 50 years would experience 600 days at or near 110°F (43°C) [2]. ASTM E1512 [12] does not provide acceptance criterion for anchor systems to pass the test. Instead, it only provides a standard testing procedure.

2.2.3 ICC-ES AC308 (2013) Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements

ICC-ES AC308 (2013) [13] is an acceptance criterion developed to qualify post-installed adhesive anchor products and is based on LRFD. This document was the source document used in the development of ACI 355.4 (2011) [1].

2.2.4 ACI 355.4 (2011): Qualification of Post-Installed Adhesive Anchors in Concrete

ACI 355.4 (2011) [1] is similar to ASTM E1512 (2007) [12] but includes several modifications to the test methodology of long-term tests and is the most current of these test methods. ACI 355.4 (2011) [1] recommends that long-term testing be performed at a stress level of 55% of the material's MSL for a total of 42 days at both ambient and elevated room temperature. At the end of the testing period, a pass/fail criteria is applied on the displacement of the anchor projected to 10 and 50 years and residual load-bearing capacity. Acceptance by ACI 355.4 (2011) [1] for long-term tests is as follows:

- The projected displacement at 10 years is less than the mean displacement at failure of the reference elevated temperature tests.
- The projected displacement at 50 years is less than the mean displacement of the reference standard temperature tests.
- The residual capacity from the static test is greater than 90% of the MSL.

2.2.5 AASHTO TP-84 (2010): Evaluation of Adhesive Anchors in Concrete under Sustained Loading

The proposed test method of AASHTO TP-84 (2010) [4] differs from the long-term test procedure of ACI 355.4 (2011) [1] and ASTM E1215 (2007) [12] in that it uses a Stress versus Time-to-Failure (SvTTF) graph to predict the life of an adhesive anchoring system under a specific long-term stress and/or time of long-term load. For these graphs, stress is assumed to be a percent of MSL, which is a direct ratio of the mean bond strength. The SvTTF graph is developed for each adhesive material by performing a series of five short-term anchor pullout tests and ten long-term tests at stress levels between 60% and 80% of MSL. For each long-term test, failure is defined as the onset of tertiary creep. After the completion of all tests, each data point is plotted on an SvTTF semi-log plot, and a linear trend line is drawn through the data points and projected to a design life of 100 years. The advantage of this plot is that it allows for a designer to evaluate an allowable load factor and specific design life. AASHTO TP-84 [4] provides a long-term capacity plot for adhesive anchors based on known failures, as opposed to the pass/fail requirements of ACI 355.4 (2011) [1] based on extrapolating displacement data.

A very similar test method to AASHTO TP-84 [4] has been proposed as a modification to ACI 355.4 (2011) [1]. At this time, it is unclear whether ACI or AASHTO will adopt this test procedure.

This page left blank intentionally.

3.0 Post-Installed Bonded Anchoring Systems Literature Review

This chapter presents a literature review and state of the art of both adhesive and cementitious anchorage systems.

3.1 Adhesive Anchoring Systems

An adhesive anchoring system has a hole less than 50% of the anchor rod diameter, as defined by Zamora et al. (2003) [10] and adopted by Cooke and Burtz (2003) [14], Cook et al. (2009) [3] and Cook et al. (2013) [2]. According to ACI 355.4 (2011) [1], "Organic polymers used in adhesives can include, but are not limited to, epoxies, polyurethanes, polyesters, methyl methacrylates and vinyl esters; or organic polymers." Most organic polymer adhesives consist of a two-part system that requires mixing just prior to application. This is typically done with a manual dispensing tool that mixes the components through a mixing nozzle before they are delivered into the hole. Inorganic adhesive anchors allow for the use of cementitious products, typically reserved for grouted anchor applications with a hole diameter greater than 1.5 times the anchor diameter. Adhesive anchor manufacturers provide a table listing of allowable load and ultimate load for their anchor system based on anchor rod diameter, embedment depth, and concrete compression capacity.

Creep of adhesive anchors is a documented problem, but the long-term capacity of the anchors under different conditions became more heavily researched in the years following the 2006 I-90 tunnel failure in Boston, Massachusetts. Published research at the time of the accident showed the poor creep performance of adhesive anchors including a warning from James et al. (1987) [15]: "It should be emphasized that resins used in structural applications can exhibit significant viscoelastic response to long-term loadings, especially at elevated temperatures." In response to the failure, additional guidelines were published. An NTSB report on the accident recommended to the FHWA that use of adhesive anchors under long-term loading conditions be prohibited until test standards were established [5]. Additionally, MassDOT introduced Engineering Directive E-10-001 on April 20, 2010, to provide guidance to designers, requiring them to always specify non-adhesive anchors unless the designer provides necessary dimensions for coring or drilling holes, including hole diameter and depth, spacing between dowels or anchors, and edge distance; or when used in crash-tested anchor bolt applications [16]. Cook et al. (2013) [2] includes an extensive review of standards of testing, behavior models, and parameters that affect the capacity of adhesive anchors. A brief synopsis of this material is presented in the rest of this chapter.

3.1.1 NCHRP Report 639: Adhesive Anchors in Concrete under Sustained Loading Conditions

NCHRP Report 639 [3] discusses the creep resistance of adhesive anchors and provides a basis for AASHTO TP-84 [4] and Cook et al. (2013) [2]. The main purpose of this research program was to develop a standard test procedure for AASHTO to qualify adhesive anchoring systems for use in federal highway projects. The SvTTF method was compared with a pass/fail method from the existing ICC-ES AC308 (2013) [13]. This project tested three adhesives for short-term capacity and performed long-term testing on two of those adhesives. Six short-term tests were conducted per adhesive to determine the MSL. Three long-term tests were conducted per adhesive per load level, for a total of 12 long term tests. Long-term loads in this testing program were 75% and 62% of MSL, with failure in creep defined as the onset of tertiary creep per ASTM D2990 (2009) [17], as shown in Figure 3.1. These load levels generally caused failures within four months of application.

The project concluded with a draft AASHTO test method, directly resulting in AASHTO TP-84 [4] and a recommendation that a SvTTF approach is superior to the pass/fail method of ICC-ES AC308 (2013) [13].

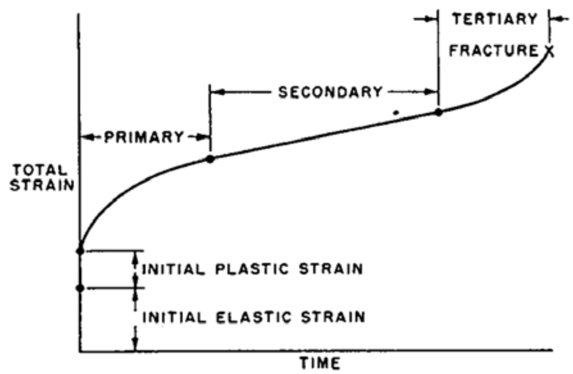


Figure 3.1: Tertiary creep

3.1.2 NCHRP Report 757: Long-Term Performance of Epoxy Adhesive Anchor Systems

NCHRP Report 757 [2] provides a thorough review of adhesive anchor research as of its publishing in 2013. The principal objective of this report was to investigate the influence of various parameters (e.g., type of adhesive, installation conditions, and in-service conditions) on the sustained-load performance of adhesive anchors. Also, a second objective was to develop recommended test methods, material specifications, design guidelines, design specifications, quality assurance guidelines, and construction specifications to AASHTO for the use of adhesive anchors in transportation structures [2].

The report includes a research program of 17 test series, where each series investigated the sensitivity of an adhesive anchor's creep capacity to a specified parameter. The proposed testing matrix for this investigation can be seen in Table 3.1. Series 1 to 16 started with five short-term tests to establish a parameter MSL. A number of long-term tests were conducted per AASHTO TP-84 [4] on the adhesive material that showed the most sensitivity to a given parameter, in order to develop a SvTTF graph of each parameter. These tests were then compared against the baseline tests for the same material, Series 1 and Series 2, to develop an alpha reduction ratio (parameter MSL/baseline MSL). The alpha reduction ratios for the short-term and the long-term tests were then compared with each other to determine if a given parameter had greater impact on long-term or short-term performance. The alpha short-term was divided by the alpha long-term to determine an influence ratio. If this influence ratio was greater than 1, then the parameter was considered to have a negative effect on creep.

This report concluded that of the parameters tested, only in-service temperatures above 120°F (49°C) and loading before the completion of the manufacturers' required cure time adversely affected the long-term loading capacity. This was an important result, as ACI 355.4 (2011) [1] mandates long-term tests at Category A temperatures of 110°F (43°C), but only an optional test at Category B temperatures greater than 110°F (43°C). Cook et al. (2013) [2] recommended that manufacturers' instructions should be followed closely for all adhesive anchor products and additional curing time should be allowed prior to loading.

Another objective of Cook et al. (2013) [2] was to recommend changes to AASHTO TP-84 [4]. The proposed changes were to include at least three load levels within the 60% to 80% MSL (instead of two), and to exclude short-term test results when constructing the SvTTF graph.

Table 3.1: Proposed testing matrix

Test Series	Test Description (Influencing parameter)	Installation Temperature	Orientation during installation	Moisture of concrete during installation/ service	Cleaning	Anchor Size x h_{ef}	Concrete Composition	Product Type A	Product Type B	Product Type C	Test Temperature	Type of support	Number of sustained load steps	Number of sustained load tests	Number of reference tests	Test Location
								(0)	(0)	(0)			(1)			(10)
1	Baseline tests UF	75°F	downward	dry/dry	full	5/8x3	Standard	X	X	X	110°F	confined	4	36	15	UF
2	Baseline tests US					M12x80		X	X	X			4	36	15	US
3	Service temperature	75°F	downward	dry/dry	full	M12/80	Standard		X (2)		>120°F	confined	3	9	5 (11)	US
4									X (2)		70°F		3	9	5 (11)	US
5	Installation direction	75°F	horizontal	dry/dry	full	M12/80	Standard	X (3)		X (3)	110°F	confined	3	18	10 (11)	US
6			overhead					X (3)		X (3)			3	18	10 (11)	US
7	Moisture during installation or service	75°F	downward	damp/dry	full	5/8x3	Standard	X (4)			110°F	confined	3	9	5 (11)	UF
8				dry/damp		M12/80			X (4a)		70°F		3	9	5 (11)	US
9	Hole cleaning	75°F	downward	dry/dry	reduced	5/8x3	Standard			X (5)	110°F	confined	3	9	5 (11)	UF
10	Installation temperature	MFR min (6) & (6a)	downward	dry/dry	full	M12x80	Standard	X (7)			MFR min (6)	confined	3	9	5 (11)	US
11								X (7)			110°F		3	9	5 (11)	US
12	DOT Concrete mix	75°F	downward	dry/dry	full	5/8x3	DOT	X			110°F	confined	3	9	5 (11)	UF
13	Type of drilling	75°F	downward	dry/dry	full	5/8x3	Standard		X		110°F	confined	3	9	5 (11)	UF
14	Concrete composition	75°F	downward	dry/dry	full	5/8x3	with FA		X (8)		110°F	confined	3	9	5 (11)	UF
15							with BFS	X (9)					3	9	5 (11)	UF
16	Test setup (wide support)	75°F	downward	dry/dry	full	5/8x3	Standard			X	110°F	un-confined	3	9	5 (11)	UF
	Concrete Age (tested at 3 days)							X	X	X			0	0	15 (11)	US
	Concrete Age (tested at 7 days)							X	X	X			0	0	15 (11)	US
17	Concrete Age (tested at 14 days)	75°F	downward	dry/dry	full	M12x80	Standard	X	X	X	75°F	confined	0	0	15 (11)	US
	Concrete Age (tested at 21 days)							X	X	X			0	0	15 (11)	US
	Concrete Age (tested at 28 days)							X	X	X			0	0	15 (11)	US
													Sum	216	185	

Notes:

(0) Type A = vinyl ester system, type B = epoxy system, type C = epoxy system.
(1) 4 sustained loads N_p / $N_{u,m}$(reference) 0.75/0.65/0.55/0.45. Creep tests with N_p = 0.55 $N_{u,m}$ will be used to compare with current approach of AC308
3 sustained loads N_p / $N_{u,m}$(reference) 0.70/0.55/0.40.
(2) Only the product that is most sensitive to increased temperature (high ratio glass transition temperature to service temperature) will be tested.
(3) Only the top two products that are most sensitive to installation direction (occurrence of voids) in static tests will be tested.
(4) Only the product that is most sensitive to wet concrete in static tests will be tested.
(4a) Product that is sensitive to high alkalinity will be tested. The tests are performed at normal ambient temperature because under increased temperature the concrete will dry out.
(5) Only the product that is most sensitive to hole cleaning (no brushing) will be tested.
(6) Concrete at manufacturer's lowest permissible concrete temeprature.
(6a) Mortar at manufacturer's lowest permissible mortar preheating temperature.
(7) Only the product that is most sensitive to low installation temperature (low degree of cross linking) will be tested.
(8) Only the product that is most sensitive to fly ash concrete will be tested.
(9) Only the product that is most sensitive to blast furnace slag concrete will be tested.
(10) UF = University of Florida, US = University of Stuttgart.
(11) It is assumed that the influence of the investigated parameter on the short-term bond strength is known from previous tests. If not, all products will be tested and the number of reference tests will increase.

Source: Cook et al., 2013 [2]. Authorized reprint from the Transportation Research Board.

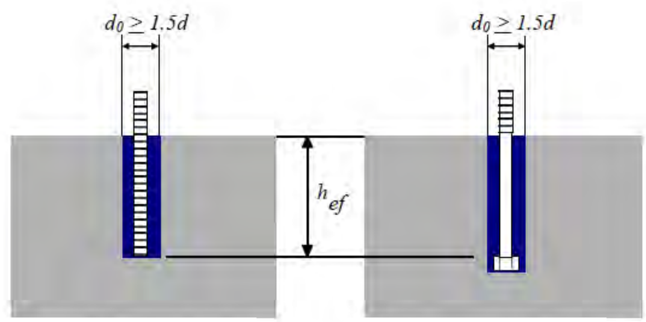
3.2 Grouted Anchor Systems

A grouted anchor system has a hole larger than 50% of the anchor rod diameter as defined by Zamora et al. (2003) [10] and adopted by Cook and Burtz (2003) [14], Cook et al. (2009) [3] and Cook et al. (2013) [2]. These anchors can be classified as either cementitious or polymer based. Cementitious bonding materials are a mixture of sand, cement, water, and other additives. Most structural applications of cementitious anchors use non-shrink grout products that conform to ASTM C1107 (2013) [18], which tests for compressive strength and shrinkage over time. Polymer grouts consist of small aggregates (i.e., sand), a resin, and a curing agent. The inclusion of small aggregates allows polymer grouts to fill larger holes, differentiating most polymer-grouted anchors from polymer adhesive anchors. ACI 355.4 [1] provides the following definition for adhesives used in adhesive anchor systems:

> Any adhesive comprised of chemical components that cure when blended together. Adhesives are formulated from organic polymers, or a combination of organic polymers and inorganic materials. Organic polymers used in adhesives can include, but are not limited to, epoxies, polyurethanes, polyesters, methyl methacrylates and vinyl esters.

Most anchor manufacturers provide tables listing allowable load and ultimate load for their anchor system based on anchor rod diameter, embedment depth, and concrete compressive capacity. Separately, a list of hole diameters to use with each acceptable anchor rod diameter are provided. Grouted anchor manufacturers generally provide a minimum oversize dimension for the hole, based on anchor diameter.

Anchor rods used in grouted anchors can be either headed or non-headed, as shown in Figure 3.2 (after Cook and Burtz [14]). Headed anchor rods include either an integrated head or a nut threaded on the end of the rod. All grouted anchors can experience the same failure modes as adhesive anchors, as shown in Figure 2.1, except that headed anchors eliminate a grout/steel interface failure according to Zamora et al. (2003) [10]. Grouted anchor bonding materials can be more difficult to use as they are typically more fluid than in an adhesive anchor, making overhead and horizontal applications very difficult due to the possibility of increased sagging of the grout material prior to curing.



Non-Headed Grouted Anchor

Headed Grouted Anchor

Source: Cook and Burtz, 2003 [14]

Figure 3.2: Examples of headed and non-headed anchors

3.2.1 Behavior Grouted Anchor Bolts in Tension

Grouted anchor systems were used in design prior to the development of polymers for adhesive anchors. The grout compositions were as follows:

- Type I: One part Type I Portland cement and three parts fine sand by volume, mixed with water.
- Type 2: One part Type I Portland cement and three parts fine sand by volume, mixed with polymer resins as liquid.
- Type 3: A pre-mixed, non-shrink grout mixed with water.

Type I grouts failed at the grout/concrete interface for the 0.50 inch (12.70 mm) and 0.75 inch (19.05 mm) diameter anchors. Type II grouts experienced grout/concrete interface failures in half of the specimens and flexural failure of the test slab for the other specimens. Type III grouts had the highest capacity, with only one bond failure of the tested specimens, while the rest failed in flexure of the slab [19]. This experiment was conducted prior to standardization of pullout tests by ASTM; therefore, the results are not easily compared with more current research. Today, non-shrink grout is almost exclusively used in structural applications.

James et al. (1987) [15] used finite element modeling to develop an approximate mathematical model to predict grouted anchor behavior. The CCD method and Uniform Bond Stress Models are now the accepted design models for grouted anchors in literature such as Zamora et al. (2003) [10]. ACI Committee 318 (2002) [20] defined a cone angle of 35°, while a value of 45° was predicted by James et al. (1987) [15]. The majority of the load transferred from the anchor rod to the concrete occcured within one or two anchor diameters from the top surface of the concrete, suggesting that a partial concrete cone will accompany any bond failure at embedment depth to anchor diameter ratios of greater than 3 to 4. This was confirmed for adhesive anchors in Cook et al., 1998 [9].

3.2.2 Behavior of Headed and Unheaded Grouted Anchors under Tensile Load

Zamora et al. (2003) [10] conducted 242 unconfined short-term tests on grouted anchors in order to determine behavior of grouted anchors loaded in tension and to develop design procedures. Testing procedures of ASTM E488 (2010) [11] and ASTM E1512 (2007) [12] were followed. Six cementitious and three polymer grouts were tested with both headed and non-headed anchors. This study varied the following parameters: bonding agent (cementitious or polymer), anchor configuration (headed or non-headed), anchor and hole diameter, embedment depth, and concrete strength. The test matrices for this research program can be found in Tables 3.2 and 3.3.

Table 3.2: Test matrix for non-headed grouted anchors

	Total	d, mm				hef, mm				d0, mm				f'c at test, Mpa			
	Number	Series				Series				Series				Series			
Product	of Tests	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
CA	25	15.9	19.1	25.4	-	102	127	172	-	50.8	50.8	50.8	-	35.6	35.6	50.8	-
CB	15	15.9	19.1	25.4	-	102	127	178	-	50.8	50.8	50.8	-	35.6	33.4	31.0	-
CC	20	15.9	19.1	25.4	12.7	102	127	178	76	50.8	50.8	50.8	50.8	34.0	34.1	34.1	33.4
CD	15	15.9	19.1	25.4	-	102	127	178	-	50.8	50.8	50.8	-	39.9	39.9	35.8	-
CE	14	15.9	19.1	25.4	-	102	127	178	-	50.8	50.8	50.8	-	34.4	34.4	33.6	-
CF	5	19.1	-	-	-	127	-	-	-	50.8	-	-	-	38.0	-	-	-
PA	12	15.9	19.1	25.4	-	102	152	178	-	50.8	50.8	50.8	-	33.8	34.5	34.4	-
PB	12	15.9	19.1	25.4	-	102	152	178	-	50.8	50.8	50.8	-	33.9	33.9	34.4	-
PC	5	19.1	-	-	-	127	-	-	-	50.8	-	-	-	37.8	-	-	-

Note: Material starting with letter "C" are cementitious grouts; products starting with the letter "P" are polymer grouts.
Source: Zamora et al., 2003, p. 225 [10].

Table 3.3: Test matrix for headed grouted anchors

	Total	d, mm				hef, mm				d0, mm				f'c at test, Mpa			
	Number	Series				Series				Series				Series			
Product	of Tests	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
CA	25	19.1	19.1	25.4	19.1	127	127	178	127 152	50.8	50.8	50.8	38.1	35.7	32.7	32.6	49.9
CB	15	19.1	19.1	25.4	-	127	127	178	-	50.8	50.8	50.8	-	34.5	34.5	32.2	-
CC	15	19.1	19.1	25.4	-	127	127	178	-	50.8	50.8	50.8	-	31.1	31.1	31.0	-
CD	15	19.1	19.1	19.1	-	114	137	127	-	38.1	38.1	38.1	-	59.2	59.2	35.8	-
CF	13	19.1	19.1	19.1	-	102	114	127	-	50.8	38.1	38.1	-	30.9	30.9	35.9	-
PA	10	19.1	19.1	-	-	127	127	-	-	50.8	50.8	-	-	37.6	27.6	-	-
PB	5	19.1	19.1	-	-	127	127	-	-	50.8	38.1	-	-	37.6	27.6	-	-
PC	10	19.1	19.1	-	-	127	127	-	-	38.1	38.1	-	-	63.7	63.7	-	-

Note: Material starting with letter "C" are cementitious grouts; products starting with the letter "P" are polymer grouts.
Source: Zamora et al., 2003, p. 225 [10]

The primary failure mode of non-headed anchors was failure at the steel/grout interface bond. Of 129 non-headed anchor tests, only 10 (7.8%) experienced a failure mode other than steel/grout interface bond failure. Five of these ten experienced failure at the grout/concrete interface. The failures at the grout/concrete interface occurred in test series with larger diameter anchor rods in the same sized hole. The authors explain that the larger anchor rods allowed for a larger steel/grout bond area and shifted the failure to the grout/concrete interface bond. The conclusion of the non-headed grouted anchor tests was that the uniform bond stress model was validated for use in design procedures. The headed grouted anchors tested showed two main failure modes as predicted: failure at the grout/concrete interface bond and failure of the concrete with a full concrete breakout cone. Of the 113 headed anchor tests using cementitious and polymer grouts, 65 (57.5%) experienced failure at the grout/concrete interface bond and 48 (42.5%) experienced a full concrete breakout cone. Five tests were disregarded because they developed an exceptionally low bond stress at failure due to improperly mixed grout. There was no correlation found between type of grout (polymer or cementitious), failure mode, and capacity. Headed anchor behavior can be predicted by the lower value of the CCD or Uniform Bond Stress Model at the grout/concrete interface.

The reported project represented in-depth research on the static pullout capacity of grouted anchors, but did not present a proposed test standard, nor did it investigate environmental parameters or creep. Further research is needed in developing a test standard for grouted anchors as is now available for adhesive anchors. “New research has led to the development of design recommendations for adhesive bonded anchors. With design standards for adhesive anchors, grouted anchors are left as the only bonded fastening system without recommended design procedures” (Zamora et al., 2003, p. 224) [10].

3.2.3 Behavior of Grout/Concrete Failure Mode of Grouted Anchors

Cook and Burtz (2003) [14] proposed changes to the Florida Department of Transportation (FDOT) anchor test criteria “Florida Method of Test for Anchor System Tests for Adhesive Anchors and Dowels” [21]. The project tested the effects of hole drilling (either diamond or carbide tip), edge distance effects, and group spacing effects on the capacity of grouted anchors under static tensile load. The main focus was to investigate the behavior of the grout/concrete failure mode. For this reason, high-strength concrete, headed anchors, and small diameter holes were used to promote failure at the grout/concrete interface. Anchor rods were 0.63 inch (16.00 mm) diameter steel rods with threaded ends. A heavy hex nut was used to head the steel rod. The rod was installed in a 1.50 inch (38.10 mm) diameter hole, just large enough to fit the head, at an embedment depth of 5.00 inch (127.00 mm). A total of 40 tests were conducted in accordance with the testing matrix shown in Table 3.4.

Table 3.4: Summary of testing program

Installation #	Tested Effect	Hole Type	Anchor Diameter d, in (mm)	Hole Diameter d_0, in (mm)	Embedment Depth h_{ef}, in (mm)	Edge Distance c, in (mm)[a]	Spacing s, in (mm)[b]	# of Tests n
1	Baseline	Core	0.625 (15.9)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	5
1	Hammer	Hammer	0.625 (15.9)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	5
1	Group	Core	0.625 (15.9)	1.5 (38.1)	5.0 (127.0)	N/A	5.0 (127.0)	3
2	Baseline	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	3
2	Hammer	Hammer	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	3
2	Edge	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	7.5 (190.5)	N/A	5
3	Baseline	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	3
3	Edge	Core	0.750 (19.1)	1.5 (38.1)	5. (127.0)	4.5 (114.3)	N/A	5
3	Edge	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	6.0 (152.4)	N/A	5
3	Group	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	N/A	9.0 (128.6)	3

[a] Edge distances designated as N/A refer to anchors installed at $\geq 8d_0$.
[b] Spacing between anchors designated as N/A refers to anchors installed at $\geq 16d_0$.

Source: Cook and Burtz, 2003 [14]

Additionally, conclusions were made based on previously conducted research at the University of Florida [10]. Hole drilling tests consisted of six specimens installed in holes drilled with a diamond core drill, and six specimens installed in holes drilled with a hammer drill. This test series resulted in the hammer-drilled hole capacities being 3% greater than those of the diamond-core drilled holes, with a coefficient of variation of 0.012. The next test series resulted in the hammer-drilled hole capacities being 17% less than those of the diamond-core drilled holes, with a coefficient of variation of 0.017.

Cook and Burtz (2003) [14] included results from other testing programs conducted at the University of Florida to make observations about behavior of grouted anchors with respect to strength versus curing time, threaded rod versus deformed reinforcing bar anchor rods, threaded anchor rods versus smooth anchor rods, regular hex nut head versus heavy hex nut head, damp hole installation, and elevated temperature effects on polymer grouted anchors. These observations are summarized as follows.

Strength versus curing time was investigated by testing three different grouted products, one polymer grout and two cementitious grouts. Full strengths were obtained at different times, with the polymer grout taking only 24 hours and the cementitious grouts taking 7 days and 14 days respectively. Four different grouted anchor products were used to test bond strength to non-headed threaded rods in comparison to bond strength to deformed reinforcing bars. Three of the four grouts showed a decrease in bond strength of 9%, 4%, and 27% when a deformed reinforcing bar was used in place of threaded rod. The fourth showed an increase of 104% but is no longer marketed for this application. Three products, one polymer grout and two cementitious grouts, were used to compare bond strengths of non-headed threaded rods to bond strengths of non-head smooth rods. The smooth anchor rod caused a decrease in capacity for all three grouts. The two cementitious grouts experienced 91% and 81% reductions in bond strength, while the polymer grout experienced a 53% reduction in bond strength with the smooth rod as compared to the pullout capacity of the threaded rod. Three cementitious grouts and one polymer grout were used to compare a regular normal headed bolt versus a heavy hex nut in headed anchors. The heavy hex nut caused reductions of 15%, 19%, and 8% in the cementitious grout and an increase of 10% in the polymer grout when compared to the static pullout capacity of the headed bolt used as an anchor rod. The report showed the coefficients of variation for each product were less than 20% and concluded that it is not necessary to test products for use with different headed anchor types. Three polymer grouts were installed in damp holes and compared to dry hole installations, as recommended by the manufacturer. Two of the polymer grouts experienced strength decreases of 17% and 27% in the wet hole as compared to the dry hole, with the third product increasing capacity 11%. Two polymer grouts were tested at elevated temperatures. Both products experienced a strength reduction of 6% when compared to ambient temperature tests. These were not significant decreases but show there could be a correlation between elevated temperature and capacity for polymer grouted anchor systems. [14]

Long-term load tests were not conducted by Cook and Burtz (2003) [14], but creep was addressed as a potential issue for grouted anchors and the authors recommended a creep test at 40% MSL with procedures similar to ACI 355.4 (2011) [1], including elevated temperature.

Subramanian et al. (2004) [21] used data from Zamora et al. (2003) [10] and Rodriquez et al. (2010) [22] to make independent conclusions and recommendations. There were no contradictory conclusions made, but additional information about the behaviour of grouted anchors was observed. Polymer grouted anchors, for example, were noted to experience larger deformations throughout the loading period when installed with a larger hole diameter. This research also proposed a capacity reduction factor (ϕ) of 0.85 based on the 5% fractile observed in Zamora et al. (2003) [10].

4.0 Test Methods and Materials

The following chapter describes the materials and procedures used in the experimental testing program conducted at UMass. The anchor installation process was conducted in accordance with all manufacturer printed installation instructions, and the anchor pullout tests followed the test procedure found in AASHTO-TP84 [4], with slight variations as noted.

4.1 Experimental Testing Program Overview

Bonding materials of different chemical compositions from different manufacturers were selected for the anchor pullout tests conducted at UMass. The material chemistries as characterized in the Manufacturer Safety Data Sheet (MSDS) are briefly described as follows:

- Material 1: Bisphenol epoxy resin with amine hardener (adhesive in cartridge format)
- Material 1B: Epoxy resin with amine hardener (adhesive in cartridge format)
- Material 2: Bisphenol epoxy resin with amine hardener (adhesive in cartridge format)
- Material 3: Bisphenol epoxy resin (hardener undeterminable from MSDS) (adhesive in cartridge format)
- Material 4: Methyl methacrylate with crystalline silica (adhesive in cartridge format)
- Material 5: Ester based material (adhesive in glass capsule format)
- Material 6: Cementitious material: calcium aluminate cement, aggregates, fillers, and additives (cementitious in capsule format)
- Material 7: Urethane methacrylate resin, dibenzoylperoxide (adhesive in cartridge format)

4.1.1 AASHTO TP-84 Materials

Materials 1 through 6 were the principal materials of this investigation and were used for the evaluation of AASHTO TP-84 [4]. To evaluate a material per the provisional standard, a minimum of five short-term tests were initially conducted and their results averaged in order to determine the MSL of the material. Subsequently, ten long-term tests were performed at two different load levels, 60% to 70% of MSL and 70% to 80% of MSL. A minimum of five anchors were tested per load level, with exceptions as noted. A displacement versus time plot was created for each long-term test, and failure of the anchor was defined as the onset of tertiary creep, as shown in Figure 4.1. The results from both the short-term and long-term tests are plotted on a Stress vs. Time-to-failure (SvTTF) graph and a linear trend line is drawn through each data point. The spring system which was used to apply long-term load for the UMass testing program decreases in load as anchor displacement increases according to the spring configuration stiffness. Therefore, all long-term tests were corrected for load loss during testing and the corrected values were reported in the SvTTF graphs.

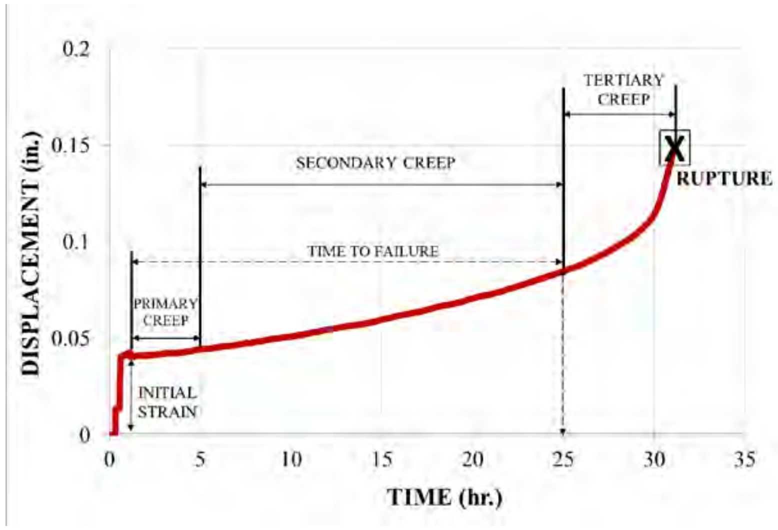


Figure 4.1: Example displacement vs. time graph for long-term tests

All short- and long-term tests were confined tests completed at a temperature range of 110°F to 120°F (43°C to 49°C), as required per the test method. Additionally, all tests were initiated within 7±5 days upon completion of the manufacturer's specified curing time for each adhesive as allowed by AASHTO TP-84. Each test series was prepared, installed and tested as follows:

- Day 1: Specimen drilling, hole cleaning, and anchor installation.
- Days 2–4: Environmental conditioning in testing chamber.
- Day 5: Short-term tests conducted.

4.1.2 Installation Direction Testing Program

Post-installed adhesive anchors can be susceptible to installation and in-service factors that affect bond strength. Installation direction has the potential to affect the performance of adhesive anchors. Horizontal or upwardly inclined holes are difficult to fill with adhesive, with the potential for air voids within the hole that reduce the bond area between the adhesive and the anchor.

A total of 20 short-term tests were conducted with variation in hole drilling and anchor installation direction. Material 1B and Material 2 were selected for supplemental short-term testing regarding the influence of installation direction. The installation procedure for horizontal or upwardly inclined holes is dependent upon the requirements of the manufacturer. For the testing program conducted at UMass, no end-cap, piston-plug, or other aiding delivery systems were used for installation, as they were not required by the manufacturers of these products.

Material 1B was a replacement product for the discontinued Material 1 product. All short-term tests were performed in accordance with the short-term testing procedure of AASHTO TP-84.

Each material was tested as a series of 10 short-term tests, where 2 of the tests in each series were installed and drilled in the downward direction in order to verify that results were similar to those of previous short-term testing. The results of these control tests are not included as part of the short-term test results of the materials due to differences in the age of the epoxy at the time of testing, though comparisons are provided. Each test series was prepared, installed, and tested as follows:

- Day 1: Specimen drilling, hole cleaning, and anchor installation.
- Days 2–6: Environmental conditioning in testing chamber.
- Day 7: Short-term tests conducted.

4.1.3 Extreme In-Service Temperature Testing Program

Post-installed adhesive anchors used in transportation structures are exposed to wide temperature variations throughout their service life. Therefore, any difference in behavior caused by the extreme in-service temperatures that may be experienced would be of importance. For these tests, a material recommended by the manufacturer for use in cold-weather applications, Material 7, was compared in performance to Material 1B and Material 2, the materials with best results in previous tests and recommended for typical installation conditions. The manufacturer-printed installation instructions of each material include an allowable concrete temperature range for anchor installation. The temperatures prescribed for Materials 1B, 2, and 7 can be found in Table 4.1.

Table 4.1: Installation temperature ranges

MATERIAL	MIN. CONCRETE TEMPERATURE (°F)	MAX. CONCRETE TEMPERATURE (°F)
1B	23	105
2	50	110
7	14	104

The test regimen developed for assessing the performance of anchoring systems in extreme in-service temperatures consisted of 65 short-term tests conducted with variation in installation and testing temperatures. Installation temperatures were selected between 20°F and 120°F (-7°C and 49°C) in order to test the behavior of each material within and outside of the allowable range described in Table 4.1. Testing temperatures were chosen from 0°F to 120°F (-18°C to 49°C), as these are representative of extreme in-service temperatures an anchoring system could be exposed to during its service life.

A 22-cubic-foot moderate cold chest freezer was used to condition and test specimens at the lower temperatures required for this regimen. Prior to initiating the testing program, preliminary tests on a sample concrete block with embedded thermistors were conducted in order to confirm the conditioning time required for a specimen to reach the desired temperatures. The sample concrete block was of identical size to the test specimens. The chest freezer was set to a temperature of 20°F (-7°C), and the sample block at ambient temperature was placed inside. Hourly resistance readings were taken from the embedded thermistors to determine the time necessary for the block to reach the designated temperature. It was determined from the resistance versus time plot shown in Figure 4.2 that the block reached the set freezer temperature after approximately 21 hours of being placed in the freezer and stabilized at that temperature thereafter. Therefore, in the testing schedule of specimens included in this program, each specimen was allowed 24 hours to reach the designated freezer temperature and an additional 24 hours to stabilize at 0°F (-18 °C), 20°F (-7 °C), 25°F (-4 °C), or 30°F (-1 °C). Each test specimen was prepared, installed, and tested as follows:

- Day 1: Specimen drilling and hole cleaning; begin conditioning of test specimen to initial concrete temperature.
- Day 2: Continue conditioning test specimen to initial concrete temperature.
- Day 3: End of initial conditioning; perform anchor installation at the designated installation and curing temperature and allow curing for 24 hours at this temperature.
- Day 4: End of curing; begin conditioning of specimen to the final testing temperature.
- Day 5–6: Continue conditioning to final testing temperature.
- Day 7: Conduct short-term tests at testing temperature.

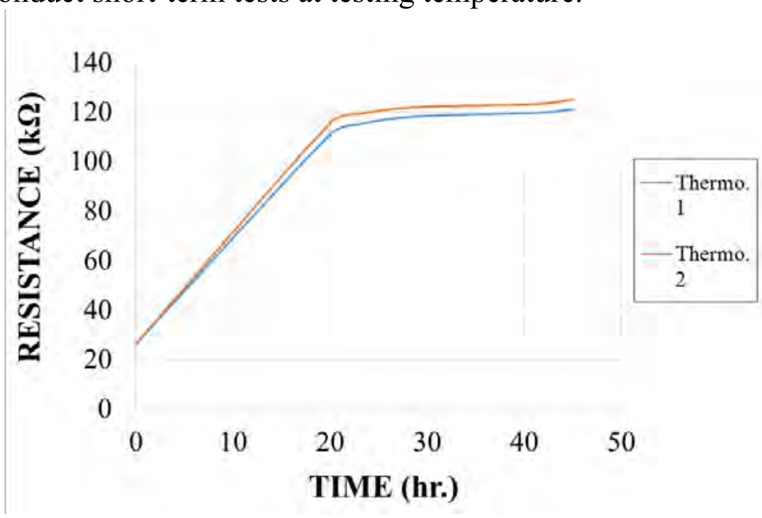


Figure 4.2: Resistance vs. time plot of sample concrete block

4.1.4 Polymer Characterization Testing

Polymer characterization testing of six of the bonding materials studied during this investigation (Materials 1, 1B, 2, 3, 4, and 7) was conducted in order to comment on technique usefulness for field quality assurance and quality control of field-installed bonded anchor materials. Only products that were delivered through a manual dispensing gun were available for testing, because samples could not be taken from materials contained in a glass capsule form (Material 5). Testing was not conducted on the cementitious material (Material 6), though future studies regarding polymer characterization of this type of material is recommended. The methods tested included FTIR and DSC. FTIR has been frequently used for the chemical analysis of cured epoxy samples, as it provides a fast and efficient way of determining their approximate chemical composition. DSC testing has also been proven effective in determining the glass transition temperature of a polymer, an important property of an anchoring material, as it is the temperature region where the polymer transitions from a hard, glassy material to a soft, rubbery state, making it more susceptible to creep.

FTIR tests were conducted at curing temperatures of 50°F (10°C), 74°F (23°C), 104°F (40°C), and 500°F (260°C) and cure times of 3, 7, and 21 days. The purpose of this testing was to determine if material variability can be identified if a product is modified and to verify that proper mixing was accomplished onsite. The curing temperatures of 50°F (10°C), 74°F (23°C), and 104°F (40°C) were selected because they are possible temperature variations a sample disk could be exposed to between the time it was cast in the field and before being placed in the final curing location. A curing temperature of 500°F (260°C) was also included in order to study the infrared spectrum of the materials at a temperature beyond their glass transition temperature, which was verified as being significantly above the glass transition temperature of the tested materials.

4.2 Test Specimens

All test specimens were constructed to meet the requirements of AASHTO TP-84 [4]. Specimens consisted of three components: concrete test member, steel anchor rod, and bonding material.

4.2.1 Concrete

A standard MassDOT 4,000 psi (27.6 MPa) mix design provided by a local ready-mix company was used for all tests described in this report. A total of six concrete batches were cast throughout the research project in order to complete the required testing programs. Details regarding the mixture design and concrete properties of each batch can be found in the Appendix: Concrete Batch Specifications.

The concrete specimens were poured in 16.00 inch (406.40 mm) diameter by 8 inch (203.20 mm) deep cylindrical sonotube cardboard forms that were sealed to a 0.5 inch (13 mm) plywood base. The specimens were covered with sheets of burlap and plastic and maintained wet for the first 7 days of curing. After 14 days, the specimens were removed from the forms and allowed to cure for a total of 28 days prior to testing. The test specimen dimensions of 16.00 inch (406.40 mm) by 8 inch (203.20 mm) were chosen in order to comply with the provisions presented in Section 6 of AASHTO TP-84 [4], which requires the concrete member to have sufficient dimensions to permit anchor placement at least 2 times the embedment depth from any edge and the depth of the member to be at least 1.5 times the embedment depth.

Approximately 45 specimens were cast per batch of concrete, along with 15 test cylinders (6.00 inch x 12.00 inch, 152.40 mm x 304.80 mm) used to measure the compressive strength of the concrete upon completion of curing. Test cylinders were cured similarly to the test specimens. Concrete compressive strength was determined by testing the cylinders in accordance with ASTM C39 [23] in a Forney FX 500 compression machine. Figure 4.3

shows sample test specimens during the curing process. Results were provided at 28 days as well as during first and last tests using this concrete batch.

(a) (b)

Figure 4.3: Sample concrete test specimens during (a) initial 7-day cure and (b) 28-day cure

4.2.2 Anchor Rod

To reduce the possibility of steel failure, ASTM A354 Grade BD steel with nominal yield strength of 130 ksi (896 kPa) and ultimate strength of 150 ksi (1034 kPa) was used for all threaded rods.

A 0.50 inch (12.70 mm) diameter threaded rod was used as the anchor for all specimens that included an adhesive bonding material. These anchors were cut to 6.00 inch (152.40 mm) lengths and installed in accordance with the minimum embedment depth of 2.75 inch (69.90 mm) prescribed in AASHTO TP-84 [4]. This depth was chosen to ensure bond failure. A 0.63 inch (16.00 mm) diameter threaded rod was used as the anchor for all Material 6 (cementitious capsule) specimens. This was due to the anchoring capsule size required for a 0.50 inch (12.70 mm) diameter rod being discontinued during the course of this project. The next available capsule size of 0.75 inch (19.05 mm) recommended for a 0.63 inch (16.00 mm) diameter rod was used for all Material 6 anchor pullout tests. These anchors were cut to 9.00 inch (228.6 mm) lengths and installed at an embedment depth of 6.00 inches (152.4 mm). This depth was chosen after anchor capacity at the minimum recommended depth of 3.13 inch (79.50 mm) was lower than expected and exhibited wide variability. Additional short-term testing was then completed for deeper embedment depths of 4.00 inches (101.60 mm) and 6.00 inches (152.40 mm). It was concluded that a 6.00 inch (152.40 mm) embedment was the most appropriate for obtaining dependable results.

4.2.3 Bonding Material

Bonding materials of different chemical compositions from four different manufacturers were selected for the anchor pullout tests conducted at UMass. The material chemistries as characterized in the Manufacturer Safety Data Sheet (MSDS) are described in Section 4.1. All products were stored in an air-conditioned space in order to maintain the materials within the temperature range specified by the manufacturer.

4.3 Specimen Preparation for Testing

All test specimens were prepared in accordance with AASHTO TP-84 [4] and their respective manufacturer's recommendations, with slight modifications as specified.

4.3.1 Conditioning Prior to Drilling

AASHTO TP-84 [4] requires all concrete specimens to stabilize at a temperature of 65°F to 85°F (18°C to 29°C) and 50 ± 10% relative humidity prior to drilling. When conditions in the laboratory were not adequate for the specimens to reach the required temperature and room humidity, the specimens were sealed under plastic with an air-conditioning system to cool them to the required state, as shown in Figure 4.4.

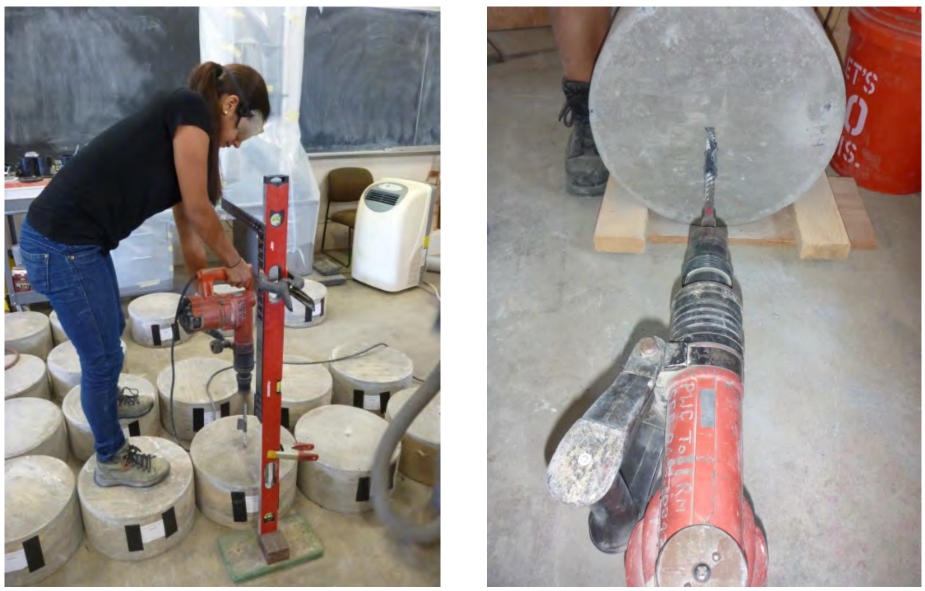
Figure 4.4: Conditioning of specimens prior to drilling

4.3.2 Drilling

The holes were drilled into the concrete using a Hilti TE-72 hammer drill and carbide-tipped hammer drill bits. A 0.63 inch (15.89 mm) diameter hole was drilled for Material 1, Material 2, and Material 4. A 0.56 inch (14.22 mm) diameter hole was drilled for Material 3, Material 5, Material 7, and Material 1B. A 0.89 inch (22.61 mm) diameter hole was drilled for Material 6. All test specimens were drilled in a downward direction, with the exception of specimens that specifically evaluated the effects of horizontal drilling. For downward drilling applications, a drilling stand was used to support vertical downward drilling as shown in

Figure 4.5(a). After each specimen was drilled, the hole was checked for correct depth and verticality.

For horizontal drilling applications, the concrete specimen was lifted to its upright position and placed on a sheet of plywood, where it was kept in place using two sections of wood, as seen in Figure 4.5(b). A level was used to ensure that surface of the concrete was perpendicular to the floor prior to drilling. The specimen was drilled horizontally by placing the base of the drill on the surface of the floor and pushing the drill into the concrete, using the floor surface as a way of maintaining the tool level throughout drilling. This allowed for a precise and controlled drilling method.



(a) (b)

Figure 4.5: (a) Downward drilling and (b) horizontal drilling of specimens

4.3.3 Hole Cleaning

The holes were cleaned as specified by the manufacturer's instructions before the bonding material and threaded rod were installed. The hole-cleaning procedure for all materials included a sequence of blowing the hole with compressed air, a water jet, or both; brushing with a wire brush; and re-blowing the hole to remove any remaining dust particles. The number of cleaning cycles varied by manufacturer and are specified for each material in Table 4.2.

Table 4.2: Hole cleaning procedure for all materials

MATERIAL	HOLE CLEANING PROCEDURE
1	• Blow with compressed air (2x) • Brush with rounded wire brush (2x) • Blow with compressed air (2x)
1B	• Blow with compressed air (2x) • Brush with rounded wire brush (2x) • Blow with compressed air (2x)
2	• Blow with compressed air (4x) • Brush with rounded wire brush (4x) • Blow with compressed air (4x)
3	• Blow with compressed air (4x) • Brush with rounded wire brush (4x) • Blow with compressed air (4x)
4	• Blow with compressed air (4x) • Brush with rounded wire brush (4x) • Blow with compressed air (4x)
5	• Blow with compressed air (2x) • Brush with rounded wire brush (2x) • Blow with compressed air (2x)
6	• Blow clean with compressed air • Fill hole with water and blow out
7	• Blow with compressed air (2x) • Brush with rounded wire brush (2x) • Blow with compressed air (2x)

4.3.4 Anchor Installation

All anchors were installed in accordance with the respective manufacturer's installation instructions, with the exception of Material 5. Material 5 is only available in a standard-length glass capsule form, which was longer than the required testing depth of 2.75 inches (69.85 mm). Therefore, an alternative testing method was adopted for this product. Several trial installations were conducted to ensure that consistent results were obtained.

Adhesive in Cartridge Format

Prior to being installed in concrete, the anchors were cleaned with a disposable rag to wipe away all dust and grease, which could disrupt the proper setting of the adhesive. Masking tape was placed on the exposed length of the anchor to ensure that only the specified length of the rod bonded with the concrete. Material 1, 1B, 2, 3, 4, and 7 adhesives are two-part chemical systems packaged in side-by-side cartridges, which were installed per their respective manufacturer's instruction cards. Prior to dispensing adhesive into the drilled hole, a minimum of three full strokes of adhesive were separately dispensed through the mixing nozzle until the adhesive became a consistent and uniform color.

For downward installation, the cleaned and taped anchors were fastened to a plastic stand with a nut placed at the correct height to allow the anchor to reach the appropriate embedment depth and support vertical placement during curing, as shown in Figure 4.6. The adhesive was delivered into the hole using the manufacturer-recommended dispensing tool and mixing nozzle. The hole was filled to approximately two-thirds full, and the anchor was immediately inserted into the filled hole. The anchor was rotated in a clockwise direction as it was installed to avoid air gaps and ensure that all threads were covered with the material. The anchors were left undisturbed in the plastic stands for 24 hours.

Figure 4.6: Downward installation of anchor

For horizontal installation, the adhesive was delivered into the hole using the manufacturer-recommended dispensing tool and mixing nozzle. No piston plugs or similar installation aids were used for the horizontal installation procedure. The hole was filled to approximately two-thirds full, as shown in Figure 4.7(a), and the anchor was immediately inserted into the filled hole, as shown in Figure 4.7(b). The anchor was installed in this way to avoid air gaps and ensure that all threads were covered with the material. The anchors were left undisturbed in the horizontal position for 24 hours.

Upon completion of the curing time, the excess hardened adhesive above the concrete surface was sawn off and lightly chipped away from around the anchor to allow a steel confining plate to sit flat against the surface of the concrete.

(a) (b)

Figure 4.7: (a) Delivery of adhesive into horizontally drilled hole; (b) horizontal anchor installation

Adhesive in Glass Capsule Format

Material 5 was only available from the manufacturer in a glass hammer-capsule form. This 0.50 inch (12.70 mm) capsule, appropriate for use with a 0.50 inch (12.70 cm) rod, is only manufactured at a standard length of 4.25 inches (107.95 mm) and consists of a hardener, resin, and quartz aggregate, which are all mixed inside the hole when the anchor rod is driven through the glass capsule using a two-pound hammer. Modifications to the installation procedure for this product were required in order to test the capsule at a 2.75 inch (69.90 mm) embedment depth.

First, several preliminary tests were conducted where anchors were installed in concrete cylinders at the minimum embedment depth of 4.25 inches (107.95 mm) recommended by the manufacturer. After the anchor was allowed to cure for 24 hours, the cylinder was split along its length in order to examine the color and consistency of the appropriately installed adhesive. Next, a second series of anchors were installed at a 2.75 inch (69.90 mm) embedment depth, using a modified installation procedure in which two pieces of wood with a 0.56 inch (14.29 mm) drilled hole were placed over the protruding end of the capsule. The protruding portion of the anchor rod was wrapped in tape to avoid bond of adhesive above the concrete, leaving only the length of the anchor that would be embedded in the concrete exposed. The rod was driven through the capsule, while the wood was firmly clamped in place. Once the anchor had reached the embedment depth, the wood was immediately removed and the excess adhesive was wiped away from the concrete face around the anchor. The anchor was allowed to cure undisturbed for 24 hours at ambient room temperature. The concrete cylinders were split along their length, and results were compared to those anchors that had been installed at the full embedment depth. Visually, the adhesive installed using the modified method had the same color and consistency as those installed per the respective manufacturer's recommendations. Therefore, this modified installation method was considered acceptable.

The hammer glass capsule is shown in Figure 4.8. The anchor installation setup for this capsule format adhesive is shown in Figure 4.9.

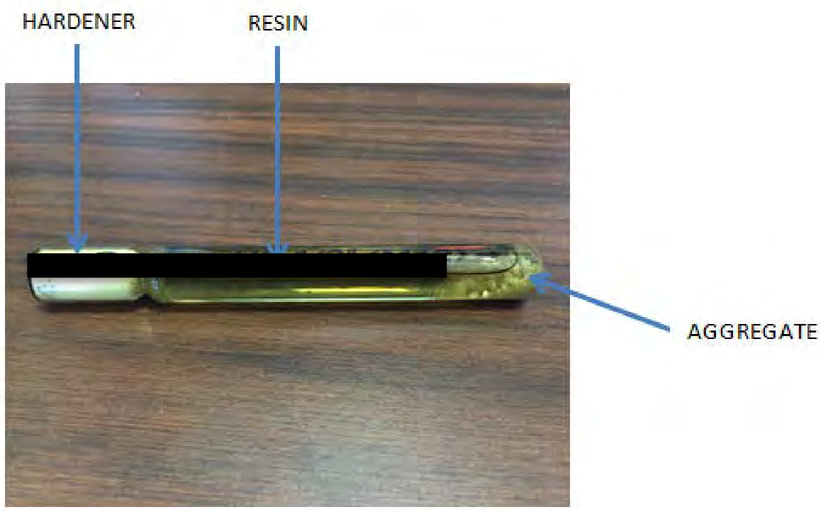


Figure 4.8: Adhesive in glass capsule format

(a) (b) (c)

Figure 4.9: Installation setup for adhesive in glass capsule format

Adhesive in Cementitious Capsule Format

Cementitious capsules are shown in Figure 4.10(a). After the hole was properly cleaned of all dust and debris, the surface of the hole was saturated with water immediately before anchor installation. Next, the capsules were placed in water and allowed to soak for one to two minutes, or until the material stopped releasing bubbles. The soaked capsule was then placed into the hole (as shown in Figure 4.10(b)) and cut to the required length. The anchor rod was placed inside the capsule (shown in Figure 4.10(c)) and hammered into the hole using a 20-pound hammer (shown in Figure 4.10(d)). Once the anchor had reached the embedment depth, the excess adhesive was carefully wiped away from the concrete surface. Discussion with the manufacturer led to uncertainty of the required curing time for this material.

Additional static testing was completed for 24-hour, 7-day, and 28-day cure times. Results showed that a 28-day cure at ambient room temperature was most appropriate for obtaining adequate results.

(a) (b)

(c) (d)

Figure 4.10: (a) Cementitious capsule; (b) insertion of capsule into clean hole; (c) insertion of anchor rod into capsule; (d) hammering of anchor into hole

4.4 Environmental Conditioning

Specimens conditioned and tested at elevated temperature were placed in a temperature- and humidity-controlled chamber to reach the testing conditions of 110°F to 120°F (43°C to 49°C) and lower than 50 ± 10% percent relative humidity, as required by AASHTO TP-84 [4]. The chamber was powered by commercial heaters that were automated to maintain the internal specimen temperature between 110°F (43°C) and 120°F (49°C). Figure 4.11(a) shows the elevated temperature chamber constructed at UMass. As per Section 8 of AASHTO TP-84 [4], the conditioning of the test specimens was started upon completion of the manufacturer-recommended cure time, and testing was initiated within 7±5 days.

A 22-cubic-foot moderate cold chest freezer was used to condition and test specimens at the lower temperatures required for later testing. The chest freezer, shown in Figure 4.11(b), included a digital temperature controller which allowed the internal freezer temperature to be set between -29°F to 50°F (-34°C to 10°C). Prior to initiating the testing program, preliminary tests on a sample specimen were conducted in order to confirm the conditioning time required for specimens to reach the desired temperatures based on internal thermistors in a test specimen.

(a)

(b)

Figure 4.11: Environmental conditioning chambers for (a) elevated and (b) low temperatures

4.5 Test Components

4.5.1 Short-Term Test Apparatus

The short-term test apparatus conformed to the requirements of ASTM E488 [11] and NCHRP Report 757 [2]. A maximum load of 40.00 kips (178.00 kN) was assumed when designing the test apparatus. The short-term test setup assembled inside the testing chamber is shown in Figure 4.12. Plans for the test apparatus are shown in Figure 4.13 and Figure 4.14.

.

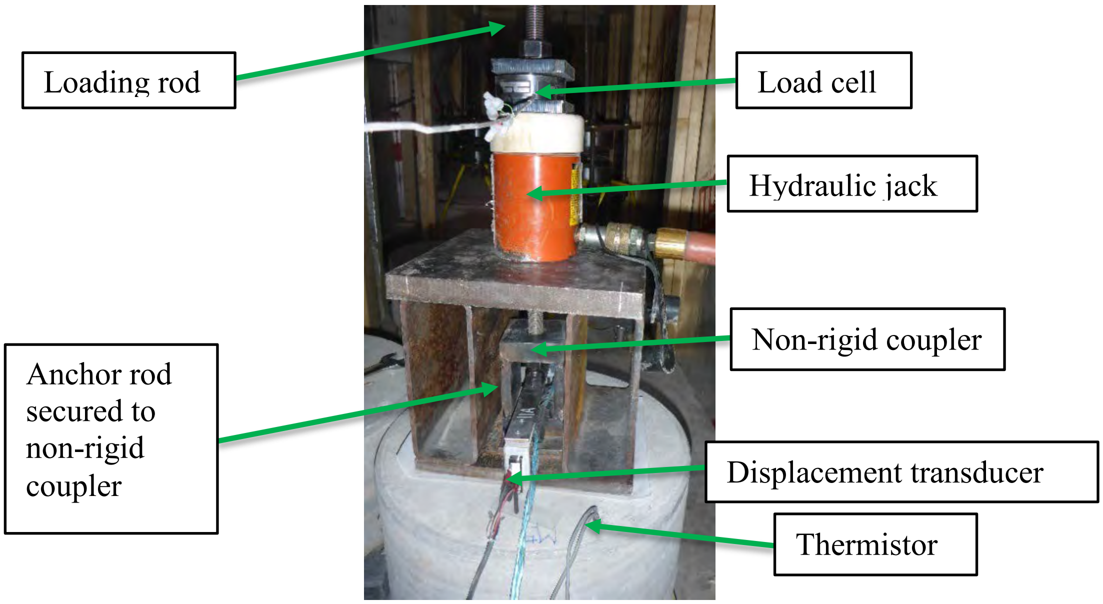


Figure 4.12: Short-term test apparatus

First, a polytetrafluoroethylene (PTFE) confining sheet and steel confining plate were placed over the anchor being tested. Then, a non-rigid coupler was secured to the anchor using a high-strength hex nut. A steel flat bar with aluminum angles, to which BEI 9610 Series Linear Position Sensors were attached, was passed through the non-rigid coupler and also attached to the anchor with an ASTM A194 2H high-strength hex nut. The linear potentiometers attached to the steel bar were placed equidistantly from the anchor and were distanced so as to not interfere with the anchor as it failed. An ASTM A500 Grade B HSS 8.00 x 3.00 x 0.25 inch (203.20 x 76.2 x 6.35 mm) section was placed on both sides of the non-rigid coupler, parallel to one another. A 10.00 x 10.00 x 1.00 inch (254.00 mm x 254.00 mm x 25.00 mm) steel plate with a 2.75 inch (69.85 mm) diameter hole was placed on top of the HSS 8.00 x 3.00 x 0.25 inch (203.20 x 76.2 x 6.35 mm) sections, along with an SPX Power Team RH-202 20-ton (178-kN) center hole hydraulic jack and a Transducer Techniques THD-50K-Z model load cell. A 0.89 inch (22.61 mm) loading rod was passed through the load cell, hydraulic jack, steel plate, and the non-rigid coupler and was secured with a heavy hex nut and washer on both ends. The loading rod was carefully aligned to be positioned directly above the anchor rod and reduce eccentricities during loading, although it was not possible to be exact with the test apparatus, which led to some visual non-alignment under full load.

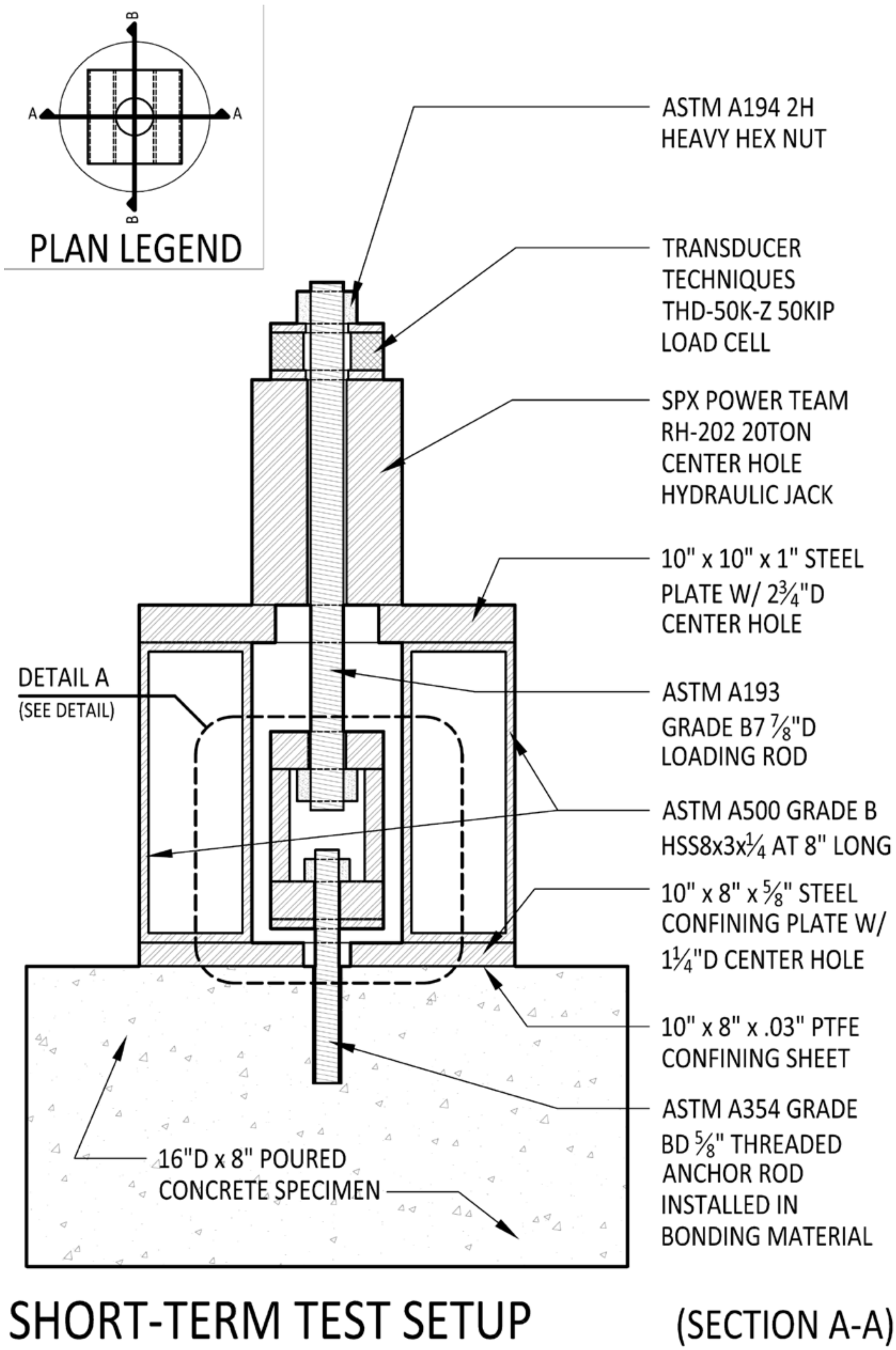


Figure 4.13: Short-term test apparatus, Section A-A

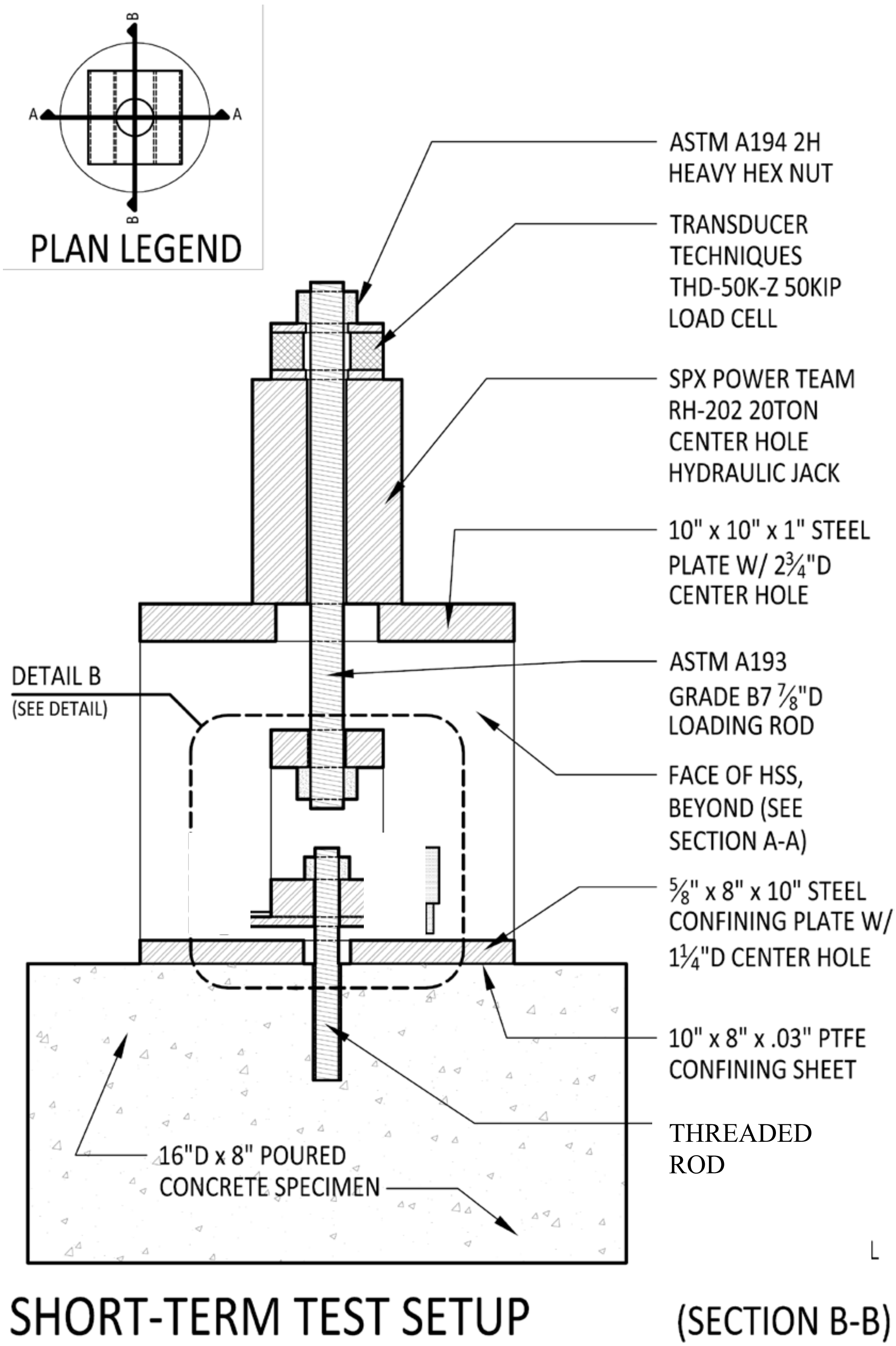


Figure 4.14: Short-term apparatus, Section B-B

4.5.2 Long-Term Test Apparatus

Long-term tests conformed to AASHTO TP-84 (2010) [4] and NCHRP 757 [2]. Three long-term test setups were on loan from the University of Florida and were used to conduct trial tests. An additional 20 test setups were manufactured to complete the long-term testing for this project. The long-term setup assembled inside of the chamber is shown in Figure 4.15. Plans for the apparatus are shown in Figure 4.17 and Figure 4.18.

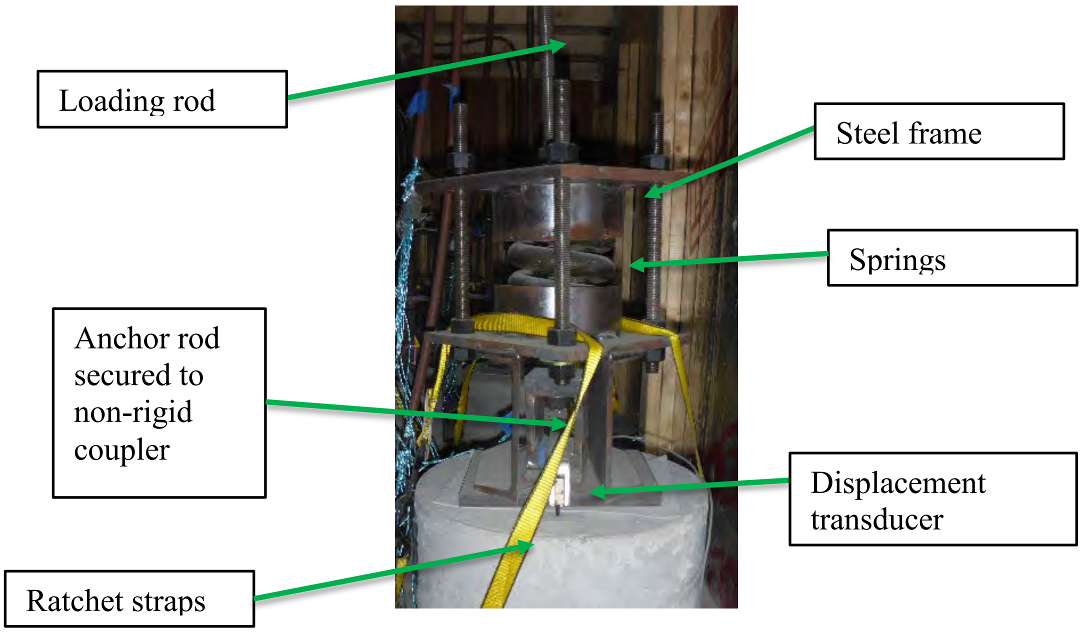


Figure 4.15: Long-term test apparatus

The anchor rod was passed through a confining sheet, confining plate, and non-rigid coupler, identical to those used in the short-term test apparatus. A steel flat bar with aluminum angles, to which BEI 9610 Series Linear Position Sensors linear potentiometers were attached, was passed through the non-rigid coupler and also attached to the anchor with an ASTM A194 2H high-strength hex nut.

On top of the confining plate, a steel frame was placed that included a top and bottom plate containing a set of Standard Car Truck Company D2 inner and D2 outer springs used to maintain long-term load. The small spring (D2 Inner) fit inside the large spring (D2 Outer) when used in parallel and was wound in opposite directions to avoid torsion during loading. The nominal properties of the springs were as follows: large springs were approximately 5.50 inch (139.70 mm) in diameter by 8.25 inch (209.55 mm) in uncompressed length, with a 1.22 inch (30.99 mm) wire diameter, maximum load of 15.96 kip (70.99 kN) at 6.63 inch (168.40 mm) height, and 9.80 kip/inch (17.20 kN/cm) stiffness. The small springs were approximately 3.00 inch (76.20 mm) in diameter by 8.25 inch (209.55 mm) in uncompressed length, with an 0.69 inch (17.50 mm) wire diameter, maximum load of 5.40 kip (24.02 kN) at 6.63 inch (168.40 mm) height, and 3.30 kip/inch (5.80 kN/cm).

When the springs are used in parallel, the expected maximum load is 21.345 kip (94.95 kN). The stiffness of each spring set in parallel was calibrated to determine the actual spring stiffness later used to calculate load loss during testing. An example of a spring calibration is shown in Figure 4.16. It was found that the springs had a stiffness of 12.56 kip/inch (22.00 kN/cm). The springs were housed in a two-piece spring retainer unit. The loading rod was secured to the top of the non-rigid coupler with an ASTM A194 2H heavy hex nut and passed through the springs in the steel frame. Two ratchet straps were placed on the specimen in order to control an excessive rebound of the steel frame upon failure of the anchor.

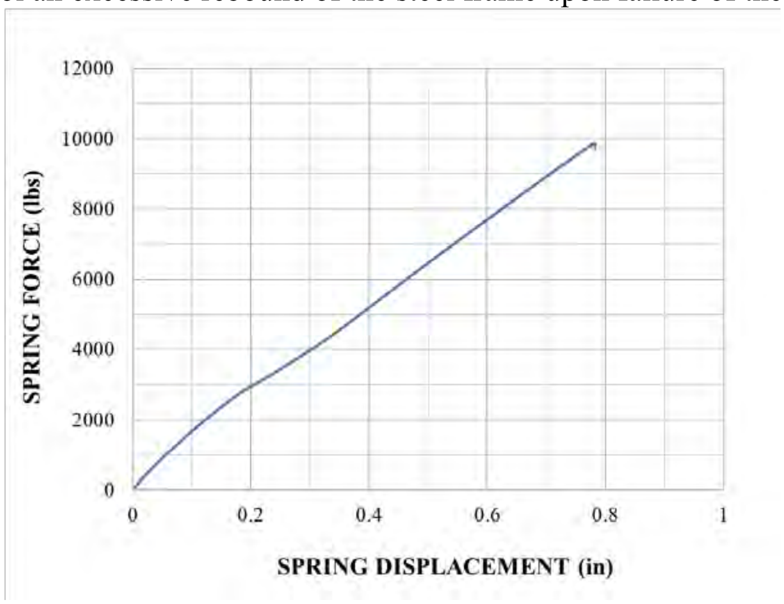


Figure 4.16: Example of spring calibration

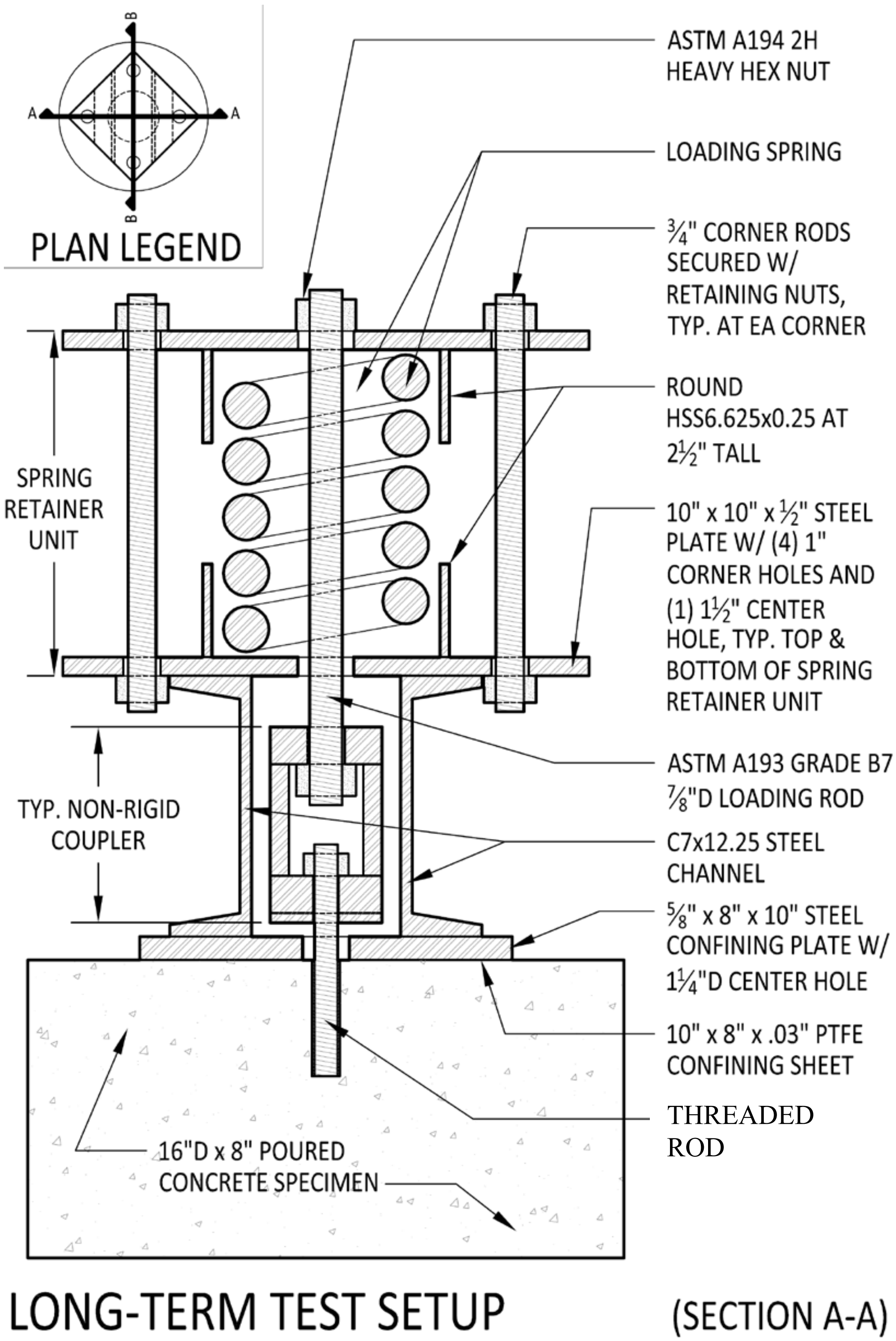


Figure 4.17: Long-term test apparatus, Section A-A

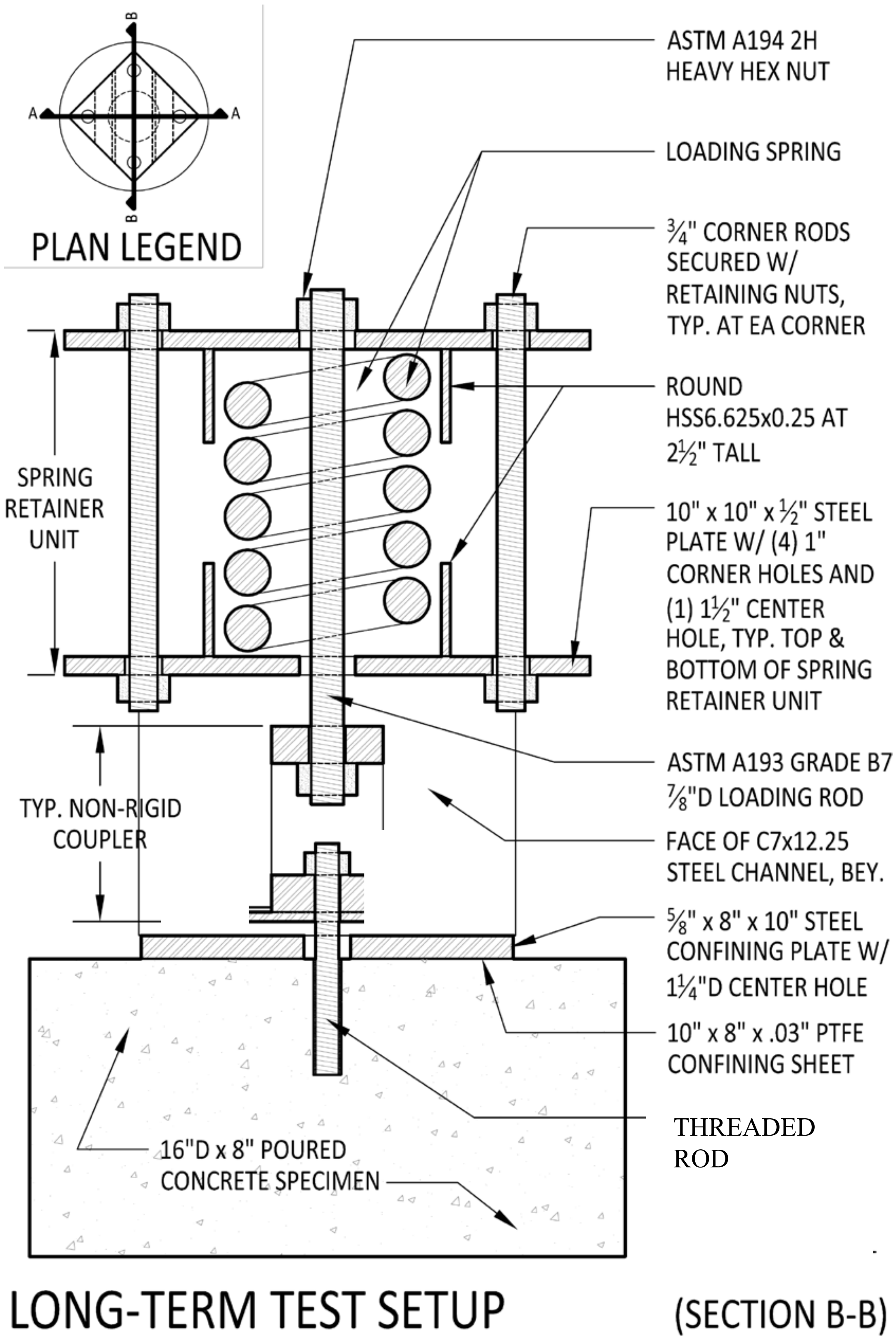


Figure 4.18: Long-term test apparatus, Section B-B

4.5.3 Loading Rod

The capacity of the loading rod was designed to be greater than the capacity of the anchor. The loading rod used for testing was a 0.88 inch (22.35 mm) diameter ASTM A193 Grade B7 Threaded Rod (yield strength of 48.50 kips (215.70 kN)).

4.5.4 Non-Rigid Coupler

A steel non-rigid coupler was used to connect the anchor rod to the loading rod. This coupler had a 0.69 inch (17.5 mm) diameter hole at the bottom where the anchor rod passed through and a 1.00 inch (25.40 mm) diameter hole at the top where the loading rod passed through. Both the anchor rod and the loading rod were secured with an A194 2H heavy hex nut. The use of the coupler is to reduce bending moments being applied to the anchor by allowing rotation at the connection points. The coupler was two 1.00 inch (25.40 mm) thick plates with an 0.69 inch (17.5 mm) diameter center hole at the bottom and 1.00 inch (25.40 mm) diameter center hole on top held apart by 0.50 inch (12.70 mm) thick plate sides. The full capacity of all the plates was required to carry loads of up to 40.00 kips (177.93 kN), so full penetration welds were used to connect the top and bottom plates to the side plates.

4.5.5 Confining Plate

A 0.63 inch (16.00 mm) thick 8.00 x 10.00 inch (203.20 mm x 254.00 mm) steel plate with a 1.25 inch (31.75 mm) diameter center hole was used to confine the tests. AASHTO TP-84 [4] requires the confining plate to be greater than or equal to the nominal anchor diameter ± 0.06 inch (± 1.52 mm). Confining the tests prevents concrete failure. This was done to allow for a more consistent measurement of bond failure.

4.5.6 Confining Sheet

A confining sheet was used between the concrete sample and the confining plate. This sheet is required by AASHTO TP-84 [4]. A 0.76 mm thick sheet of PTFE of roughly the same dimensions as the confining plate, with a 1.25 inch (31.75 mm) diameter center hole, was placed between the concrete and the steel confining plate to correct surface irregularities.

4.5.7 Hydraulic Jack/Pump

The load was applied to the loading rod with an SPX Power Team RH-202 20-ton center hole hydraulic jack. The pressure was applied to the jack with an SPX Power Team P460d hydraulic hand pump.

4.6 Test Procedure

The test procedures of AASHTO TP-84 [4] consist of two types of tests, short-term and long-term. Short-term tests are initially conducted to determine the MSL of the system, and long-term tests are subsequently conducted at various percentages of MSL. All tests must be confined tests performed at the environmental conditions of 110°F to 120°F (43°C to 49°C) and relative humidity lower than 40%. The test specimens must be allowed to stabilize at the required environmental conditions for 24 hours before initiating testing.

4.6.1 Short-Term Test Procedure

In order to conduct a short-term test, an initial tensile load of 5% of the expected ultimate load capacity of the anchor must be applied in order to bring all members into full bearing. Next, the load is increased at a constant load rate, which causes the anchor fail within 2 ± 1 minutes. Data (load, temperature, and displacement readings) was collected at a sampling rate of 0.5 seconds through failure of the anchor. A minimum of five anchors were tested and their results averaged to determine MSL for each material.

To determine the short-term load strength of an anchor, a load versus displacement curve was created with the data collected from the test. The short-term load strength was determined to be the peak of the curve, after which a sudden reduction in the stiffness of the anchor was typically observed.

4.6.2 Long-Term Test Procedure

To begin a long-term test per AASHTO TP-84 [4], a tensile load not exceeding 5% of MSL was initially applied in order to bring all members into full bearing. Next, the load is increased at constant load rate, which allows the desired long-term load to be reached within 2 ± 1 minutes. Anchors are tested at two different load levels, 60% to 70% MSL and 70% to 80% MSL. A minimum of five anchors must be tested per load level.

To load the springs to the desired tension for the long-term applied load (percentage of MSL), a load system was placed above the top plate of the spring retainer unit. A load chair, center hole hydraulic jack, and load cell with plates above and below were stacked to allow for compressing the springs. The springs were compressed with the hydraulic jack to the desired force measured by the load cell. An ASTM A194 2H heavy hex nut within the jack chair secured the springs at the compressed distance, and the hydraulic jack and load cell were removed. Trial runs utilizing multiple load cells were completed to evaluate the load loss during seating of the nut. It was found that a consistent pressure of a wrench beyond hand tight resulted in a final released spring load within 200 pounds of the desired load and was used during testing. Long-term load was maintained through the compression of the spring. The amount of load available in the spring was then closely monitored through the displacement of the anchor where the displacement of the anchor rod resulted in loss of spring compression in accordance with the spring calibration stiffness. The lower value of spring compression throughout testing was reported as the load on the anchor, though if losses were excessive, the spring was re-compressed per the preceding procedure.

Per AASHTO TP-84 [4], failure for long-term tests is defined as initiation of tertiary creep. The onset of tertiary creep is found by analyzing the change in slope of the creep curve. Tertiary creep is defined as the time the change in slope becomes positive for the last time prior to fracture.

4.7 Instrumentation

4.7.1 Temperature and Relative Humidity

Air temperature and relative humidity inside the environmental chamber were measured using an Omega HX93B Series temperature/relative humidity transmitter. The internal temperature of each test specimen was measured using QTI Sensing Solutions model QTSSP thermistors. The thermistors were inserted into a hole located on the top surface of the concrete. The thermistors were placed in 0.50 inch (12.70 mm) diameter holes, 1.40 inch (35.56 mm) deep, and the hole was sealed with a rubber stopper in order to more accurately measure the temperature of the concrete. For initial tests, the hole was filled with sand prior to being sealed with the rubber stopper to allow a better reading of the concrete temperature. However, the sand did not make a significant difference in readings and was omitted for all further testing.

The temperature of each specimen and the humidity of the chamber were consistently monitored to ensure compliance with the test method. For any amount of time the specimen or chamber conditions were outside the allowable environmental condition temperatures, the time was discounted from the total testing time reported for the specimen.

4.7.2 Displacement

BEI 9610 Series linear position sensors were used to measure anchor displacement. The potentiometers were attached to a steel flat bar with aluminum angles, as shown in Figure 4.19. A thin glass slide was placed underneath each transducer prior to testing, to provide a smooth surface for the potentiometer to rest on.

Figure 4.19: Linear potentiometers attached to steel bar

4.7.3 Load

A Transducer Techniques THD-50K-Z 50-kip capacity load cell was used to measure load for all short-term anchor pullout tests and when loading the springs to the desired compression for the long-term applied load. The load for long-term tests after initial loading was measured indirectly through the displacement of the anchor, assuming it to be equal to the extension of the spring. Load loss of long-term specimens was calculated using a calculated spring stiffness of 12.56 kip/inch (22 kN/cm). The reported long-term load value of an anchor was corrected for load-loss. The test procedure found in AASHTO TP-84 [4] does not provide recommendations on how to report the individual load values and percentage of MSL values of each anchor at failure.

4.8 Data Management

4.8.1 Data Acquisition System

A LabVIEW 8.6 program, developed by the University of Florida and modified at UMass to match their equipment, was used to collect and record all data. Data acquisition was conducted with multiple National Instruments NI 9206 modules connected to a National Instruments NI cDAQ 9188 chassis. Measurements taken with each data sampling iteration of a test frame included a time stamp, chamber temperature and relative humidity, concrete temperature, load (for static tests only), and anchor displacement.

4.8.2 Data Sampling

During short-term tests, data readings were taken every 0.5 seconds for the duration of test as prescribed per the test method. For long-term tests, the frequency of data readings was as follows:

- Every 0.5 seconds during loading.
- Every 5 seconds for 120 iterations (10 minutes).
- Every 30 seconds for 120 iterations (60 minutes).
- Every 5 minutes for 120 iterations (10 minutes).
- Every hour thereafter until termination of test.

For some specimens, the data acquisition needed to be restarted. When this occurred, sampling temporarily proceeded at a higher rate than that listed above.

This page left blank intentionally.

5.0 Anchor Pullout Test Results

This chapter includes the results of the anchor pullout tests conducted at UMass. Only the results of those specimens that exhibited a pullout failure of the anchor were reported.

5.1 Nomenclature

The nomenclature used to identify each anchor pullout test is as follows.

AASHTO TP-84 Materials

M - S/L - #
Where,
M: Material (1–7)
S/L: Test type (S: Short-term; L: Long-term)
#: Test number (1–5 for short-term tests; 1–10 for long-term tests)

Installation Direction Tests

M - D_1/H_1 - D_2/H_2 - #
Where,
M: Material (1B or 2)
D_1/H_1: Drilling direction (D: downward; H: horizontal)
D_2/H_2: Installation direction (D: downward; H: horizontal)
#: Test number (1–10)

Extreme In-Service Temperature Tests

M - T1 - T2 - T3 - #
Where,
M: Material (1B, 2, 7)
T1: Initial concrete temperature
T2: Installation and curing temperature
T3: Testing temperature
#: Test number (1–3)

5.2 Short-Term Test Results

All short-term anchor pullout tests followed the test procedure found in AASHTO TP-84 [4], with slight modifications as noted. The testing of each product began with a minimum of five short-term anchor pullout tests to determine the MSL. The load versus displacement graphs for the short-term tests of each material are shown in Figure 5.1 to Figure 5.9, all of which presented a bond failure.

5.2.1 Material 1

Material 1, an epoxy adhesive with amine hardener, presented consistent short-term results, as shown in Figure 5.1. An MSL of 19.17 kip (85.27 kN) and COV of 5% were determined for this material, with a minimum result of 18.38 kip (81.76 kN) and a maximum result of 20.50 kip (91.19 kN).

While only five tests are reported herein, an additional five specimens were tested but load readings were not recorded. However, load and displacement readings were observed during testing, and it was found that all tests failed at approximately 0.04 inches (1.02 mm) with similar peak load to those shown in Figure 5.1. Although data for these initial short-term tests were not collected, they provide additional confidence in the reliability of this material's short-term performance.

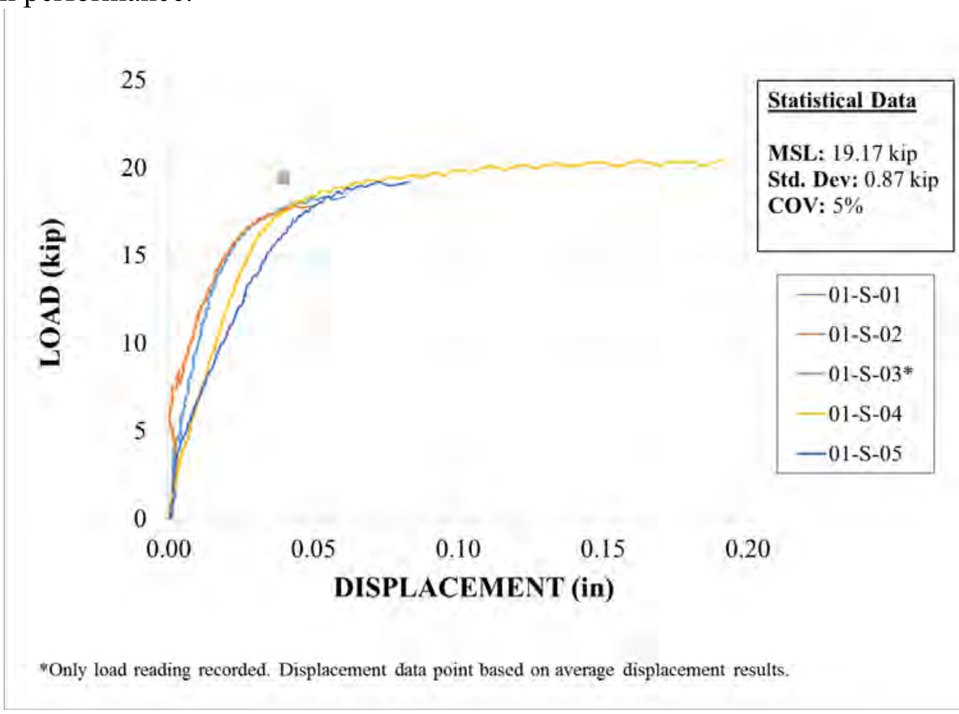


Figure 5.1: Material 1 short-term tests: load vs. displacement

5.2.2 Material 1B

Material 1B, an epoxy adhesive with amine hardener, presented consistent short-term results as shown in Figure 5.2. An MSL of 20.10 kip (89.41 kN) and COV of 7% were determined for this material, with a minimum result of 19.17 kip (85.27 kN) and a maximum result of 21.07 kip (93.72 kN).

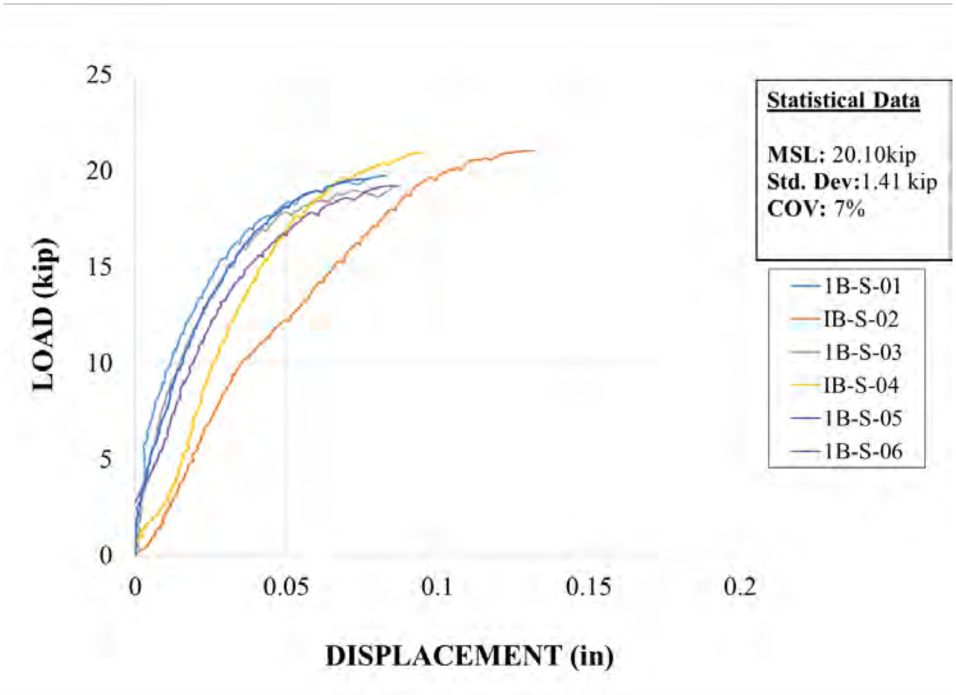


Figure 5.2: Material 1B short-term tests: load vs. displacement

5.2.3 Material 2

Material 2, an epoxy adhesive with amine hardener, presented consistent short-term results, as shown in Figure 5.3. An MSL of 18.33 kip (81.54 kN) and COV of 5% were determined for this material, with a minimum result of 17.40 kip (77.39 kN) and a maximum result of 19.90 kip (88.52 kN).

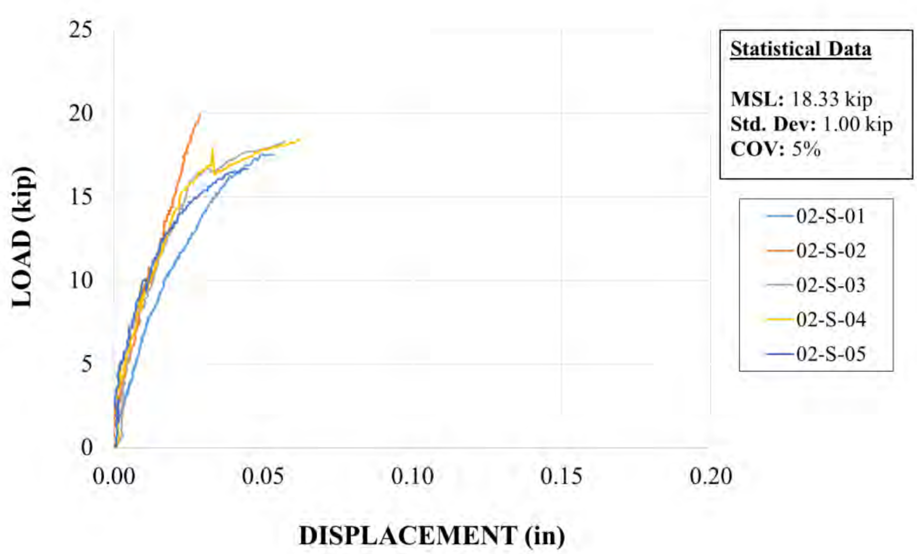


Figure 5.3: Material 2 short-term tests: load vs. displacement

5.2.4 Material 3

Material 3, an epoxy with an unknown hardener, presented less consistent short-term test results than Materials 1, 1B, and 2. Material 3 short-term test results are shown in Figure 5.4. An MSL of 16.45 kip (73.17 kN) and COV of 14% were determined for this material, with a minimum result of 13.69 kip (60.90 kN) and a maximum result of 19.53 kip (86.87 kN).

During the installation of this product, it was noted that the manufacturer-provided dispensing tool was not as stable as those from other manufacturers, allowing for some slight rotation of the plunger, potentially leading to an unequal disbursement from each cartridge. Per the manufacturer's instruction card, prior to dispensing adhesive into the drilled hole, full strokes of adhesive were separately dispensed through the mixing nozzle until the adhesive became a consistent and uniform color. However, during the installation process, the adhesive presented slight variability in color, shifting from darker to lighter shades of the expected color, as seen in Figure 5.5. Figure 5.5(a) shows a bright and consistent adhesive color after disposing of first strokes as indicated by the manufacturer, and Figure 5.5(b) shows a duller shade of adhesive with color streaks later in the installation process after additional strokes. Some shifting in the alignment of the dispensing tool was noticeable.

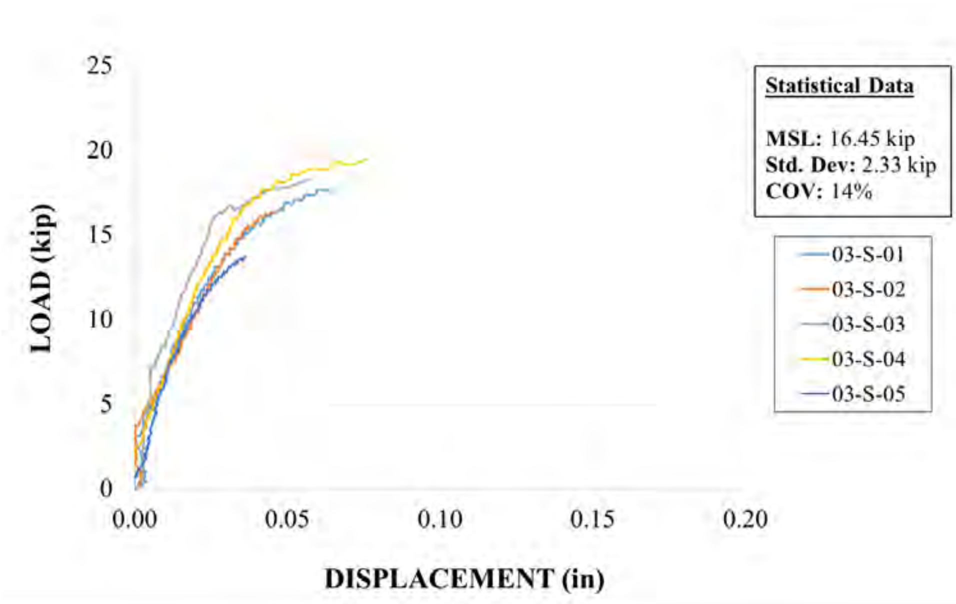


Figure 5.4: Material 3 short-term tests: load vs. displacement

(a) (b)

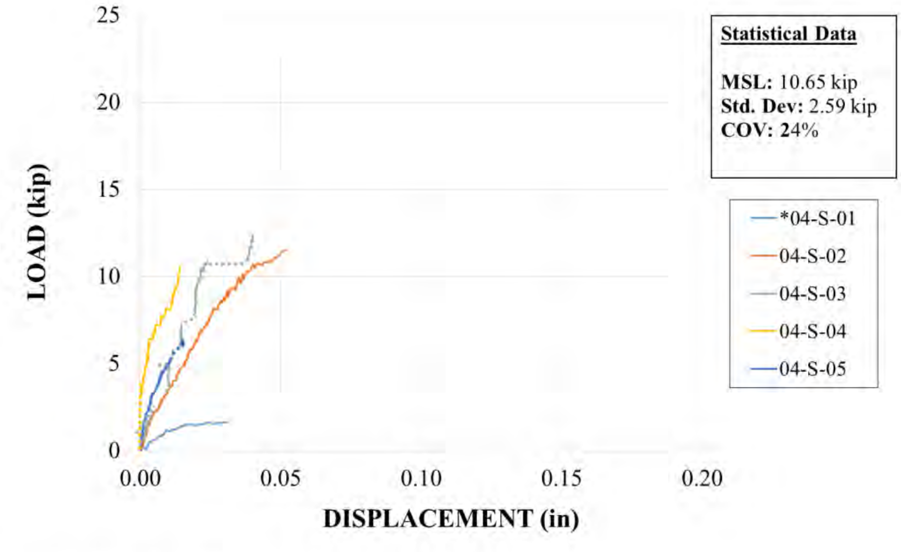
Figure 5.5: Material 3 adhesive color differences after disposing of first strokes as required by manufacturer, (a) initial bright and consistent color, and (b) duller shade with color streaks later in the dispensing of the material

5.2.5 Material 4

Material 4, a methyl methacrylate, presented less consistent short-term results than Materials 1, 1B, 2, and 3. Material 4 short-term test results are shown in Figure 5.6. An MSL of 10.65 kip (47.37 kN) and COV of 24% were determined for this material, with a minimum result of 6.79 kip (30.20 kN) and a maximum result of 12.39 kip (55.11 kN).

Short-term test 04-S-01 was excluded from the data results, as this test specimen had not fully cured at the time of testing, resulting in significantly lower capacity. In onsite field testing, the tacky consistency of the material from this insufficiently cured anchor would likely have been noticed or diagnosed through proof testing. It was deemed justifiable to exclude this test result from the statistical data, but this also indicated the wide variability of this material, which was shown by the remaining four tests.

Due to electrical problems with the data acquisition system encountered during the conduct of short-term tests 04-S-03 and 04-S-05, the load readings became discontinuous for a few seconds during the tests. However, the anchors were monitored through displacement readings during these lapses. The dashed lines included in the graphs of tests 04-S-03 and 04-S-05 represent the lapses in time during which load readings were not available.



*Excluded from results.

Figure 5.6: Material 4 short-term tests: load vs. displacement

5.2.6 Material 5

Material 5, an ester-based material in glass capsule format, presented less consistent short-term results than Materials 1, 1B, and 2. Material 5 short-term test results are shown in Figure 5.7. An MSL of 6.76 kip (30.07 kN) and COV of 31% were determined for this material, with a minimum result of 4.18 kip (18.59 kN) and a maximum result of 9.00 kip (40.03 kN).

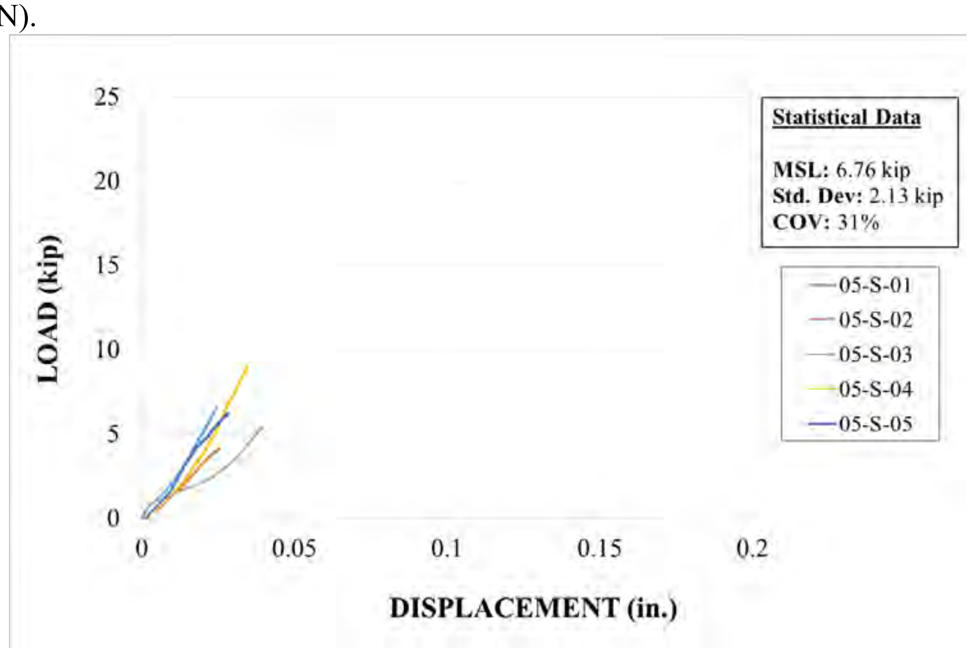


Figure 5.7: Material 5 short-term tests: load vs. displacement

5.2.7 Material 6

Material 6, a cementitious material in capsule format, presented less consistent short-term results than Materials 1, 1B, and 2. The anchors had lower capacities than expected from manufacturer literature and exhibited variable behavior during initial short-term testing. Earlier discussions with the manufacturer had also led to uncertainty of the required curing time for material; therefore, four series of Material 6 short-term tests were conducted with variations in embedment depth and cure time, in order to evaluate their effects. Results of all short-term tests of Material 6 are shown in Figure 5.8.

Test Series 1 of the short-term tests was conducted for five anchors at the minimum embedment depth allowed by AASHTO TP-84 [4]. For Material 6 specimen 0.63 inch (16.00 mm) diameter threaded rod, the minimum embedment depth of 3.13 inch (79.50 mm) was initially applied. The anchors were allowed to cure for 24 hours prior to initiating conditioning to the range of 110°F to 120°F (43°F to 49°F) inside the testing chamber. Under these conditions, an MSL of 3.88 kip (17.26 kN) and COV of 43% were determined for this material, with a minimum result of 1.96 kip (8.72 kN) and a maximum result of 6.11 kip (27.18 kN). Given the variability in results, further short-term tests were conducted at an increased embedment depth.

Test Series 2 of the short-term tests was conducted for two anchors at an embedment depth of 4.00 inches (101.60 mm), with the anchors allowed to cure for 24 hours prior to initiating conditioning to the range of 110°F to 120°F (43°F to 49°F). At this embedment depth, an MSL of 4.03 kip (17.93 kN) and COV of 13% were determined for this material, with a minimum result of 3.65 kip (16.24 kN) and maximum result of 4.40 kip (19.57 kN). Due to the low MSL of the material, additional tests were performed at an increased cure time and embedment depth.

Test Series 3 of the short-term tests was performed for five anchors at an embedment depth of 6.00 inches (152.40 mm), with the anchors allowed to cure for 28 days prior to initiating conditioning inside the testing chamber. An MSL of 13.60 kip (60.50 kN) and COV of 35% were determined for this test series, with a minimum result of 8.55 kip (38.03 kN) and maximum result of 19.70 kip (87.63 kN). The capacity of the anchors increased compared to the previous test series; however, an embedment depth of 6.00 inches (152.40 mm) applied to the 16.00 inch by 8.00 inch (406.40 mm by 203.2 mm) test specimens violated the concrete test specimen dimensions allowed by the test method. Therefore, it was necessary to verify short-term test results by retesting five anchors in larger test specimens (24.00 inch by 9.00 inch) (609.60 mm by 228.60 mm), which conformed to AASHTO TP-84 concrete cylinder dimensions.

Test Series 4 of the short-term tests was conducted for five anchors in larger test specimens (24.00 inch by 9.00 inch) (609.60 mm by 228.60 mm) with the same embedment depth and cure time as Test Series 3 in order to verify results. An MSL of 9.43 kip (41.95 kN) and COV of 25% were determined for this test series, with a minimum result of 5.98 kip (26.60 kN) and maximum result of 11.61 kip (51.64 kN). Although the MSL of this test series was 44% lower than the MSL obtained in Test Series 3, all specimens fit within the wide range of results from Test Series 3. It was concluded that larger test specimen results were similar to those of the smaller specimens, and therefore short-term tests per Test Series 3 presented reliable results for this material. Therefore, the short-term tests reported in the evaluation of Material 6 per AASHTO TP-84 [4] include the five tests of Test Series 3 performed at an embedment depth of 6.00 inches (152.40 mm) and cured for 28 days prior to conditioning.

Throughout all Material 6 testing, the ultimate displacement of the anchor at failure was significantly larger than for Materials 1 through 5. Therefore, it would be practical to define a displacement-based failure for this material rather than ultimate strength capacity.

In discussing the wide variability of results, the manufacturer later confirmed that the batch of anchoring capsules delivered to UMass for testing were provided with inadequate performing sleeves. Therefore, the behavior of the material presented in this report may not be representative of current material performance. In addition, while manufacturer literature and correspondence confirm that the material can be used with threaded rods, all documentation from the manufacturer is based on reinforcing bar anchorage. Replacement capsules have been received by UMass, and supplemental testing will be completed of Test Series 3 with new capsules, as well as tests to determine if capacities are significantly different for reinforcing bars.

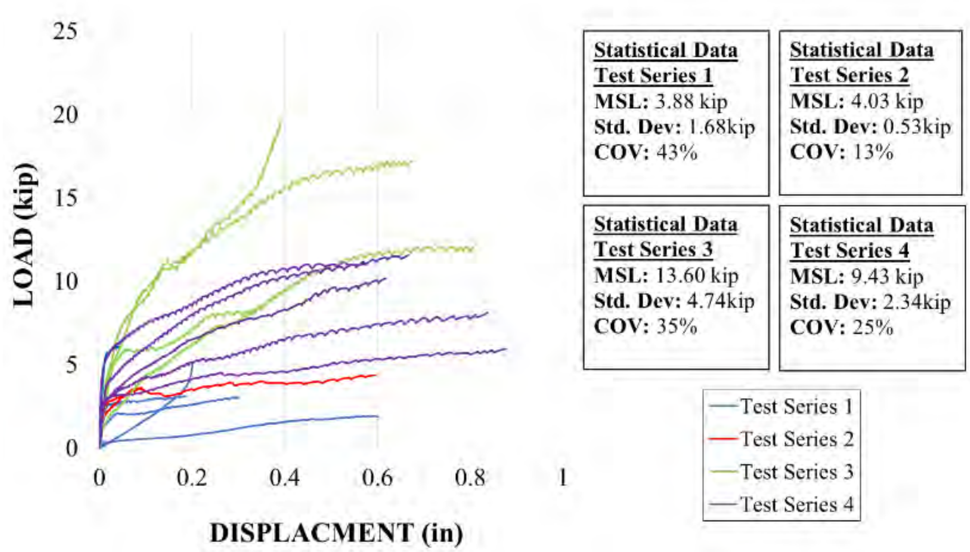


Figure 5.8: Material 6 short-term tests: load vs. displacement

5.2.8 Material 7

Material 7, a urethane methacrylate resin with dibenzoylperoxide hardener, presented consistent short-term results, as shown in Figure 5.9. An MSL of 17.42 kip (77.49 kN) and COV of 4% were determined for this material, with a minimum result of 16.57 kip (73.70 kN) and a maximum result of 18.42 kip (81.94 kN).

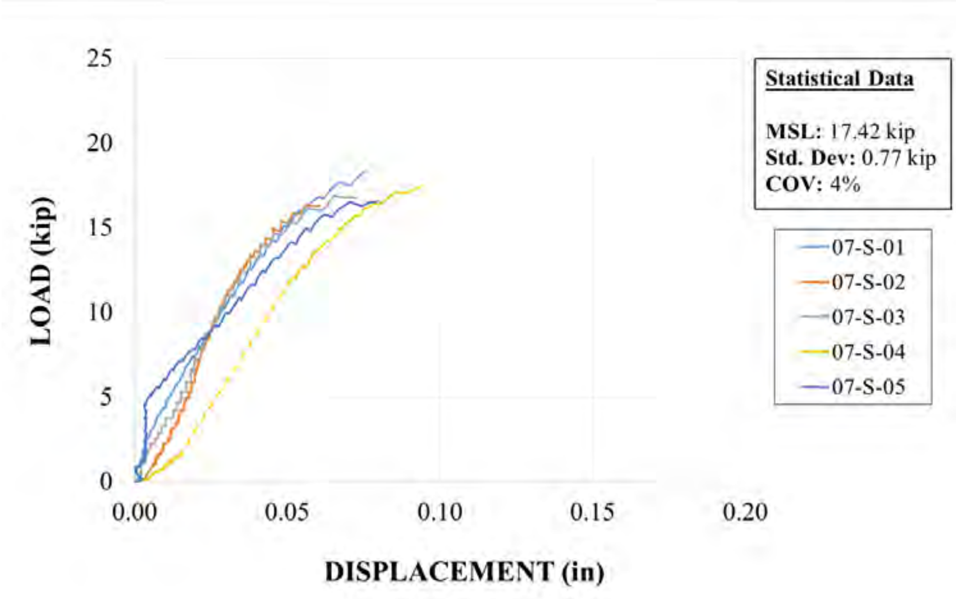


Figure 5.9: Material 7 short-term tests: load vs. displacement

5.2.9 Statistical Analysis of Short-Term Results

The results of a statistical analysis conducted for the short-term tests of all materials are presented in Table 5.1. This analysis includes the MSL, standard deviation, COV, and α_{COV} adjustment factor for those materials not meeting the requirements on COV stipulated in Chapter 10 of ACI 355.4 (2011) [1]. Section 10.4.2 of this standard prescribes a maximum limit of 15% on the COV for short-term reference tests. If a tests series exceeds this allowable threshold, a reduction of α_{COV} is taken on the bond stress value. This reduction factor is calculated in accordance with Equation 6.

$$\alpha_{COV} = \frac{1}{1+0.03(vtest,x - COV)} \qquad \text{Eq. 6}$$

Where,

$vtest,x$: Sample COV for test series x equal to the mean divided by the sample standard deviation, percent

COV: Threshold COV for adhesive anchors, percent (20 for peak loads from reliability tests and 15 for peak loads from tests for reference)

Table 5.1: Statistical analysis of short-term test results

MATERIAL	MSL (kip)	STD. DEV. (kip)	COV	α_{COV}
1	19.17	0.87	0.05	1.00
1B	20.10	1.41	0.07	1.00
2	18.33	1.00	0.05	1.00
3	16.45	2.33	0.14	1.00
4	10.65	2.59	0.24	0.78
5	6.76	2.13	0.31	0.67
*6	13.60	4.15	0.31	0.68
7	17.42	0.77	0.04	1.00

Note: Only results from Test Series 3 are included in the statistical analysis

The short-term tests conducted during this research program concluded that Material 1B (20.10 kip (89.41 kN)), Material 1 (MSL=19.17 kip (85.27 kN)), Material 2 (18.33 kip (81.54 kN)), all epoxies with amine hardeners, and Material 7 (MSL=17.42 kip (77.49 kN)) presented the highest MSL values. Also, the statistical analysis of short-term tests concluded that these four materials also had the lowest values of COV (Material 1B COV = 7%; Material 1 COV = 5%; Material 2 COV = 5%; Material 7 COV = 4%) and did not require a reduction factor ($\boldsymbol{\alpha_{COV}}$) to be taken from the MSL. The high bond strengths of these materials approached the yield and ultimate tensile strength, 18.50 kip (82.29 kN) and 21.3 kip (94.75 kN) respectively, of the 0.50 inch (12.70 mm) high-strength steel rod. The significance of this is that further bond material improvements may make AASHTO TP-84 testing difficult to perform and maintain bond failures. It is also worth noting that standard steels used in construction would have failed well before reaching the bond capacities listed in Table 5.2.

Material 3, an epoxy product with an unidentified hardener, had an MSL of 16.45 kip (73.17 kN) but exhibited greater variability in short-term test results compared to the other epoxy products tested (Material 3 COV = 14%). It is important to note that although Material 3 had less consistent performance than Materials 1B, 1, and 2 during short-term testing, the COV is less than the maximum limit of 15% prescribed by ACI 355.4 [1] and thus does not require a reduction factor to be applied to its bond stress capacity.

The lowest MSL values recorded in polymer materials tested were those of Material 4 and Material 5, 10.65 kip (47.37 kN) and 6.76 kip (30.07 kN) respectively. Furthermore, these materials surpassed the limit of 15% on the COV for short-term tests prescribed by ACI 355.4 [1]. For cases that exceed this threshold, a reduction must be taken on the bond stress in the form of α_{COV}. The variability of the short-term tests of these products was significant enough to lead to reduction factors of 0.78 for Material 4 and 0.67 for Material 5 on their bond stress capacity.

Differences in material performance were also observed between the epoxy materials and Material 6, a cementitious material. As shown in Figure 5.8, the short-term test anchor displacements were significantly larger during testing of Material 6 than during testing of any other materials. These anchors deformed from 0.40 inches (10.16 mm) to 1.00 inch (25.4 mm) at failure, values that are likely higher than allowable in an actual field application. Therefore, it is recommended to define failure for this material per a maximum allowable displacement.

While running the short-term test series of all materials per Section 9 of AASHTO TP-84 [4], it was observed that Section 9.3, which prescribes that a minimum of five anchors be tested and their results averaged in order to calculate the product's MSL, does not specify when the results from a test may be omitted from reporting. Therefore, it was up to the research team to decide to omit a specimen. In the testing program conducted at UMass, it was deemed justifiable to exclude short-term test 04-S-01 from data results, as this specimen had not fully cured at the time of testing. It is recommended that consistent criteria be established for the rejection of test results from data.

5.3 AASHTO TP-84 Materials Test Results

Six bonding materials of different chemical compositions were selected to be evaluated per the provisional standard, AASHTO TP-84 [4]. All anchor pullout tests followed the test procedure found in AASHTO TP-84 [4], with slight modifications as noted. The testing of each product began with a minimum of five short-term anchor pullout tests to determine the MSL, results of which were presented in Section 5.2 of this report.

Testing per AASHTO TP-84 [4] requires loading of specimens between 60% and 80% of MSL and sustaining that load until a failure. Results from both the short-term and long-term tests are plotted on a stress versus time-to-failure (SvTTF) graph, and a linear trend line is drawn through each data point. The SvTTF graphs created for all materials are shown in Figure 5.10 to Figure 5.15. In these plots, two different trend lines are shown: a solid line, which includes both short-term and long-term tests as prescribed by AASHTO TP-84 [4], and a discontinuous line, which includes only long-term tests as recommended in NCHRP Report 757 [2]. Each trend line is projected to a design life of 100 years.

Table 5.2 includes a summary of the tests included in the SvTTF of each material. The description of the chemical composition of each material can be found in Section 4.1 of this report.

Table 5.2: Summary of AASHTO TP-84 tests

MATERIAL	TEST TYPE	TP-84 REQUIRED TESTS	COMPLETED TESTS
1	Short-Term	5	5
	Long-Term (60%–70% MSL)	5	5
	Long-Term (70%–80% MSL)	5	5
2	Short-Term	5	5
	Long-Term (60%–70% MSL)	5	5
	Long-Term (70%–80% MSL)	5	5
3	Short-Term	5	5
	Long-Term (60%–70% MSL)	5	5
	Long-Term (70%–80% MSL)	5	5
4	Short-Term	5	5
	Long-Term (60%–70% MSL)	5	5
	Long-Term (70%–80% MSL)	5	2[1]
5	Short-Term	5	5
	Long-Term (60%–70% MSL)	5	0[1]
	Long-Term (70%–80% MSL)	5	0[1]
6	Short-Term	5	5
	Long-Term (60%–70% MSL)	5	8[2]
	Long-Term (70%–80% MSL)	5	0[1]

[1]No further testing was recommended due to poor material performance.
[2]Long-term tests were loaded to a displacement of 0.10 inch (2.54 mm).

5.3.1 Material 1

The SvTTF graph of Material 1 is shown in Figure 5.10. When short-term and long-term data are included in the trend line, the projected 50-year and 100-year capacities of the material are 48% MSL and 46% MSL, respectively. When only long-term tests are included in the trend line, the 50-year and 100-year capacities of the material are 57% MSL and 56% MSL, respectively.

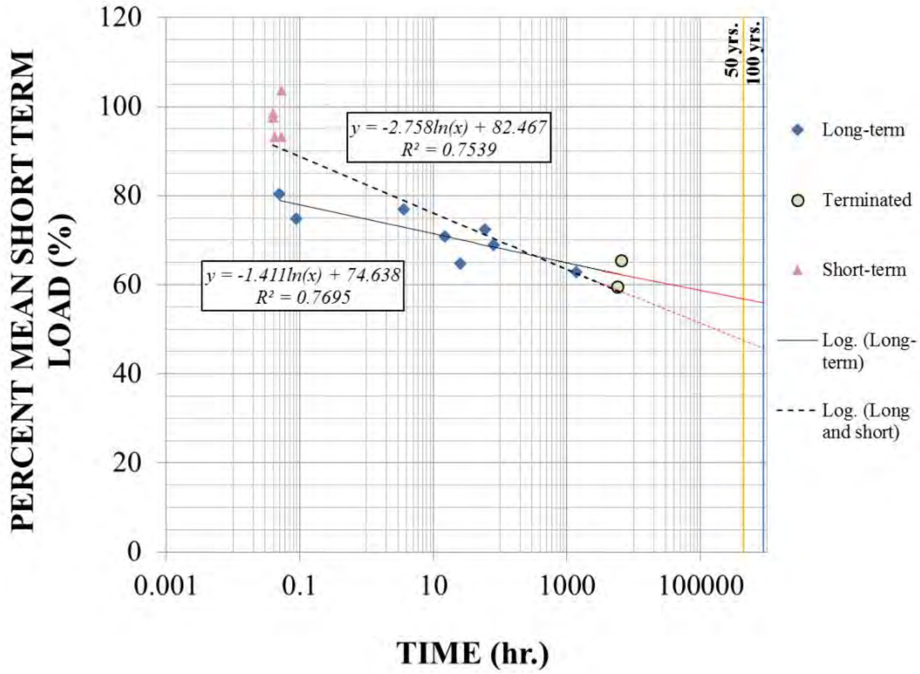


Figure 5.10: Material 1 SvTTF graph

5.3.2 Material 2

The SvTTF graph of Material 2 is shown in Figure 5.11. When short-term and long-term data are included in the trend line, the projected 50-year and 100-year capacities of the material are 40% MSL and 38% MSL, respectively. When only long-term tests are included in the trend line, the 50-year and 100-year capacities of the material are 51% MSL and 49% MSL, respectively.

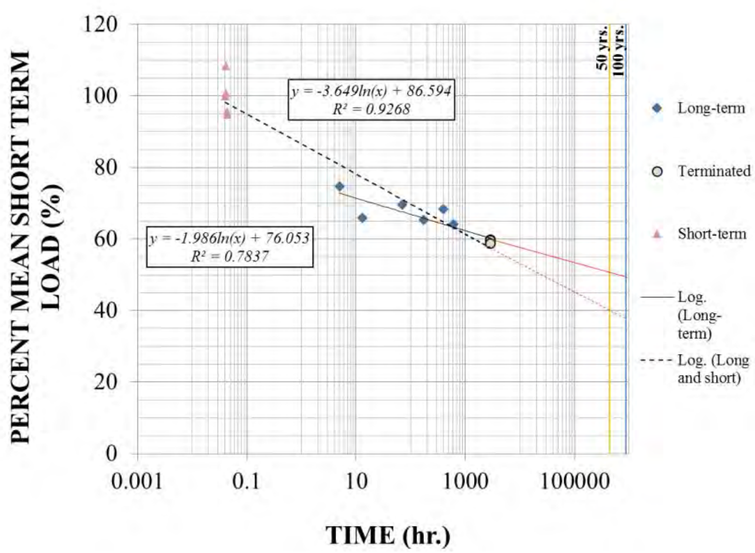


Figure 5.11: Material 2 SvTTF graph

5.3.3 Material 3

The SvTTF graph of Material 3 is shown in Figure 5.12. When short-term and long-term data are included in the trend line, the projected 50-year and 100-year capacities of the material are 58% MSL and 56% MSL, respectively. When only long-term tests are included in the trend line, the 50-year and 100-year capacities of the material are 59% MSL and 58% MSL, respecetively. Tests loaded outside of the allowable load range of 60% to 80% MSL were not included in the trend lines of the SvTTF graph.

As noted previously, Material 3 presented higher variablity in short-term test results than did Materials 1 and 2. This led to a flatter slope in the trend line of the material's projected load capacity with time. This was also true when short-term tests were omitted. This is attributed to a more variable MSL, resulting in less accuracy in the load applied during long-term testing as a percentage of MSL, and resulting in greater variation in long-term load results. The result is that the SvTTF approach could potentially reward a material with a higher variability in short-term load capacities (through a flatter long-term prediction line), which needs to be addressed in AASHTO TP-84 [4].

While a predictive curve was possible in Material 3, it was observed that it was difficult to move forward with the long-term testing of materials that showed significantly more inconsistent short-term capacities. When initiating long-term tests, it was difficult to predict the actual percentage of MSL being applied to each anchor, leading to great variability in long-term test results or failures upon initial loading. The SvTTF plot of Material 3 shown in Figure 5.12 is an example of an adhesive with scatter in long-term data due to a high COV in short-term tests that the authors feel is beyond the limit for potential application of the test method.

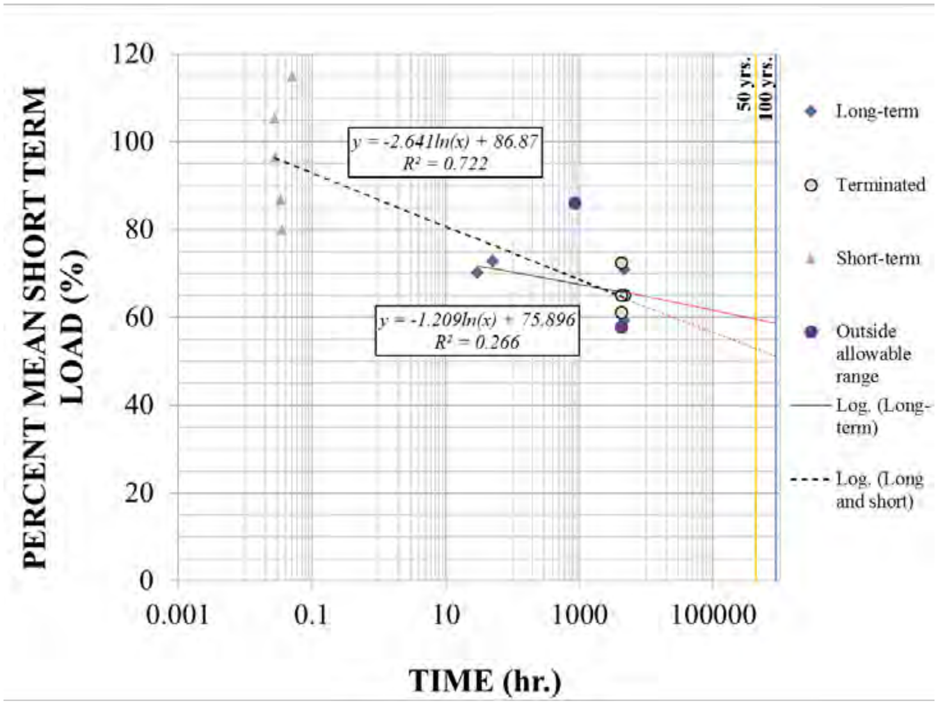


Figure 5.12: Material 3 SvTTF graph

5.3.4 Material 4

The SvTTF graph of Material 4 is shown in Figure 5.13. When short-term and long-term data are included in the trend line, the projected 50-year and 100-year capacities of the material are 5% MSL and 1% MSL, respectively. When only long-term tests are included in the trend line, the 50-year and 100-year capacities of the material are 33% MSL and 31% MSL, respecetively. Due to the poor results, long-term testing of this material was ended after the completion of seven long-term tests.

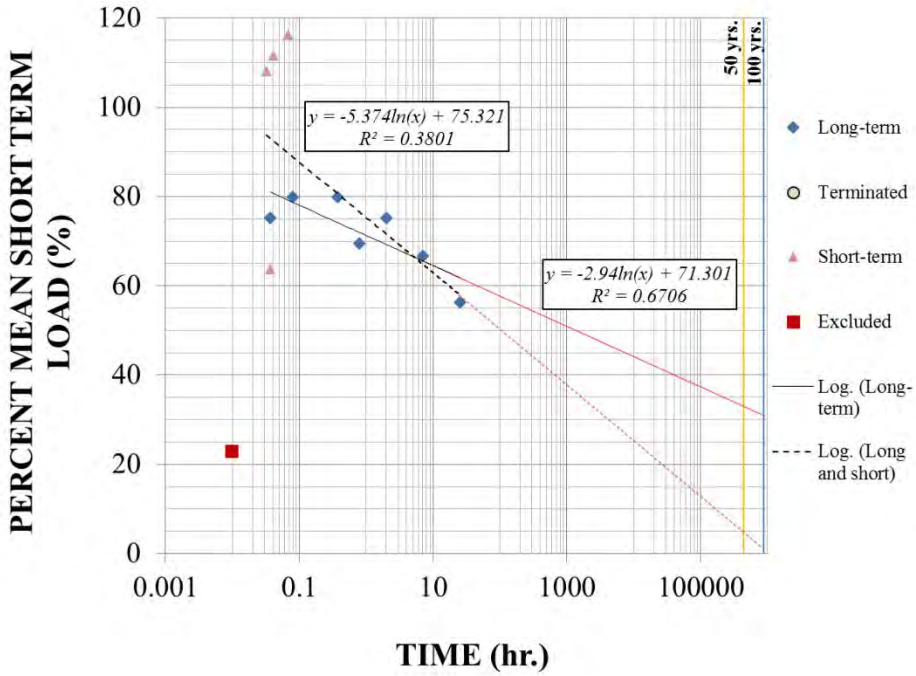


Figure 5.13: Material 4 SvTTF graph

5.3.5 Material 5

The SvTTF graph of Material 5 is shown in Figure 5.14. Due to the wide scatter of short-term test data, this material was not deemed suitable for use in long-term testing. The SvTTF graph for Material 5 shows the long-term testing of Material 5 would likely be less reliable in behavior to that of Material 4, as this material exhbited an even larger COV in short-term testing (Material 4 COV = 24%; Material 5 COV = 31%).

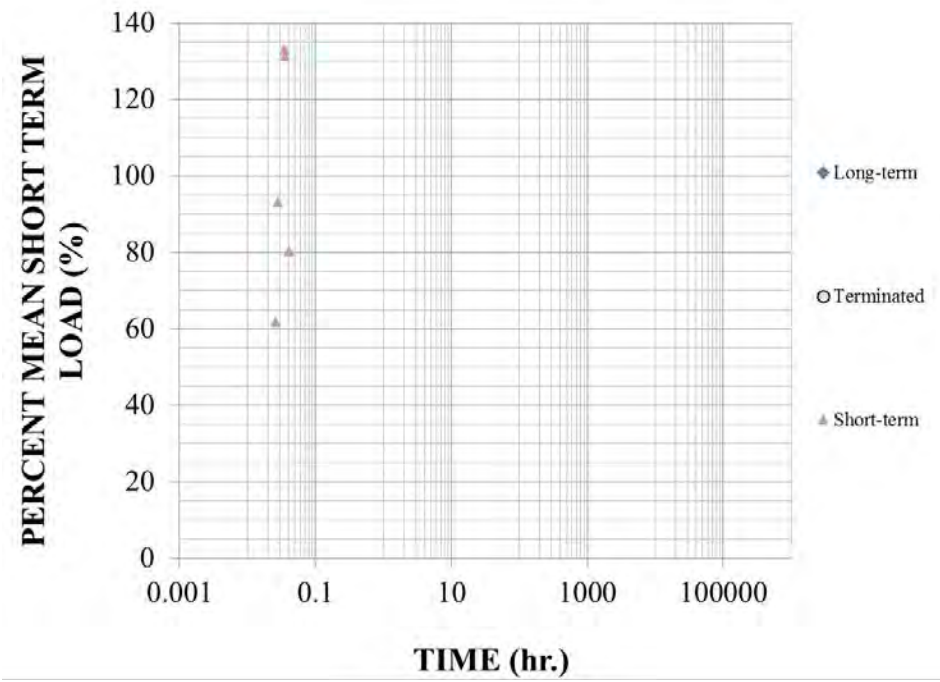


Figure 5.14: Material 5 SvTTF graph

5.3.6 Material 6

Material 6 presented inconsistent short-term capacities and was thus a difficult material to test in long-term loading. The wide scatter in data made it difficult to calculate the actual percentage of MSL being applied to the anchor, which led to the first long-term test to fail during initial loading of the anchor. For this cementitious material, it was determined that a more dependable approach to predict the sustained load value of an anchor was to base the initial loading on a limiting displacement value rather than a load. All long-term tests performed thereafter of this material were loaded until reaching a displacement of 0.10 inch (2.54 mm). This value was chosen based on the short-term test displacement data shown in Figure 5.8, where it can be seen that at this value, the anchors are still within the elastic range.

The SvTTF graph of Material 6 is shown in Figure 5.15. When short-term and long-term data are included in the trend line, the projected 50-year and 100-year capacities of the material are 29% MSL and 27% MSL, respectively. When only long-term tests are included in the trend line, the 50-year and 100-year capacities of the material are 56% MSL and 58% MSL, respectively.

It was insightful during loading to 0.10 inch (2.54 mm) that a real-time comparison to the load in Figure 5.8 provided guidance on which of the static tests were most likely similar capacity to those in the long-term test. Therefore, a real-time assessment such as this may be able to be used in determining the percentage of MSL that each specimen was actually loaded to for specimens with high COV on their short-term results. However, such an assessment in the field would not be realistic, as each anchor's load and deformation would need to be monitored.

The spring system which was used to apply long-term load for the UMass and University of Florida testing programs decreases in load as anchor displacement increases according to the spring configuration stiffness, as per Figure 4.16. For failures which occur at a small displacement of the anchor (Materials 1 through 5), this loss is minimal. However, the short-term testing of Material 6 showed a significantly larger deformation of the anchor as it approached its final capacity (Figure 5.8) and related loss of load applied. Maintaining a constant load on the anchors during long-term loading was therefore difficult and required re-loading of the specimens during testing. This would not be required if a hydraulic system were used, but such systems are costly to implement for long-term testing. Load was re-applied to a test specimen when a load loss greater than 250 pounds occurred. Some specimens failed suddenly during re-loading which required significant monitoring to provide safety to workers while the specimens were under high loads. This criterion was applied for the testing conducted at UMass only as there is no recommendation provided by AASHTO TP-84 [4] concerning the re-loading of anchors. Specific addressing of this issue would be needed for the testing of anchors with high ultimate displacements such as cementitious materials.

Of all materials tested per AASHTO TP-84 [4], Material 6 showed the greatest coefficient of variation in short-term tests (Material 6 COV = 36%). It can be seen from Figure 5.15 that large variations in results of short-term testing can result in an unrealistic trend line. The trend line for Material 6 excluding short-term tests predicts that the material will increase in capacity over time, an illogical result. The cause of this is that each long-term test may be loaded at a very different percentage of short-term capacity than expected based on the MSL as compared to a wide spectrum of possible short-term capacities of individual anchors. Due to these poor results, long-term testing of this material was ended after the completion of eight long-term tests. Subsequent to testing, it was determined that the batch of materials supplied by the manufacturer included a sheath material that was being recalled and may not be representative of product performance.

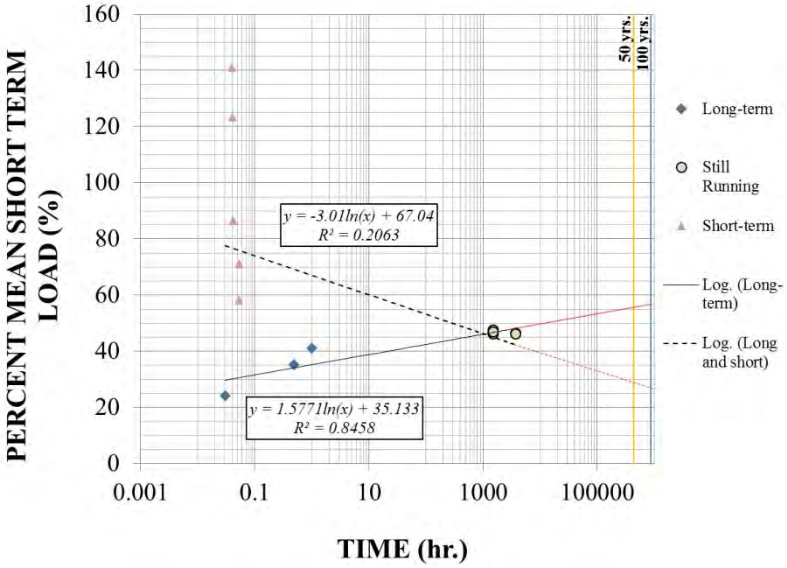


Figure 5.15: Material 6 SvTTF graph

5.3.7 Analysis of AASHTO TP-84 Materials Results

The results presented in this section were reported per the SvTTF approach found in AASHTO TP-84 [4]. This method requires a series of short- and long-term tests in order to predict the acceptable load capacity of an adhesive anchoring system under a specific long-term load (percentage of MSL and/or time of long-term load). This test method is very promising and would provide a powerful design tool for providing capacity of anchors referenced to design life, though restrictions are recommended. Based on the findings of this research project, it can be seen that there are wide variations in material performance. Material 1 and Material 2 showed the most reliable long-term load performance, while the test procedure for Material 4, Material 5, and Material 6 was ended early due to large COVs in short-term testing leading to wide variability in results under long-term load, since the percentage of MSL does not correlate well with the percentage of the individual anchor short-term capacity. Similar results can be seen in SvTTF graphs brought forth in NCHRP Report 757 [2] for the testing of Adhesive A in a Standard DOT mix (see Figure 67 of that document). These results reiterate the need for a more limiting criteria on the allowable maximum COV to calculate MSL. Moreover, the results of Material 6, which presented greatest COV in short-term tests, showed that such variability can result in nonsensical trend lines. Therefore, in order to obtain meaningful results from the test method, a strict limitation on COV is required to validate the long-term test results. The research team recommends a maximum COV of 10% of the results in short-term tests in order to allow long-term testing to proceed with the full SvTTF procedure.

Currently, AASHTO TP-84 [4] recommends the extrapolation of four months of long-term testing data to a design life of 100 years. Due to the inherent variability in material behavior and the unknown effect of physical aging on bonding materials, the research team recommends further verification of the acceptability to extrapolate results to this length of time. This recommendation would also apply to current creep test provisions of ACI 355.4

[1]. An acceptable criterion may be the use of SvTTF predictions, but with increasing inspection requirements for anchors initiating at ages beyond ten times the actual test protocol and increasing with further design life. Approved materials may be tested beyond the four-month protocol to minimize inspection requirements. With data collected from these inspections, it is expected that requirements could be relaxed in the future for similar materials.

It was found that the test method has a slight inconsistency in how short-term data is reported that can affect results if the data is included in the trend line. As seen in Figure 5.16, the long-term time to failure initiates after initial loading. However, SvTTF plots reported in NCHRP Reports [2] and [3] and AASHTO TP-84 [4] show that short-term tests should be plotted as the time at the end of the short-term test. The log scale of the plot makes the results slightly sensitive to even the two- to three-minute short-term test duration, though it was found that the difference is minimal for well-performing materials. Figure 5.16 shows a modified SvTTF plot of short-term tests of Material 1 where short-term data has been moved to time zero. The SvTTF graph shows that when short-term tests are plotted at time zero, the projected 50-year and 100-year capacities of the material increase from 48% MSL and 46% MSL to 50% MSL and 48% MSL, respectively.

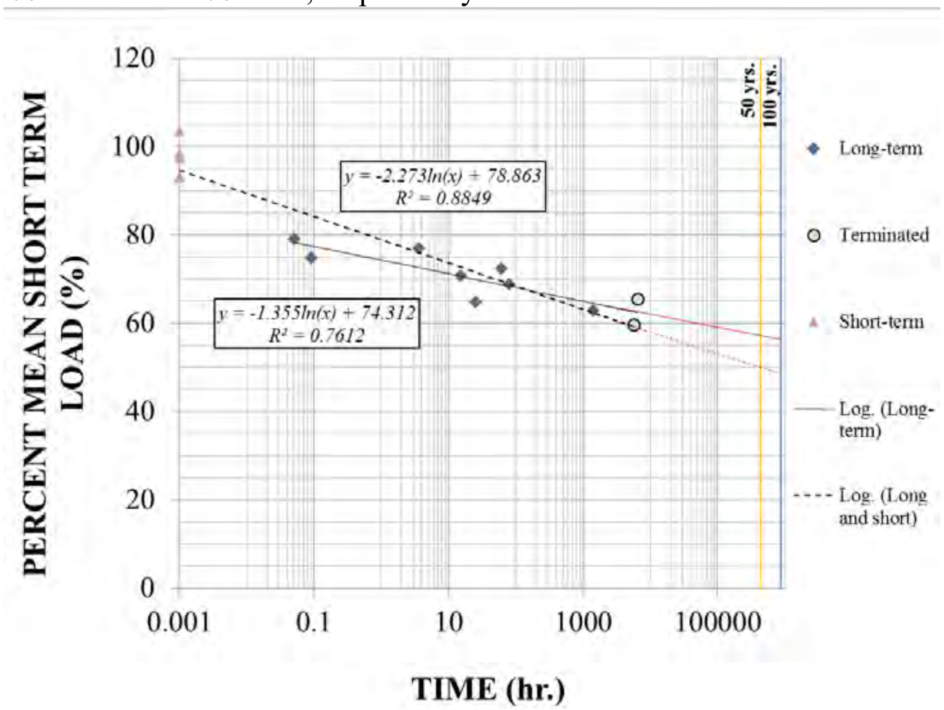


Figure 5.16: Material 1: Short-term tests plotted at time zero

The SvTTF graphs of Material 1 (Figure 5.10) and Material 2 (Figure 5.11) are comparable to the results of the epoxy materials (Adhesives B and C) tested at the University of Florida and reported in NCHRP Report 757 [2] (see Figures 73 and 74 of that document). During the long-term testing of Material 1 conducted at UMass, one anchor failed during initial loading. Similar cases were reported in NCHRP Report 757 [2] for the testing of Adhesive B and Adhesive C. Three long-term tests were excluded from the SvTTF plot for Adhesive B and five long-term tests for Adhesive C due to the anchors failing during initial loading. If included, the results would falsely increase the long-term load prediction of the material. However, excluding the results omits data points that reflect more variability in performance. The elimination of long-term tests from the SvTTF plot can alter the outcome of results. Section 9.4 of AASHTO TP-84 [4] requires a minimum of five anchors per test series to be tested, but does not place an upper limit on the number of anchors that may be tested and included in the results. A larger database would provide more statistically significant results, but it is not clarified what constitutes a successful long-term test or one that may be excluded from the SvTTF plot. It is recommended that additional guidance be included in AASHTO TP-84 [4] addressing how to report such results.

The SvTTF graph created of each material includes two different trend lines: a solid line, which includes both short-term and long-term tests as prescribed by AASHTO TP-84 [4], and a discontinuous line, which includes only long-term tests as recommended in NCHRP Report 757 [2], with each trend line projected to a design life of 100 years. The results showed that the inclusion of the short-term test results in the trend line of materials led to a more conservative load prediction at a design life of 100 years and is recommended by the authors.

5.4 Installation Direction Test Results

Testing the materials per AASHTO TP-84 [4] concluded that Material 1 and Material 2 were the best-performing materials. Therefore, these were selected to be used for supplemental short-term testing regarding the influence of installation direction. However, at that time, the manufacturer of Material 1 discontinued the product and replaced it with an improved version, referred to in this report as Material 1B. Thus, Material 1B and Material 2 were used for tests related to the effect of installation direction on bond strength.

All short-term tests of this program were performed in accordance with the short-term testing procedure of AASHTO TP-84 [4]. The definition of downward and horizontal orientation used in this report can be seen in Figure 5.17(a) and (b), respectively. The installation procedure for horizontal or upwardly inclined holes is dependent upon the requirements of the manufacturer. For the testing program conducted at UMass, no end-cap, piston-plug, or other aiding delivery systems were used for installation, as they were not required by the manufacturers of these products.

The load versus displacement graphs of each test series used to calculate the short-term capacity of each anchor are shown in Figure 5.18 for Material 1B and Figure 5.19 for Material 2. A summary of the average short-term load capacity of the materials tested under various drilling and installation directions is shown in Figure 5.20. Further details regarding the specifications of each test are shown in Table 5.3.

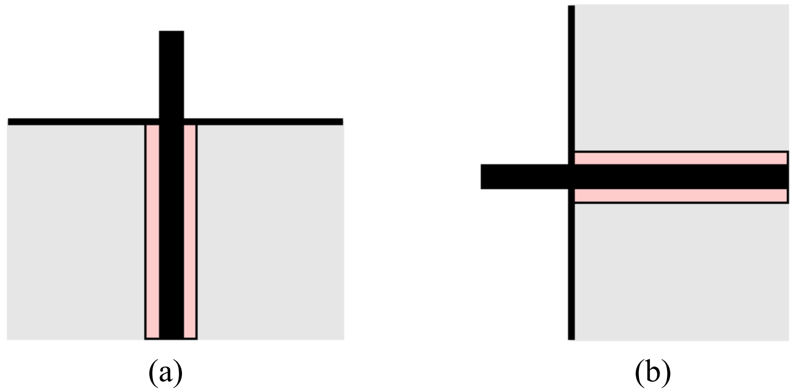


Figure 5.17: Drilling installation, (a) downward orientation and (b) horizontal orientation

5.4.1 Installation Direction Tests: Analysis of Results

Short-term capacity for the new cartridges and laboratory conditions were verified for each material through control tests (installed and drilled in the downward direction) conducted for each test series. Per Section 5.2, the Material 2 short-term reference tests performed in July 2015 had a minimum result of 17.40 kip (77.39 kN) and a maximum result of 19.90 kip (88.52 kN). The control tests conducted in June 2016 for Material 2 had results of 19.89 kip (88.48 kN) and 19.61 kip (87.23 kN), both within the range of previous short-term tests. Per Section 5.2, Material 1B short-term reference tests performed in July 2016 had a minimum result of 19.17 kip (85.27 kN) and a maximum result of 21.07 kip (93.72 kN). The control tests conducted in July 2016 for Material 1B had results of 18.74 kip (83.36 kN) and 19.20 kip (85.41 kN), both with the range of previous short-term tests.

For Material 2, the combination of downward drilling/horizontal installation resulted in an MSL of 18.75 kip (83.40 kN), equivalent to a decrease in 7% from the MSL of control tests, and a COV of 9%. The same test type for Material 1B resulted in an MSL of 17.94 kip (79.80 kN), equivalent to a decrease in 11% from the MSL of control tests, and COV of 13%. These were the lowest short-term capacities and highest COVs observed for both materials. This is possibly related to the fact that downward drilling produces a hole that is not perfectly vertical. This does not pose a problem for downward installation, as gravity helps the adhesive flow to the bottom of the hole and completely surround the anchor when it is inserted. However, when a downwardly drilled test specimen was lifted to its vertical position after drilling, a slope of the drilled hole may be introduced at any orientation. If the drilled hole was angled downward, it may have aggravated the loss of adhesive caused by the installation orientation, while it may have aided retention of adhesive if angled upward.

It was observed that both materials showed better results when tested in horizontal drilling and horizontal installation directions. For this test type, Material 2 had an MSL of 19.90 kip (88.52 kN), equivalent to an increase in 1% from the MSL of control tests, and COV of 4%. The same test type for Material 1B resulted in an MSL of 18.43 kip (81.98 kN), equivalent to a decrease in 3% from MSL control tests, and 8% COV. This difference in results could be attributed to the drilling technique used for horizontal drilling being more controlled and precise than downward drilling, as noted in Section 4.3.

In conclusion, it was found that horizontal installations could result in a loss of capacity on the order of 10% and up to two times the COV of downward-installed specimens for these materials and specimens.

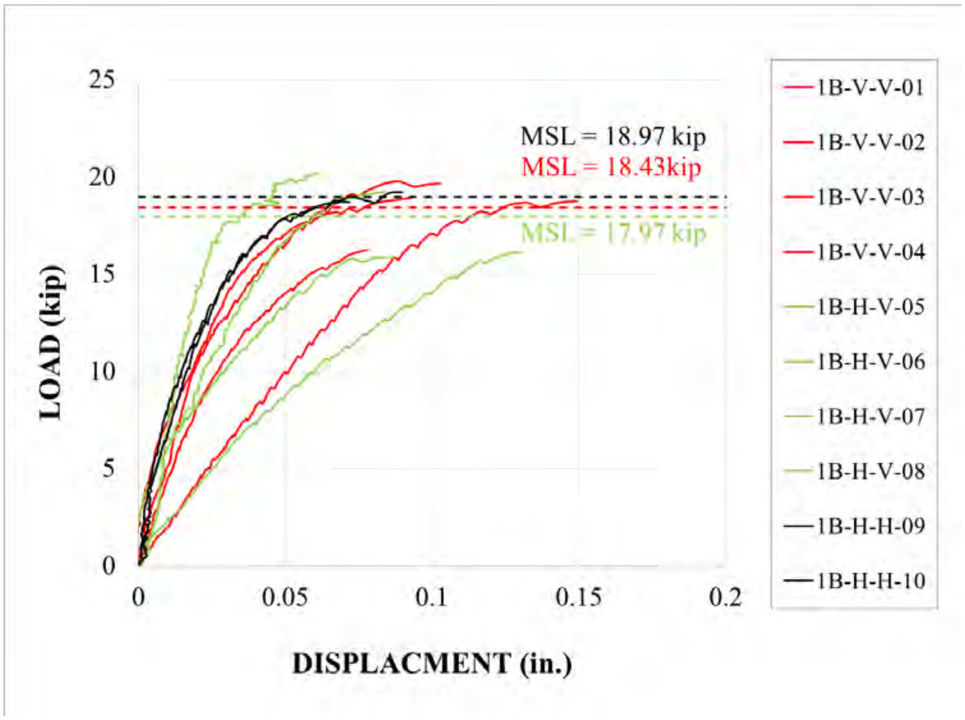


Figure 5.18: Material 1B installation direction: load vs. displacement

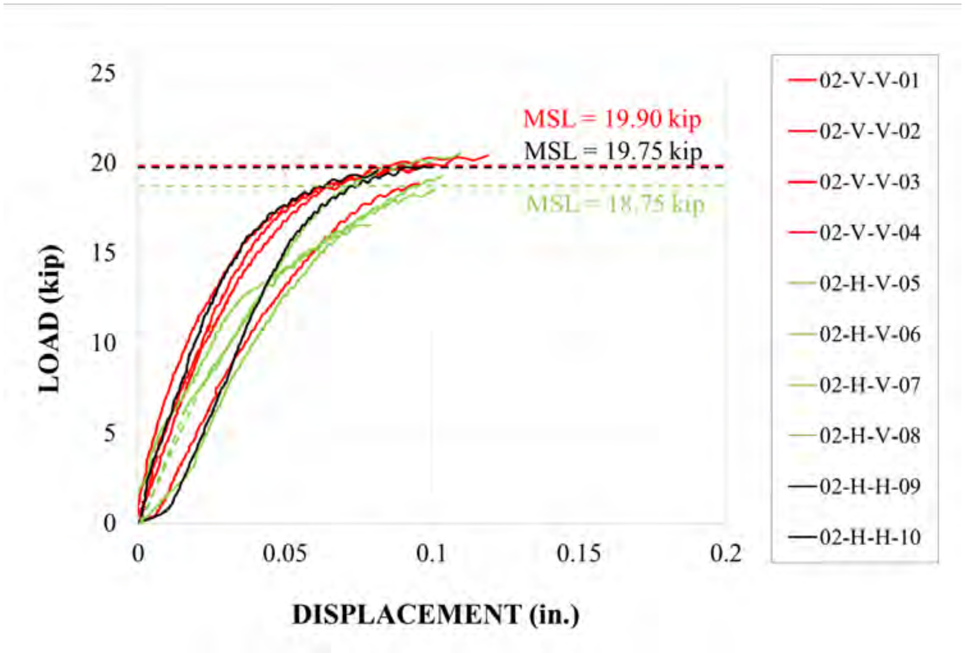


Figure 5.19: Material 2 installation direction: load vs. displacement

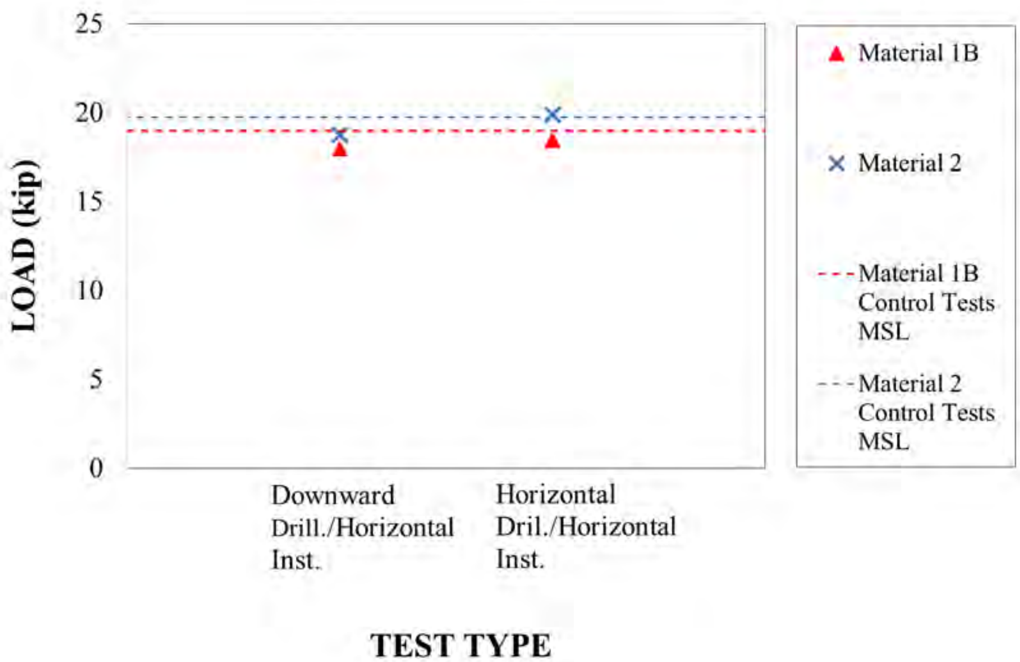


Figure 5.20: Summary of installation direction results

Table 5.3: Installation direction testing program

	DRILLING DIRECTION	INSTALLATION DIRECTION	TEST NAME	LOAD (kip)	AVERAGE LOAD (kip)	STD. DEV.	COV	CONCRETE BATCH	INSTALL	TESTED
MATERIAL 2	HORIZONTAL	HORIZONTAL	02-H-H-01	20.45	19.90	0.74	0.04	4	1-Jun-16	8-Jun-16
			02-H-H-02	19.82				4	1-Jun-16	8-Jun-16
			02-H-H-03	20.43				4	1-Jun-16	8-Jun-16
			02-H-H-04	18.88				4	1-Jun-16	8-Jun-16
	DOWNWARD	HORIZONTAL	02-D-H-05	19.34	18.75	1.69	0.09	4	1-Jun-16	8-Jun-16
			02-D-H-06	20.58				4	1-Jun-16	8-Jun-16
			02-D-H-07	16.55				4	6-Jun-16	13-Jun-16
			02-D-H-08	18.53				4	1-Jun-16	8-Jun-16
	DOWNWARD	DOWNWARD	02-D-D-09	19.89	19.75	0.20	0.01	4	1-Jun-16	8-Jun-16
			02-D-D-10	19.61				4	1-Jun-16	8-Jun-16
MATERIAL 1B	HORIZONTAL	HORIZONTAL	1B-H-H-01	18.92	18.43	1.51	0.08	4	6-Jul-16	13-Jul-16
			1B-H-H-02	16.26				4	6-Jul-16	13-Jul-16
			1B-H-H-03	18.76				4	6-Jul-16	13-Jul-16
			1B-H-H-04	19.78				4	6-Jul-16	13-Jul-16
	DOWNWARD	HORIZONTAL	1B-D-H-05	15.88	17.94	2.25	0.13	4	6-Jul-16	13-Jul-16
			1B-D-H-06	20.19				4	6-Jul-16	13-Jul-16
			1B-D-H-07	19.56				4	6-Jul-16	13-Jul-16
			1B-D-H-08	16.12				4	6-Jul-16	13-Jul-16
	DOWNWARD	DOWNWARD	1B-D-D-09	18.74	18.97	0.23	0.01	4	6-Jul-16	13-Jul-16
			1B-D-D-10	19.20				4	6-Jul-16	13-Jan-16

5.5 Extreme In-Service Temperature Test Results

Supplemental anchor pullout tests were conducted to study temperature effects on the performance of adhesive anchoring systems. For these tests, a material recommended by the manufacturer for use in cold weather applications, Material 7, was compared in performance to Material 1B and Material 2, the materials with best performance in previous tests and recommended for typical installation temperatures.

A summary of the average short-term capacity for each extreme in-service temperature parameter tested is shown in Figure 5.21. The test types named in this figure are defined per the nomenclature in Section 5.1 for extreme in-service temperature tests. Further details regarding each test are shown in Table 5.4 for Material 1B, Table 5.5 for Material 7, and Table 5.6 for Material 2.

5.5.1 Extreme In-Service Temperature Tests: Analysis of Results

Material 1B and Material 2 had an MSL of 20.10 kip (89.41 kN) and 18.33 kip (81.54 kN), respectively, while Material 7 had an MSL of 17.43 kip (77.53 kN) for short-term reference tests. It can be observed from the test results that Material 7 exhibited excellent performance in extreme cold temperature testing, while both Material 1B and Material 2 had severely reduced capacities when tested at temperatures lower than their recommended installation temperatures. At the lowest testing temperature of 0°F (-18 °C), Materials 1B and 2 exhibited only 58% and 57%, respectively, of the MSL capacity, though they were installed and cured within acceptable temperatures.

Material 1B generally had less capacity and more spread in results when cured and tested outside of ambient conditions of 70°F to 80°F (21°C to 27°C). The results showed that there was generally no reduction in capacity observed for Material 1B when the anchors were installed at the lower temperature and then tested at ambient conditions of 70°F to 80°F (21°C to 27°C). However, material performance was unfavorably affected when anchors were installed at the lower temperature and tested at low or elevated temperatures.

Material 7, a product recommended for use in cold temperature applications, was not adversely affected by colder installation, curing, or testing conditions and presented its highest average load capacities when installed and tested at low temperature. It was observed that the capacity of Material 7 was most adversely affected when installed and tested at the elevated temperature of 110°F to 120°F (43°C to 49°C), where a reduction in capacity of 11% was observed. These results show that the performance of these materials were influenced not just by temperature occurring during the installation, but through the service life of the anchor. Post-installed adhesive anchors can be exposed to significant in-service temperature variations, which can result in different capacities than those anchors maintain at ambient conditions. Therefore, it is important to consider the service life temperature of post-installed adhesive anchors as well as the installation temperature.

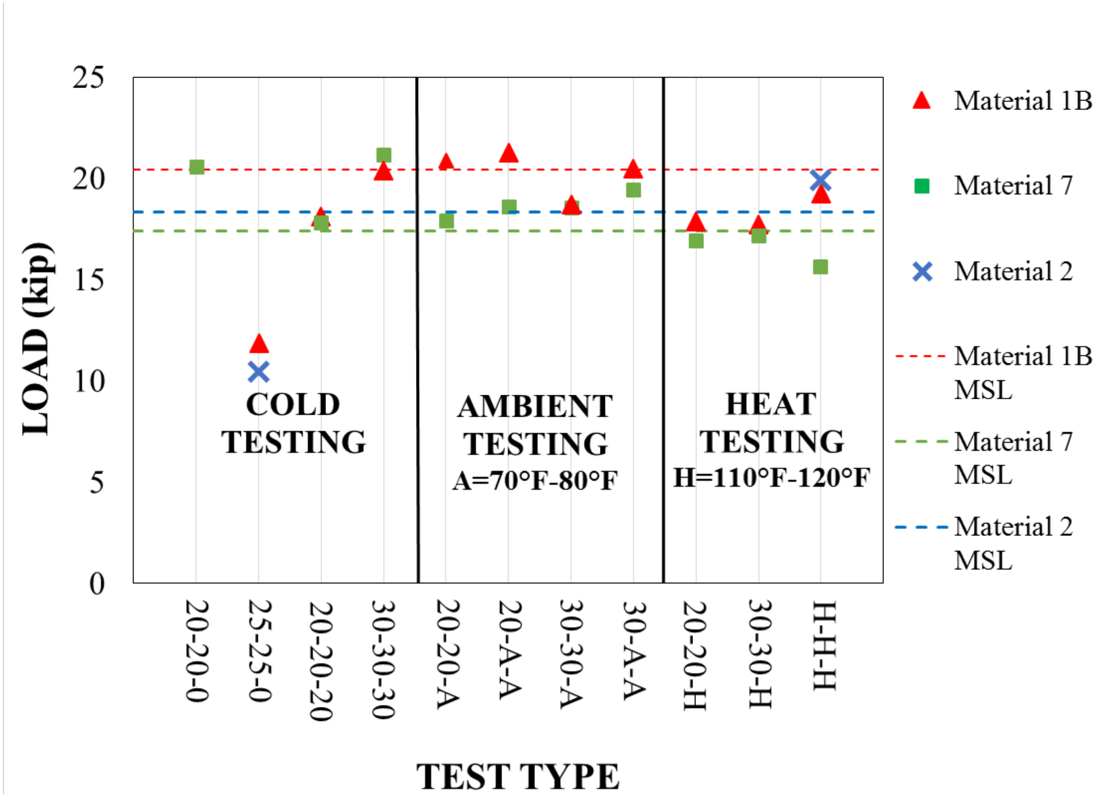


Figure 5.21: Summary of extreme in-service temperature test results

Table 5.4: Material 1B extreme in-service temperature test results

	INITIAL CONCRETE TEMP.	INSTALLATION AND CURING TEMP.	TESTING TEMPERATURE	TEST NAME	LOAD (kip)	AVERAGE LOAD (kip)	STD. DEV.	COV	MIX	INSTALL	TESTED
MATERIAL 1B	30°F	30°F	70°F - 80°F	1B-30-30-A-01	21.02	18.68	3.32	0.18	5	8-Jul-16	12-Jul-16
	30°F	30°F		1B-30-30-A-02	16.33				5	8-Jul-16	12-Jul-16
	30°F	70°F - 80°F	70°F - 80°F	1B-30-A-A-01	21.03	20.46	0.81	0.04	6	20-Oct-16	24-Oct-16
	30°F	70°F - 80°F		1B-30-A-A-02	19.89				6	20-Oct-16	24-Oct-16
	30°F	30°F	110°F - 120°F	1B-30-30-H-01	17.92	17.71	0.52	0.03	5	8-Jul-16	12-Jul-16
	30°F	30°F		1B-30-30-H-02	17.12				5	8-Jul-16	12-Jul-16
	30°F	30°F		1B-30-30-H-03	18.10				5	8-Jul-16	12-Jul-16
	30°F	30°F	30°F	1B-30-30-30-01	19.79	20.36	0.59	0.03	6	24-Sep-16	28-Sep-16
	30°F	30°F		1B-30-30-30-02	20.32				6	24-Sep-16	28-Sep-16
	30°F	30°F		1B-30-30-30-03	20.96				6	24-Sep-16	28-Sep-16
	25°F	25°F	0°F	1B-25-25-0-01	12.79	11.86	0.89	0.07	6	10-Nov-16	14-Nov-16
	25°F	25°F		1B-25-25-0-02	11.77				6	10-Nov-16	14-Nov-16
	25°F	25°F		1B-25-25-03	11.02				6	10-Nov-16	14-Nov-16
	20°F	20°F	70°F - 80°F	1B-20-20-A-01	20.4	20.88	0.68	0.03	5	15-Jul-06	19-Jul-16
	20°F	20°F		1B-20-20-A-02	21.36				5	15-Jul-06	19-Jul-16
	20°F	70°F - 80°F	70°F - 80°F	1B-20-A-A-01	21.13	21.25	0.17	0.01	5	15-Jul-06	19-Jul-16
	20°F	70°F - 80°F		IB-20-A-A-02	21.37				5	21-Jul-16	25-Jul-16
	20°F	20°F	110°F - 120°F	1B-20-20-H-01	19.22	17.89	1.35	0.08	5	21-Jul-16	25-Jul-16
	20°F	20°F		1B-20-20-H-02	16.52				5	15-Jul-06	19-Jul-16
	20°F	20°F		1B-20-20-H-03	17.93				5	15-Jul-06	19-Jul-16
	20°F	20°F	20°F	1B-20-20-20-01	19.9	18.13	1.69	0.09	5	18-Aug-16	22-Aug-06
	20°F	20°F		1B-20-20-20-02	16.53				5	25-Aug-16	29-Aug-06
	20°F	20°F		1B-20-20-20-03	17.97				5	25-Aug-16	29-Aug-06
	70°F - 80°F	70°F - 80°F	110°F - 120°F	1B-A-A-H-01	19.77	19.7	1.57	0.08	5	7-Jul-16	11-Jul-16
	70°F - 80°F	70°F - 80°F		1B-A-A-H-02	21.07				5	7-Jul-16	11-Jul-16
	70°F - 80°F	70°F - 80°F		1B-A-A-H-03	17.17				5	7-Jul-16	11-Jul-16
	70°F - 80°F	70°F - 80°F		1B-A-A-H-04	20.93				5	7-Jul-16	11-Jul-16
	70°F - 80°F	70°F - 80°F		1B-A-A-H-05	19.58				5	7-Jul-16	11-Jul-16
	110°F - 120°F	110°F - 120°F	110°F - 120°F	1B-H-H-H-01	18.08	19.26	1.67	0.09	5	20-Oct-16	24-Oct-16
	110°F - 120°F	110°F - 120°F		1B-H-H-H-02	20.44				5	19-Aug-16	23-Aug-16

***A**: 70°F - 80°F; **H**: 110°F - 120°F

Table 5.5: Material 7 extreme in-service temperature test results

	INITIAL CONCRETE TEMP.	INSTALLATION AND CURING TEMP.	TESTING TEMPERATURE	TEST NAME	LOAD (kip)	AVERAGE LOAD (kip)	STD. DEV.	COV	MIX	INSTALL	TESTED
MATERIAL 7	30°F	30°F	70°F - 80°F	07-30-30-A-01	19.25	18.56	0.98	0.05	6	30-Sep-16	4-Oct-16
	30°F	30°F		07-30-30-A-02	17.86				6	19-Sep-16	23-Sep-16
	30°F	70°F - 80°F	70°F - 80°F	07-30-A-A-01	17.83	19.45	2.28	0.12	6	30-Sep-16	4-Oct-16
	30°F	70°F - 80°F		07-30-A-A-02	21.06				6	30-Sep-16	4-Oct-16
	30°F	30°F	110°F - 120°F	07-30-30-H-01	17.3	17.18	1.18	0.07	6	30-Sep-16	4-Oct-16
	30°F	30°F		07-30-30-H-02	15.95				6	30-Sep-16	4-Oct-16
	30°F	30°F		07-30-30-H-03	18.3				6	30-Sep-16	4-Oct-16
	30°F	30°F	30°F	07-30-30-30-01	21.23	21.13	0.09	0.00	6	20-Oct-16	24-Oct-16
	30°F	30°F		07-30-30-30-02	21.07				6	24-Sep-16	28-Sep-16
	30°F	30°F		07-30-30-30-03	21.1				6	24-Sep-16	28-Sep-16
	20°F	20°F	0°F	07-20-20-0-01	19.72	20.55	0.72	0.03	6	3-Nov-16	7-Nov-16
	20°F	20°F		07-20-20-0-02	20.99				6	3-Nov-16	7-Nov-16
	20°F	20°F		07-20-20-0-03	20.94				6	3-Nov-16	7-Nov-16
	20°F	20°F	70°F - 80°F	07-20-20-A-01	16.76	17.9	1.61	0.09	5	29-Jul-16	2-Aug-16
	20°F	20°F		07-20-20-A-02	19.04				6	20-Oct-16	24-Oct-16
	20°F	70°F - 80°F	70°F - 80°F	07-20-A-A-01	19.54	18.59	1.34	0.07	5	29-Jul-16	2-Aug-16
	20°F	70°F - 80°F		07-20-A-A-02	17.64				6	20-Oct-16	24-Oct-16
	20°F	20°F	110°F - 120°F	07-20-20-H-01	15.44	16.93	1.67	0.10	5	29-Jul-16	2-Aug-16
	20°F	20°F		07-20-20-H-02	16.63				5	29-Jul-16	2-Aug-16
	20°F	20°F		07-20-20-H-03	18.73				5	29-Jul-16	2-Aug-16
	20°F	20°F	20°F	07-20-20-20-01	18.71	17.84	1.03	0.06	5	10-Sep-16	14-Sep-16
	20°F	20°F		07-20-20-20-02	16.7				5	10-Sep-16	14-Sep-16
	20°F	20°F		07-20-20-20-03	18.12				5	10-Sep-16	14-Sep-16
	70°F - 80°F	70°F - 80°F	110°F - 120°F	07-A-A-H-01	18.42	17.42	0.77	0.04	5	28-Jul-16	1-Aug-16
	70°F - 80°F	70°F - 80°F		07-A-A-H-02	16.75				6	30-Sep-16	4-Oct-16
	70°F - 80°F	70°F - 80°F		07-A-A-H-03	17.52				5	28-Jul-16	1-Aug-16
	70°F - 80°F	70°F - 80°F		07-A-A-H-04	17.82				5	28-Jul-16	1-Aug-16
	70°F - 80°F	70°F - 80°F		07-A-A-H-05	16.57				5	28-Jul-16	1-Aug-16
	110°F - 120°F	110°F - 120°F	110°F - 120°F	07-H-H-H-01	16.15	15.61	0.77	0.05	5	19-Aug-16	23-Aug-16
	110°F - 120°F	110°F - 120°F		07-H-H-H-02	15.06				5	19-Aug-16	23-Aug-16

***A**: 70°F - 80°F; **H**: 110°F - 120°F

Table 5.6: Material 2 extreme in-service temperature test results

	INITIAL CONCRETE TEMP.	INSTALLATION AND CURING TEMP.	TESTING TEMPERATURE	TEST NAME	LOAD (kip)	AVERAGE LOAD (kip)	STD. DEV.	COV	MIX	INSTALL	TESTED
MATERIAL 2	110°F - 120°F	110°F - 120°F	110°F - 120°F	02-H-H-H-01	19.63	19.92	0.40	0.02	6	20-Oct-16	24-Oct-16
	110°F - 120°F	110°F - 120°F		02-H-H-H-02	20.2				6	1-Dec-16	5-Dec-16
	25°F	25°F	0°F	02-25-25-0-01	10.02	10.47	0.41	0.04	6	1-Dec-16	5-Dec-16
	25°F	25°F		02-25-25-0-02	10.82				6	1-Dec-16	5-Dec-16
	25°F	25°F		02-25-25-0-03	10.56				6	1-Dec-16	5-Dec-16

***H**: 110°F - 120°F

This page left blank intentionally.

6.0 Polymer Characterization Tests

This chapter summarizes the results and findings of the polymer characterization testing of six adhesive products through FTIR and DSC testing. The purpose of this testing is to explore these polymer characterization techniques in order to provide guidance on their use as supplemental tools for analyzing the performance of adhesive anchoring products and use as quality assurance and quality control for field projects.

FTIR is a simple and straightforward technique that can identify the compounds that an adhesive material contains. FTIR testing could be used in field applications to verify that the anchoring adhesive used for installation was properly mixed or that a product maintains a consistent formulation from batch to batch. The recommendations brought forth in this report are intended to provide guidance on the use of FTIR testing as a quality assurance and quality control method for post-installed adhesive anchors.

DSC is an effective method used to investigate the response of polymers under heating and cooling cycles. It can be used to study the thermal transitions of a polymer, such as the glass transition temperature (T_g). The glass transition temperature is one of the most important properties of any epoxy, as it is the temperature region where the polymer transitions from a hard, glassy material to a soft, rubbery state, making it more susceptible to creep.

6.1 Overview

Anchoring adhesives are proprietary products available in many different formulations designed to comply with a variety of performance requirements. When analyzing the behavior of a specific adhesive product, it is important to consider the chemical constituents of the compound as well as cure time and temperature of cure, as these conditions affect an adhesive's ability to develop its designed final properties [24].

Post-installed anchoring adhesives are formed by polymerizing a mixture of two main compounds, a resin and a curing agent, also known as a hardener. In the case of epoxy formulations, amine-based hardeners are among the most frequently used curing agents [25]. When the resin and hardener are mixed, the curing process is initiated. During this process, important cross-links are formed between the resin and hardener groups that lead to a final hardened structure of the material. The final properties of the cured epoxy are greatly dependent upon the type and amount of hardener used, as these determine the degree and density of cross-linkage of the polymer [26]. Adhesive anchoring products that are manually dispensed from a two-part cartridge system require correct mixing in order to fully develop their designed final properties. If the dispensing tool has unbalanced pistons or the cartridge cap is not properly removed, the ratio of resin to hardener that is dispensed into the hole can be affected. Evaluation of differences in the chemical composition of a cured epoxy can be an appropriate way to investigate the differences in expected performance.

FTIR and DSC testing were conducted on six of the bonding materials studied during this investigation (Materials 1, 1B, 2, 3, 4, and 7).

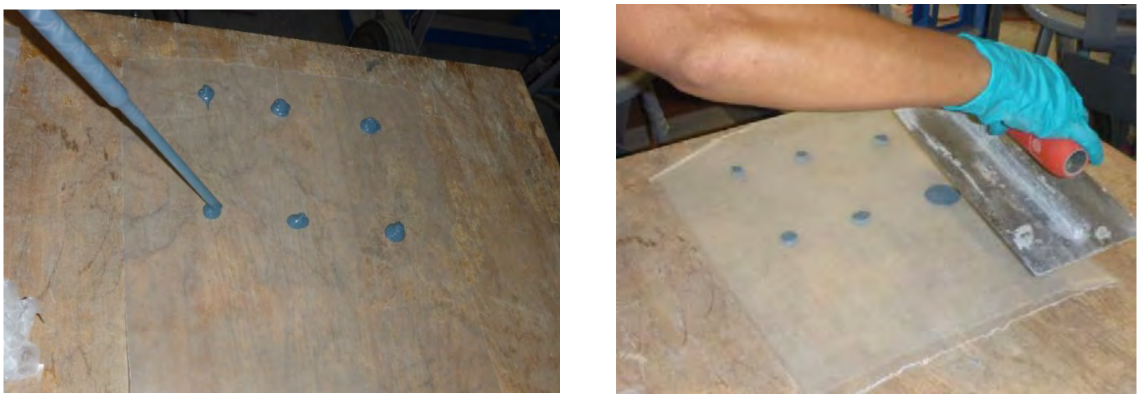
6.2 Preparation of Sample Disks

A common method used for preparing a solid sample for FTIR testing involves grinding the material to a fine powder and dispersing it in a liquid to form a mull. The most commonly used liquid is a mineral oil known as Nujol [27]. The suspension between the ground sample and liquid is then placed between salt plates and analyzed using infrared spectroscopy. The main disadvantage of this method is that proper results are obtained only if the average size of the particle can be reduced to one to two microns [27]. This posed a significant problem in the case of hardened epoxy samples, as the pulverization of this material to a fine powder would require an extensive amount of time and the use of specialized equipment. Preliminary samples were created by crushing the hardened epoxy samples with tools readily available to a general DOT testing laboratory. However, it was not possible to obtain valid results through this method. A study conducted by Dannenberg and Harp revealed similar problems in sample preparation. The authors moved forward by creating thin films of each epoxy material about 0.025 mm thick between rock salt plates. Though well-resolved spectra were obtained, the authors reported that this method was not practical for repeated testing, as the rock salt plates had to be discarded after every test [28].

Given the difficulties of pulverizing hardened epoxy samples to the size required for traditional methods of solid sample preparation, it was necessary to develop a more practical procedure for the purposes of this research project. Therefore, a system was created in which epoxy samples were prepared as thin disks between nonstick wax paper rather than a fine powder.

The samples used to record the infrared spectrum and glass transition temperature of each material were prepared as thin disks between sheets of nonstick wax paper. The manufacturer-recommended dispensing tool and mixing nozzle were used for each material. The first few full strokes of adhesive were discarded prior to initiating sample preparation to ensure the disk was a representative sample of a properly mixed material.

Small drops of the mixed adhesive were delivered onto a sheet of nonstick wax paper and immediately covered with a second sheet of wax paper lightly placed on top of the drops to avoid contamination of the samples. Next, a steel finishing trowel was used to lightly press down on each drop of material to form a thin disk approximately 1.5 inches in diameter and 0.03 to 0.05 inches thick. This procedure is shown in Figure 6.1(a) and (b).



(a) (b)

Figure 6.1: (a) Delivery of adhesive onto nonstick wax paper; (b) use of steel finishing trowel to prepare disk

Figure 6.2 shows the completed sample disks prior to final cure and conditioning. Samples for DSC testing were also prepared in accordance with this method.

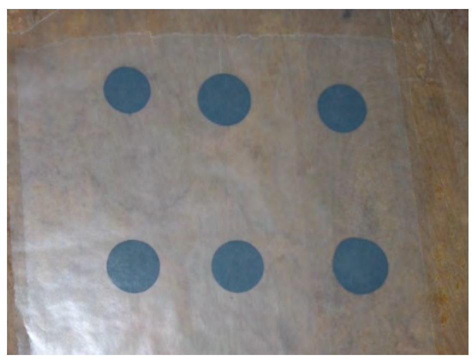


Figure 6.2: Completed sample disks

Sample disks of these dimensions proved to be suitable for the FTIR testing conducted during this research project. Preliminary experiments showed that disks that were cast too thin were prone to air gaps or areas of uneven thicknesses, whereas overly thick samples did not produce a well-resolved spectrum when tested. Considering that it is difficult to control the exact thickness of the disks, it is suggested that several samples be cast in preparation for a test in order to ensure that a proper reading will be available.

6.3 Curing of Sample Disks

Immediately after the disks were cast, they were allowed to cure undisturbed for varying cure times and cure temperatures. One disk per material was cured for a 3-, 7-, and 21-day period in a controlled environment at 74°F. Also, one disk per material was cured at a constant temperature of 50°F, 104°F, and 500°F for three days. Figure 6.3 shows the disks curing inside the laboratory refrigerator at 50°F, inside an environmental incubator at 74°F, and inside a laboratory oven at 104°F. Disks must be carefully moved to their final curing location promptly after casting, as the cross-link rate of the adhesive is related to cure temperature and cure time.

(a) (b) (c)

Figure 6.3: Curing of samples at (a) 50°F; (b) 74°F; and (c) 104°F

6.4 Testing Procedure

6.4.1 FTIR

After a sample completed its designated cure time, an FTIR test was completed at the UMass Amherst Polymer Science and Engineering Department using a Perkins Elmer Spectrum 100 instrument. Each test was conducted between a wavenumber range of 1575 in^{-1} and 250 in^{-1} (4,000 cm^{-1} and 650 cm^{-1}) for a duration of four scans and a resolution of 10.16 in^{-1} (4.00 cm^{-1}). All infrared spectra were plotted on a percent transmittance versus wavenumber plot, where different functional groups can be identified by a peak on the graph at a given wavenumber that is characteristic of that group. The peak (e.g., narrow, broad) gives indication as to the type of molecular bond occurring (e.g., stretching, bending). When looking at spectral comparisons of the samples, a difference in the locations of peaks is indicative of differences in chemical compositions. If peaks are located at the same location but differ in intensity of percent transmittance, this could be an indication of similar composition but different concentrations of the components.

Prior to testing, the surface of the instrument and diamond crystal were properly cleaned using acetone to avoid cross-contamination with previous samples. Next, a background spectrum was obtained by running a scan with no sample placed on the surface of the diamond. This background spectrum was automatically saved to the computer and later subtracted from the spectrum of that of a sample to eliminate noise in the reading caused by the surrounding environment [28]. Then, the sample disk was placed over the diamond crystal, and pressure was applied with the piston until close contact between the disk and the diamond crystal was ensured, as shown in Figure 6.4. Due to the hardness of the epoxy samples, a high amount of pressure was required to produce a well-resolved spectrum. Preliminary testing showed that samples from all material types required between 85% and 90% of the available piston pressure to produce spectra in which the strongest peaks of the reading exceeded values of at least 80% transmittance.

Figure 6.4: FTIR test of epoxy sample

6.4.2 DSC

DSC testing was conducted for all materials after completion of a 7-day cure at 74°F. Each test was completed at the UMass Amherst Polymer Science and Engineering Department using a TA Instruments Q200 Series instrument. All tests and results were plotted on a heat flow versus temperature graph.

A steel pestle and mortar were used to crush the cured adhesive disk in order to obtain a sample size of 5 mg. for each test. The sample was then placed between a hermetic pan and lid and sealed in a pressing device as shown in Figure 6.5(a). The pan was placed in the testing instrument as shown in Figure 6.5(b), and the following heating and cooling procedure was run.

- Step 1: Heat to 482°F (250°C) at a rate of 18°F/min. (10°C/min).
- Step 2: Cool to 32°F (0°C) at a rate of 18°F/min. (10°C/min).
- Step 3: Heat to 482°F (250°C) at a rate of 18°F/min. 10°C/min.

(a)

(b)

Figure 6.5: (a) Preparation of sample for DSC testing; (b) DSC testing instrument

6.5 Polymer Characterization Test Results

This section presents the FTIR test results conducted at UMass Amherst during the months of July 2016 to January 2017. All infrared spectra were plotted on a percent transmittance versus wavenumber plot, where data was collected between a wavenumber range of 1575 in^{-1} and 250 in^{-1} (4,000 cm^{-1} and 650 cm^{-1}). Articles such as [25] and [29] regarding the study of epoxy materials with FTIR suggest that spectral comparisons of data are more significant below a wavenumber of 790 in^{-1} (2,000 cm^{-1}), also known as the fingerprint region. For the FTIR results presented in Figure 6.6 to Figure 6.17, all data of the spectra has been provided for completeness; however, the region above a wavenumber of 790 in^{-1} (2,000 cm^{-1}) has been shaded in order to highlight the fingerprint region.

6.5.1 FTIR Testing Results with Varying Temperatures

FTIR testing was conducted for Materials 1, 1B, 2, 3, 4, and 7 at cure temperatures of 50°F (10°C), 74°F (23°C), 104°F (40°C), and 500°F (260°C), after a cure time of three days. The results of these tests are shown in Figure 6.6 to Figure 6.11.

The spectral comparisons of each material show differences in the location of peaks and transmittance intensity of the samples when cured at varying temperatures. It can be seen that the infrared spectrum of a material is influenced by the temperature at which cure takes place. Therefore, it is recommended that a single curing temperature be selected and applied to all sample disks for consistency. Given these results, the research team adopted a single curing temperature of 74°F (23°C) for later FTIR testing conducted at varying cure times.

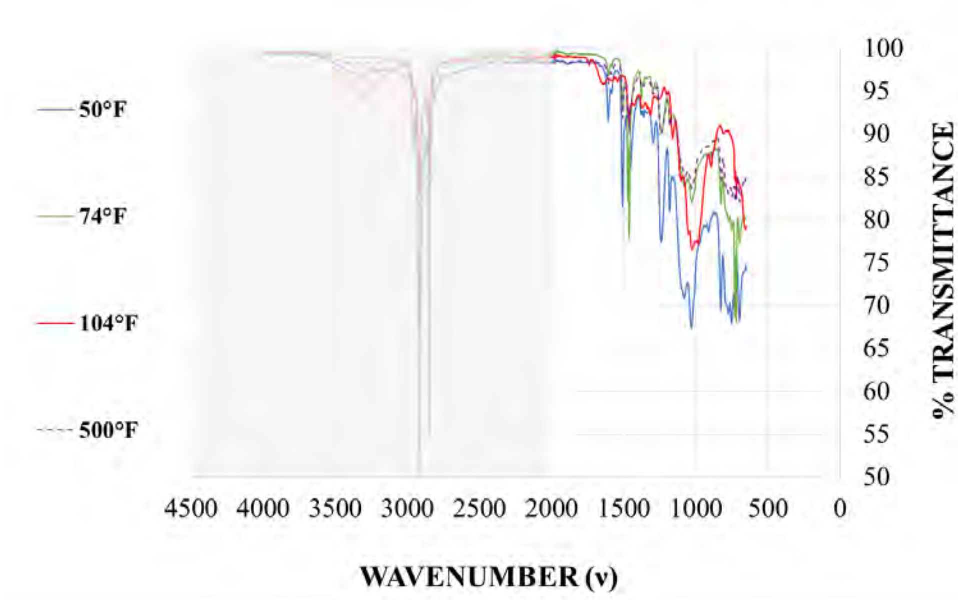


Figure 6.6: Material 1 FTIR results with varying cure temperature

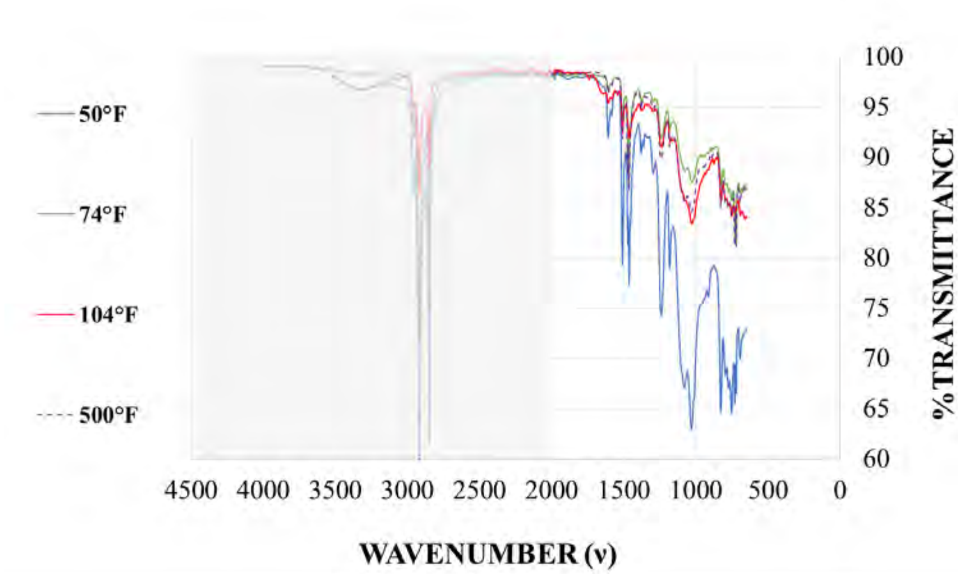


Figure 6.7: Material 1B FTIR results with varying cure temperature

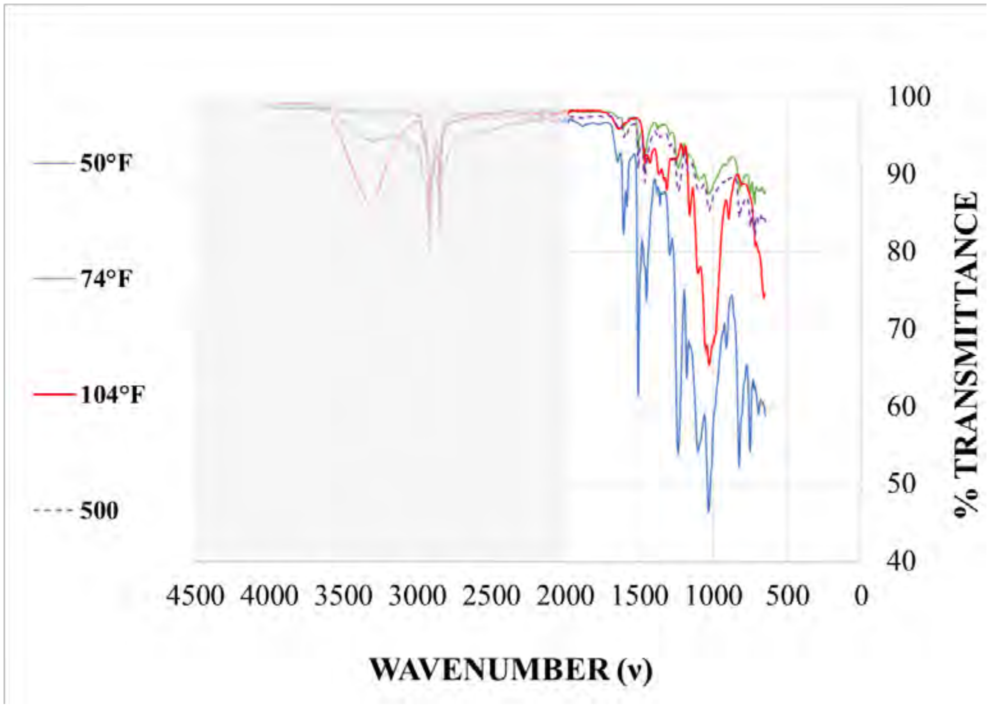


Figure 6.8: Material 2 FTIR results with varying cure temperature

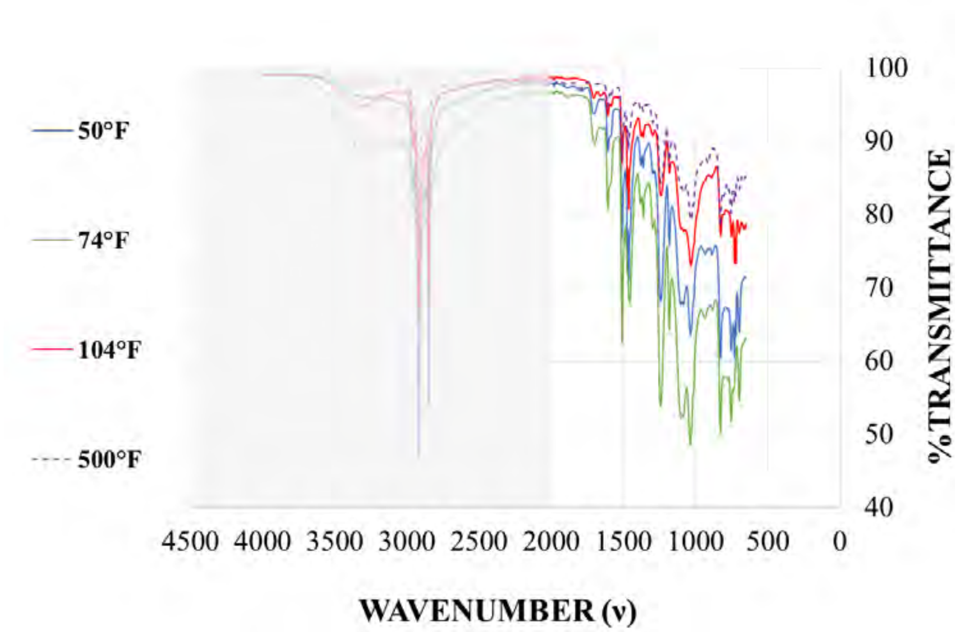


Figure 6.9: Material 3 FTIR results with varying cure temperature

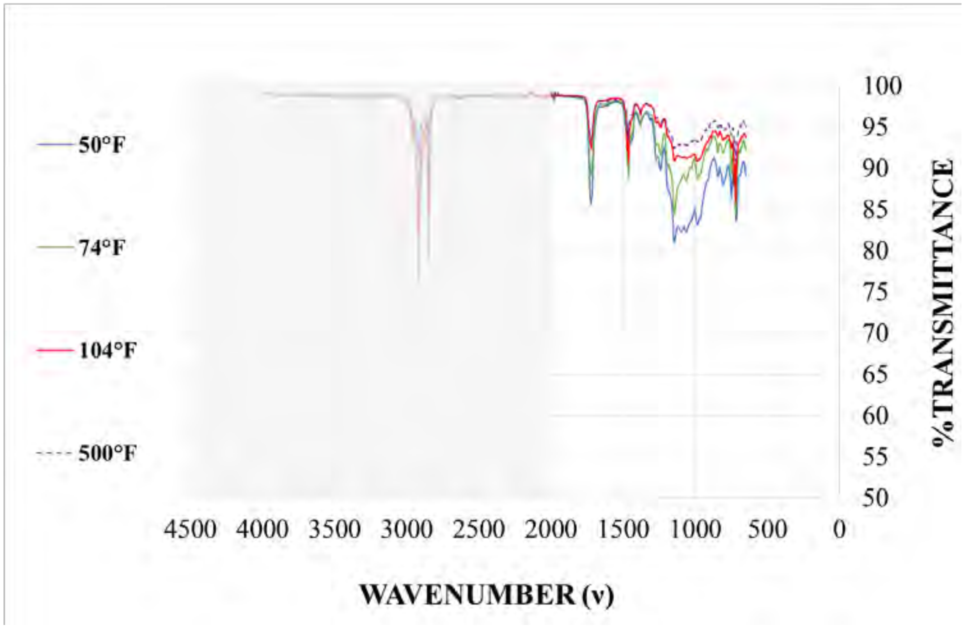


Figure 6.10: Material 4 FTIR results with varying cure temperature

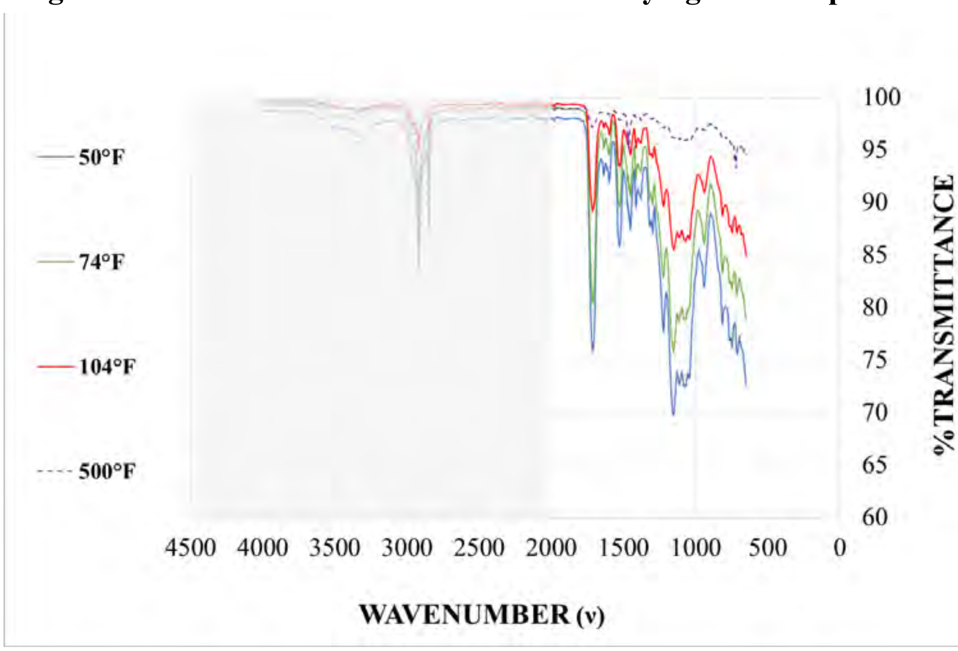


Figure 6.11: Material 7 FTIR results with varying cure temperature

6.5.2 FTIR Test Results with Varying Cure Times

FTIR testing was conducted for Materials 1, 1B, 2, 3, 4, and 7 at cure times of 3, 7, and 21 days. A fourth sample was cast approximately eight weeks later and also cured for 7 days in order to verify that the procedure for the preparation of samples described in this document was capable of producing replicable results. This sample is referred to as “7 day Sample B” in the graph of each material. The results of FTIR tests with varying cure times are shown in Figure 6.12 to Figure 6.17.

The spectral comparisons of each material show differences in the location of peaks and transmittance intensity of the samples when cured at varying times. Based on these results, it is recommended that a single cure time be selected and applied to all sample disks for consistency. The results show that the 7-day sample and 7-day Sample B of all materials have similar spectra, providing confidence in the sample preparation method presented in this report. Due to the reproducibility of FTIR data at this cure time, it is recommended that samples be allowed to cure for 7 days prior to testing until further studies can be conducted to demonstrate reproducible results at shorter cure times. Additionally, a 7-day cure will ensure that the testing of the sample will occur during a regular workday.

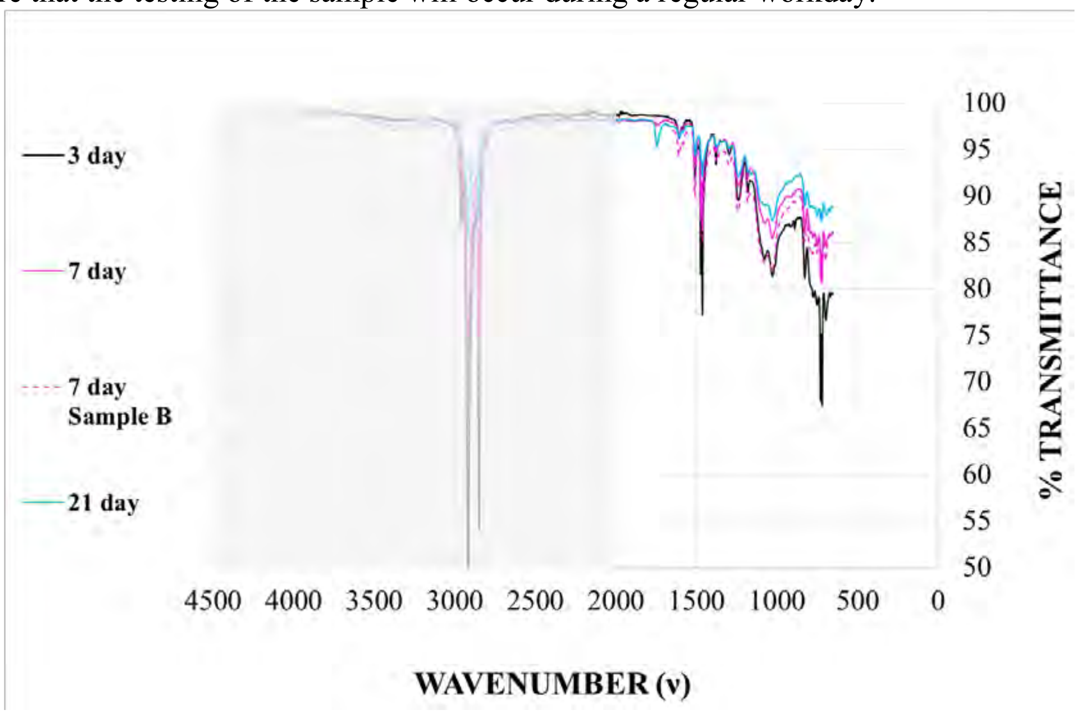


Figure 6.12: Material 1 FTIR results with varying cure time

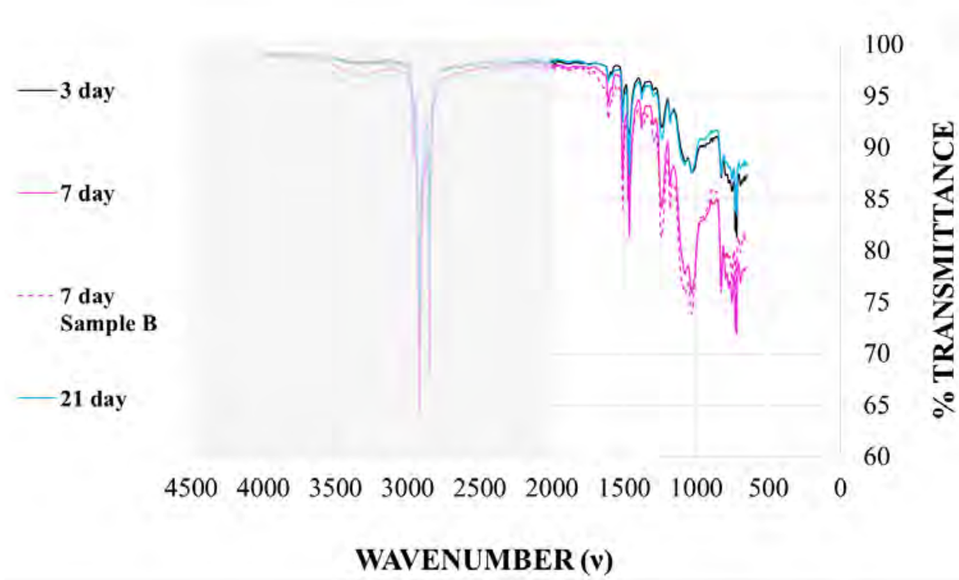


Figure 6.13: Material 1B FTIR results with varying cure time

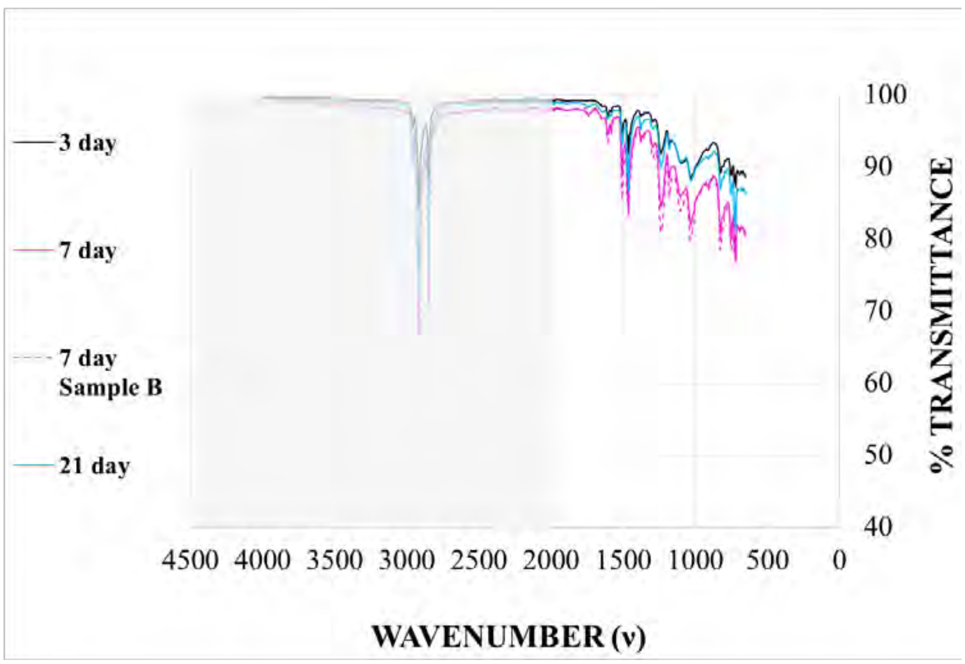


Figure 6.14: Material 2 FTIR results with varying cure time

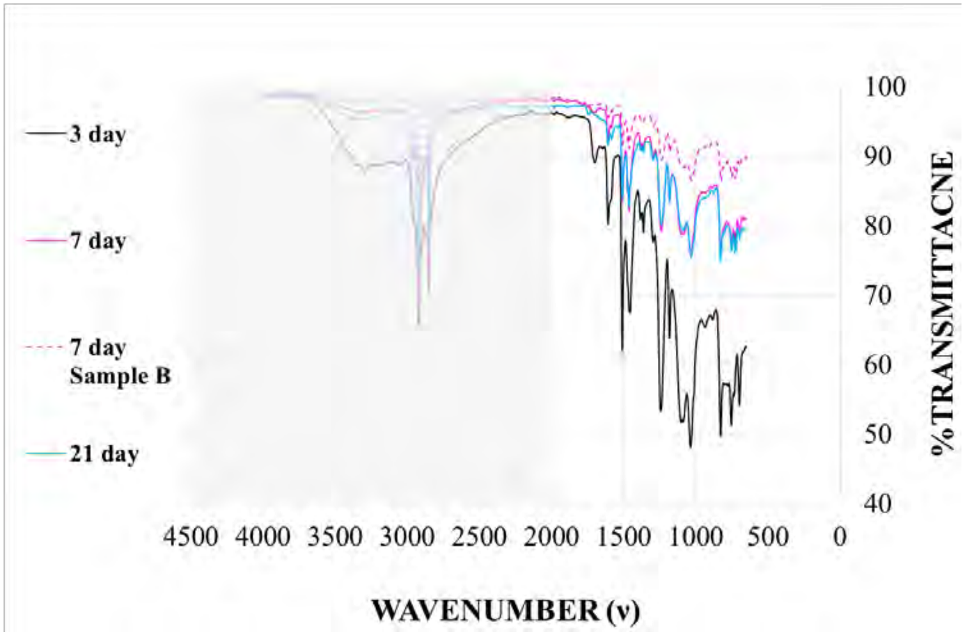


Figure 6.15: Material 3 FTIR results with varying cure time

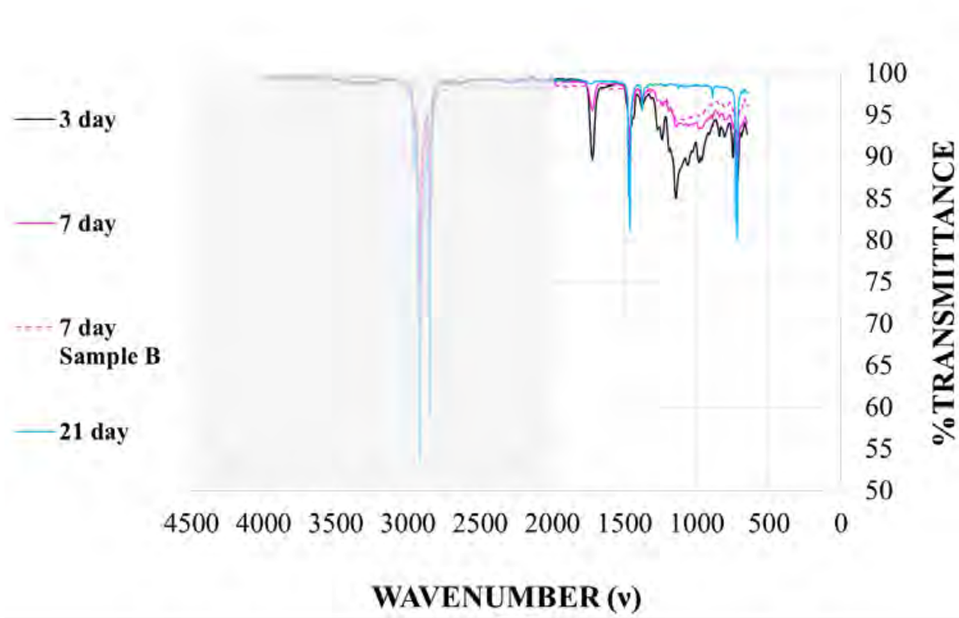


Figure 6.16: Material 4 FTIR results with varying cure time

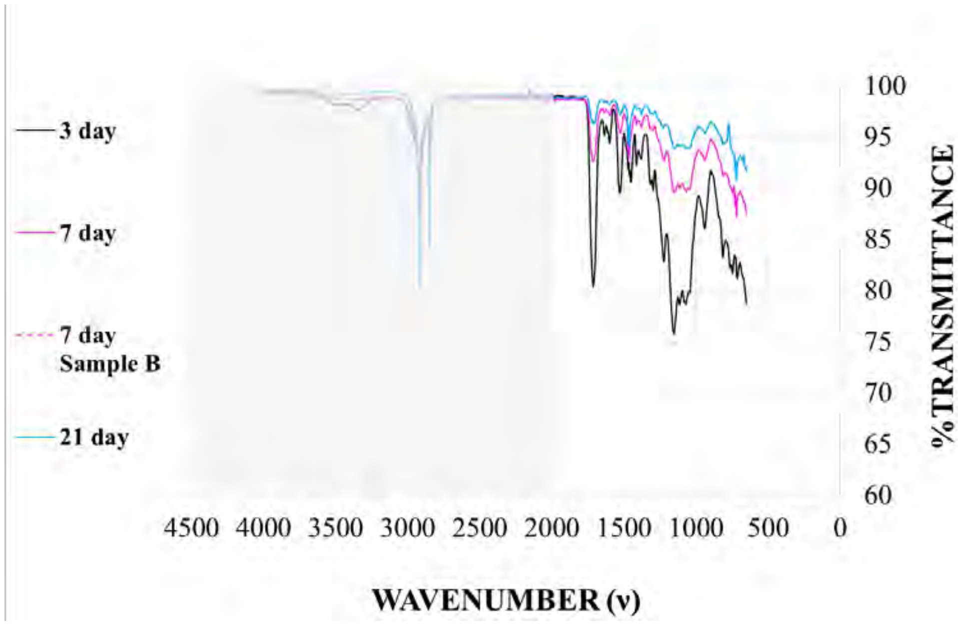


Figure 6.17: Material 7 FTIR results with varying cure time

6.5.3 DSC Testing Results

DSC tests were performed for each material to study the glass transition temperature of the product. DSC tests involve multiple cycles of heating and cooling. The convention is to report the glass transition temperature of a polymer using the data obtained during the second heating cycle, since the first heating cycle is used to erase the thermal history of the sample. However, the objective of this testing is to study the phase change of the adhesive the first time it is exposed to elevated temperature in the field. Therefore, the glass transition temperature of each material was recorded from the first heating cycle for the DSC testing performed at UMass. The glass transition temperature recorded for each material is shown in Table 6.1 The heat flow versus temperature graph for each material can be found in Figure 6.18 to Figure 6.23.

Table 6.1: Glass transition temperatures from DSC tests

MATERIAL	Tg (°F)
1	131
1B	122
2	133
3	131
4	113
7	113

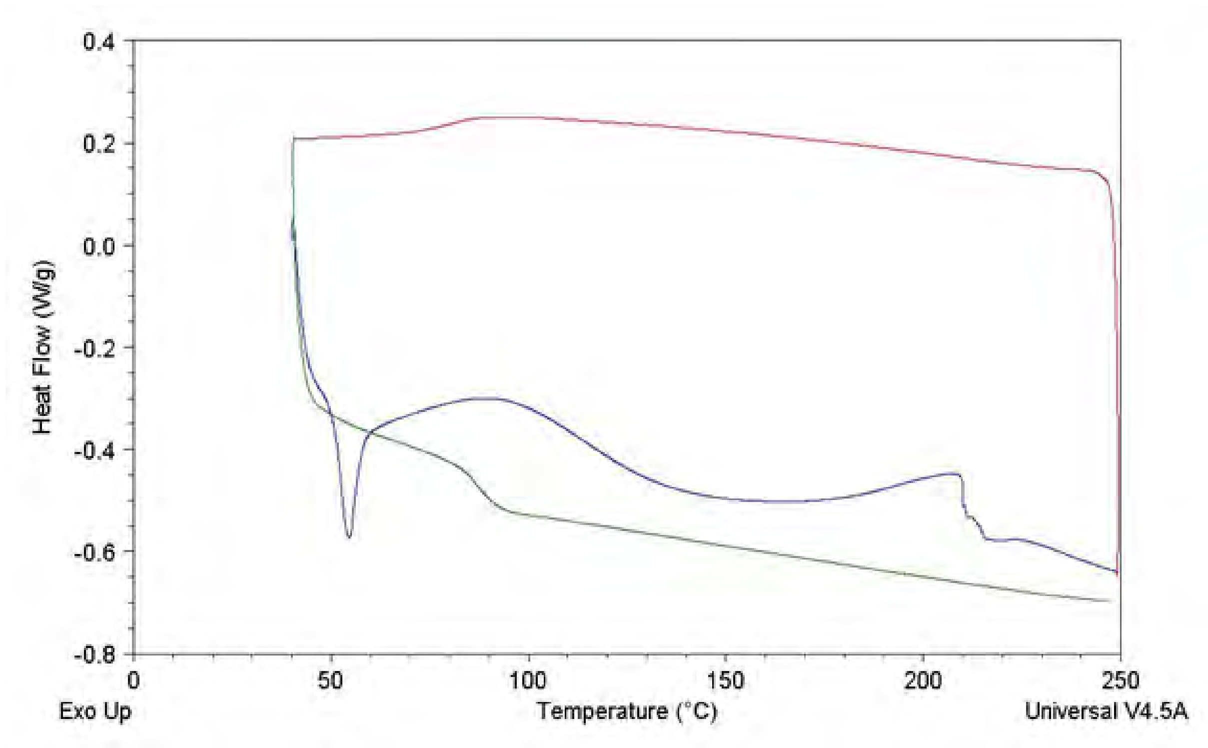


Figure 6.18: Material 1 DSC test results

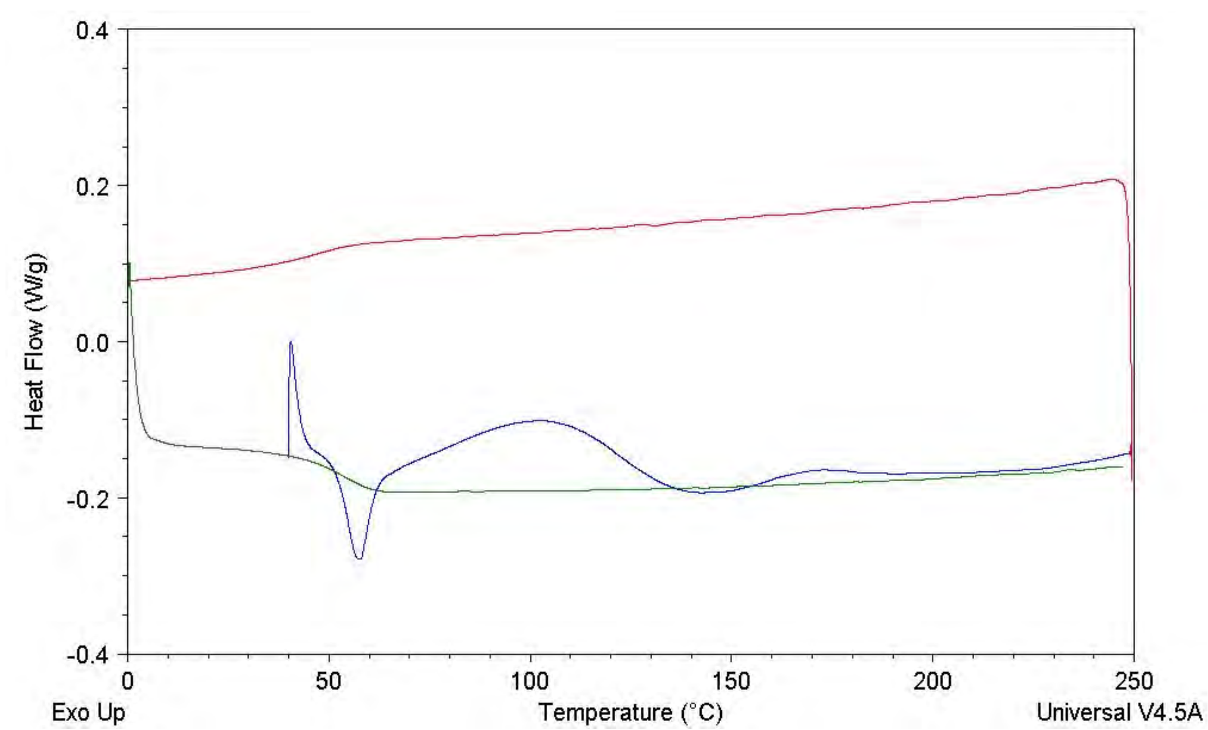


Figure 6.19: Material 2 DSC test results

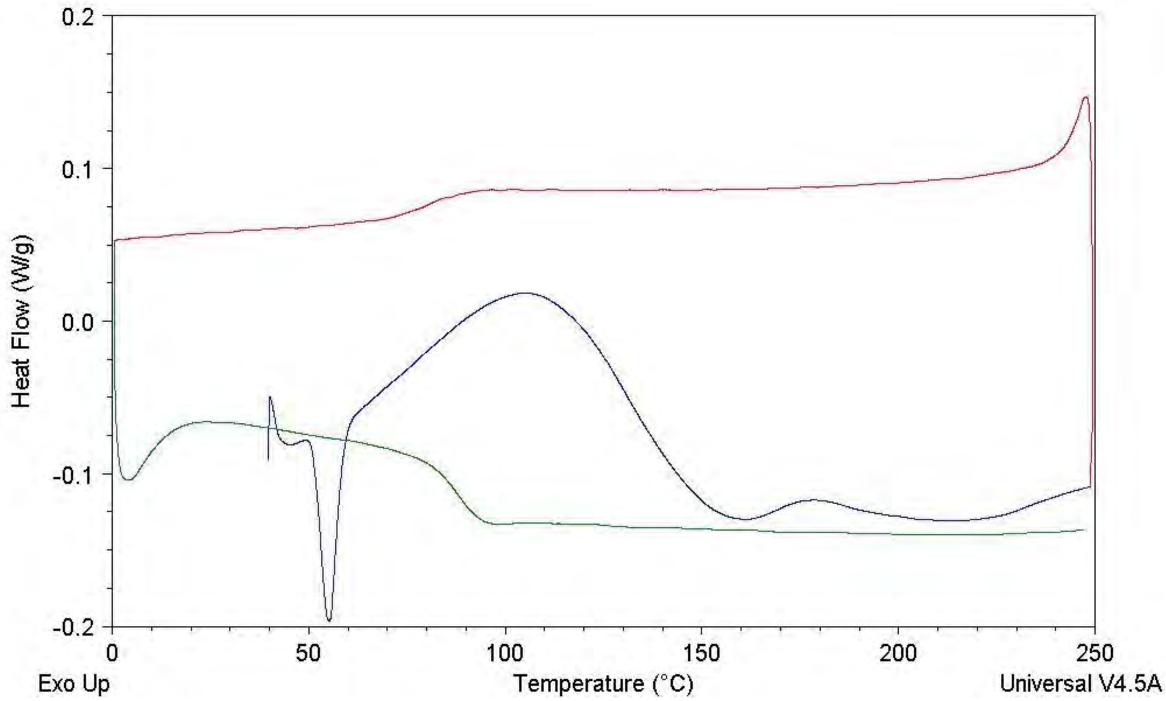


Figure 6.20: Material 3 DSC test results

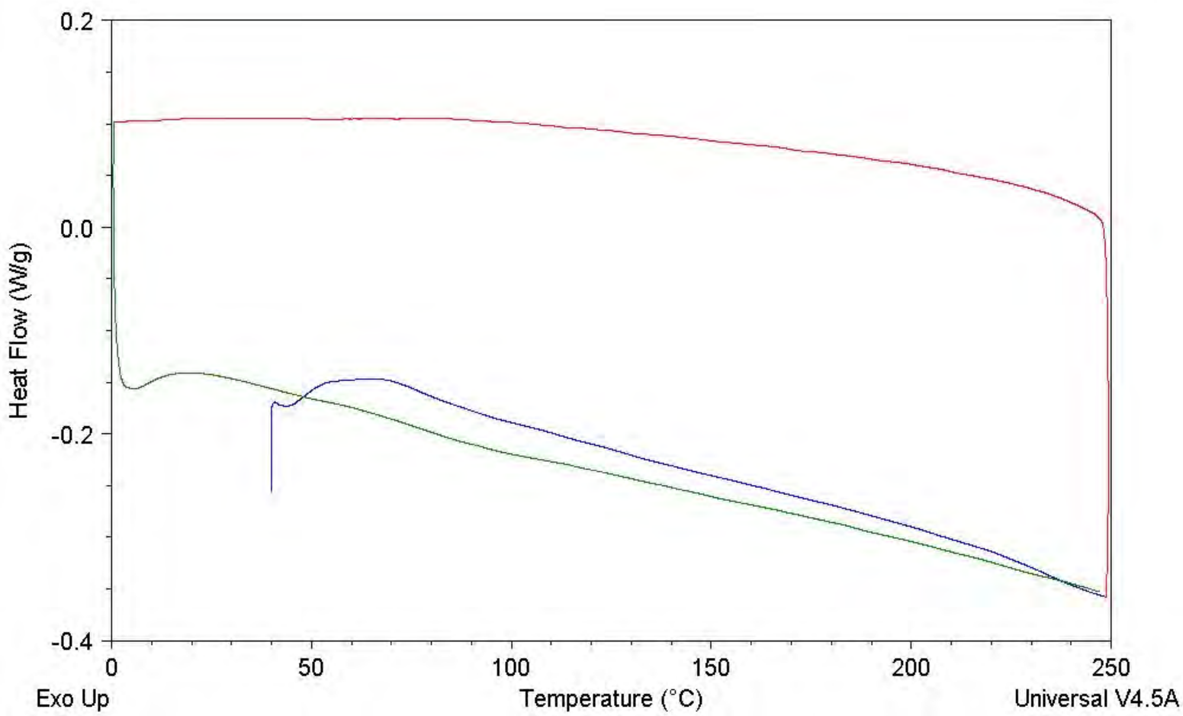


Figure 6.21: Material 4 DSC test results

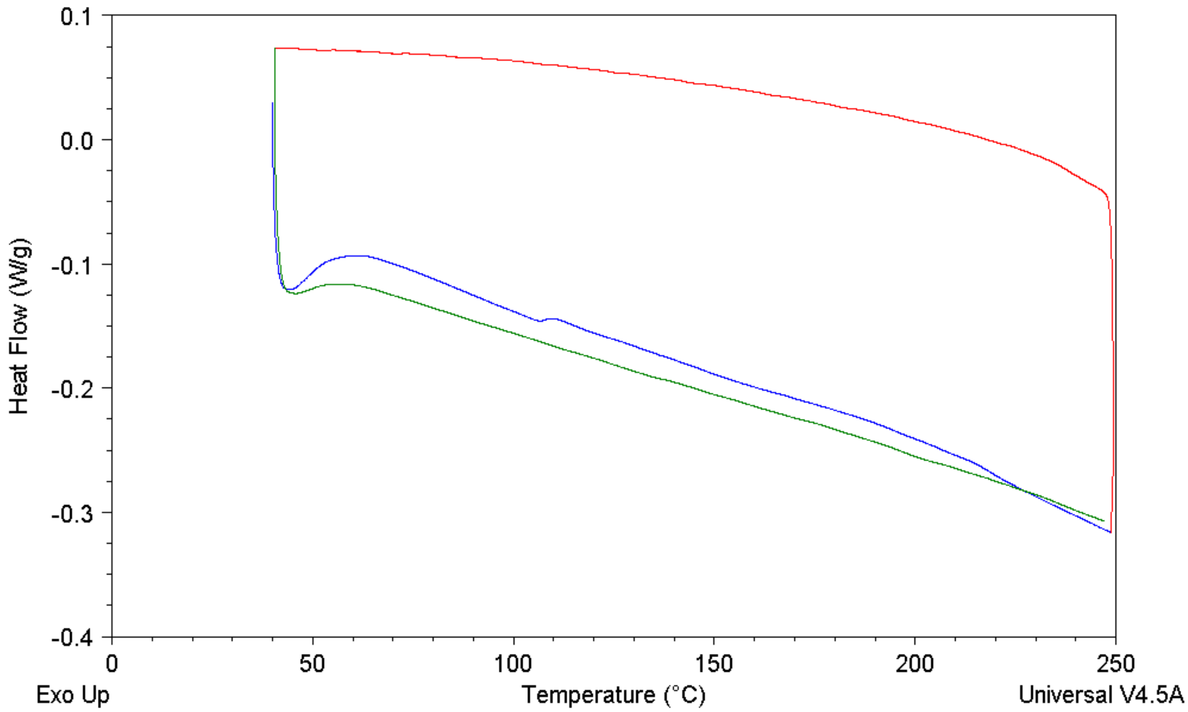


Figure 6.22: Material 7 DSC test results

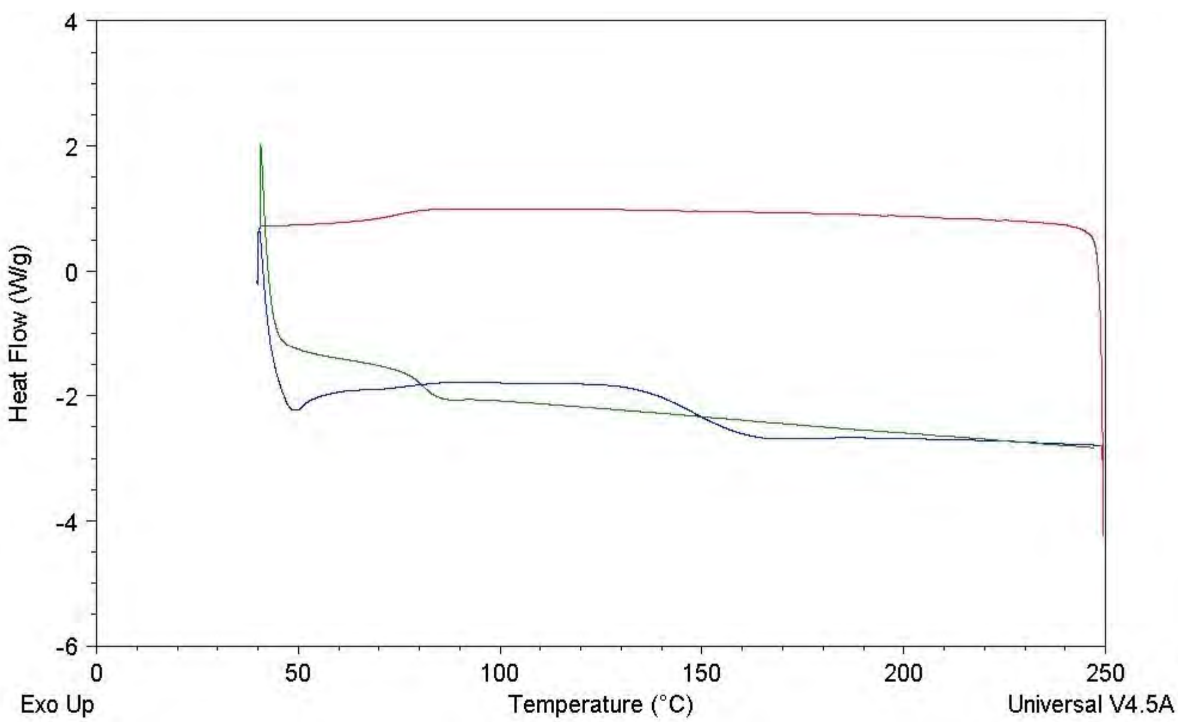


Figure 6.23: Material 1B DSC test results

6.6 Polymer Characterization Tests: Analysis of Results

6.6.1 FTIR Testing

In other studies regarding the analysis of cured epoxy adhesives, such as [25] and [29], it has been reported that scaling the spectra to equalize the intensity of the infrared transmittance at a characteristic wavenumber can be helpful when comparing multiple samples. This method was applied to the spectral data reported in Section 6.5 to provide insight on the usefulness of this data processing technique.

Figure 6.24 shows the FTIR results of Material 1 directly rationed to equal a transmittance of 68% at a wavenumber of 404 in^{-1} (1027 cm^{-1}). This peak was chosen as it was the greatest peak in the fingerprint region prior to normalizing data (Figure 6.6). Next, all spectra were shifted so as to have the same initial transmittance at wavenumber 790 in^{-1} (2,000 cm^{-1}), as shown in Figure 6.25. It was found that for the FTIR results reported in this document, this method did not provide further clarity regarding the interpretation of results. However, it is recommended that this and other data processing techniques of FTIR results be further studied.

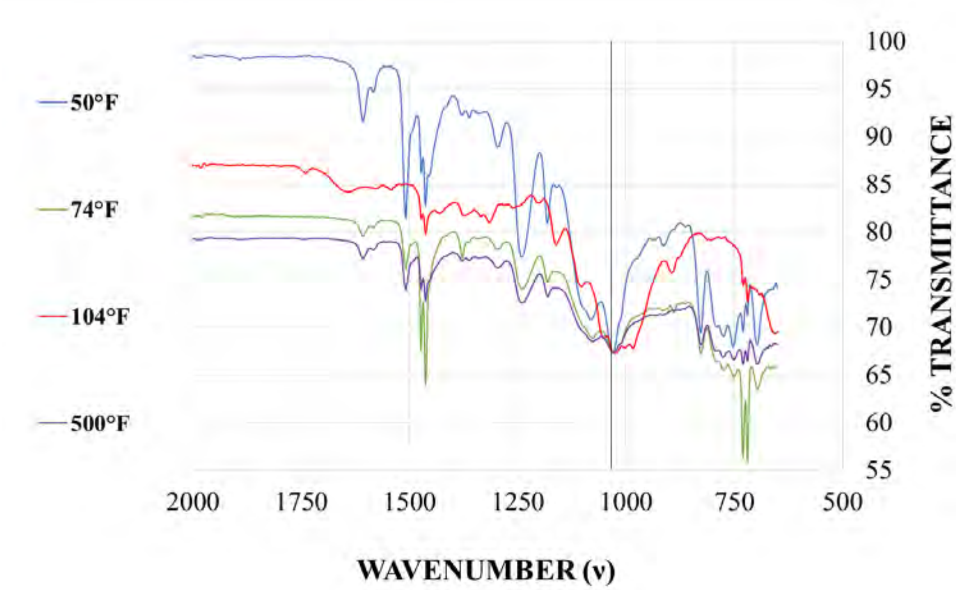


Figure 6.24: Material 1 FTIR results with varying cure temperatures, rationed spectra

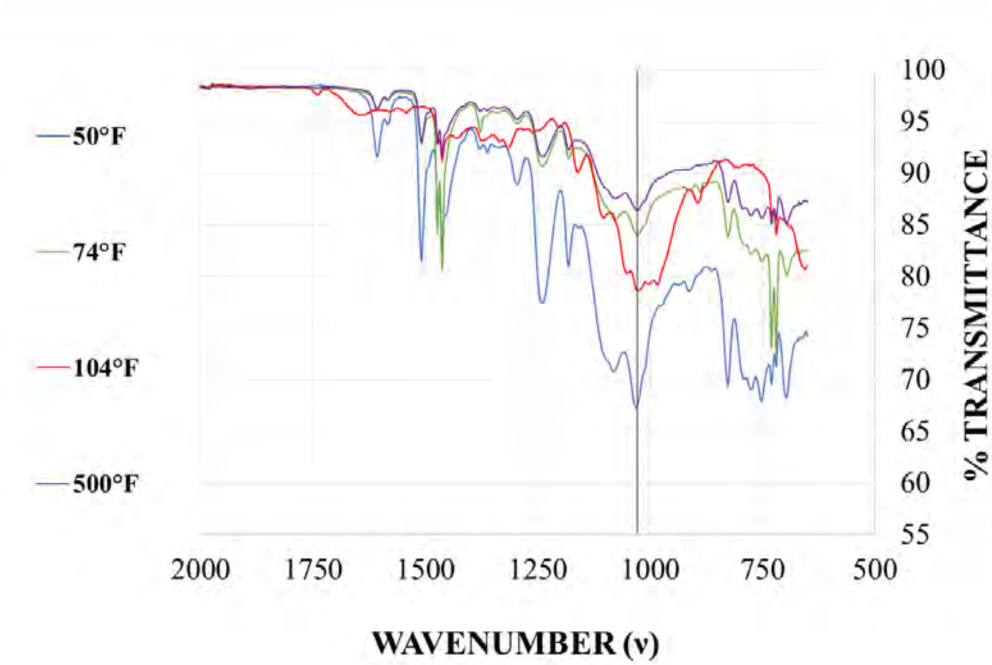


Figure 6.25: Normalized Material 1 FTIR results with varying cure temperatures

6.6.2 DSC Testing

It can be observed from the glass transition temperatures reported in Table 6.1 that Material 7 and Material 4 had the lowest recorded glass transition temperature during the first heating cycle, 113°F. This temperature is within the testing temperature range of 110°F to 120°F, at which short-term reference tests were conducted. As was reported in Section 5.1.1 of this report, Material 4 exhibited poor short-term performance, with an MSL of only 10.65 kip and a COV of 0.24. The poor performance of Material 4 under elevated temperatures is likely related to the material's low T_g.

Material 7, a material recommended for use in cold temperature applications, was not as severely affected by the elevated testing temperatures as Material 4. However, results from the extreme in-service temperature testing concluded that this material had less capacity when tested at elevated temperatures.

From these results, it can be seen that it is possible for DSC testing to provide an initial indication of a material's sensitivity to high temperatures. It is recommended that further testing be conducted to obtain a larger sample set for each material and continue studying the use of this technique to be used as a supplemental tool in analyzing the performance of adhesive materials.

7.0 Conclusions and Recommendations

Post-installed anchoring systems are used extensively in MassDOT projects due to their ease of attachment to existing structures. However, recommendations on materials from various manufacturers are currently lacking for certain situations such as long-term tension loading. The 2006 Boston, Massachusetts, I-90 connector tunnel ceiling collapse, caused by the long-term tension failure of adhesive anchors, revealed an insufficiency in the understanding of the behavior of post-installed anchoring systems and a need to conduct further research to improve the acceptance criteria for these systems under long-term load applications.

The purpose of the investigation presented in this report was to provide guidance to MassDOT on the use of anchoring systems. This research project evaluated the behavior of adhesive and cementitious bonded anchoring systems per the SvTTF approach found in the provisional standard AASHTO TP-84 [4] in order to provide recommendations pertaining to the test method. To study the effects of certain in-service and installation parameters on bond strength, additional short-term anchor pullout tests were conducted using the best-performing materials as evaluated by AASHTO TP-84 [4]. The parameters studied included installation direction and extreme in-service temperatures. Polymer characterization testing of adhesive products were also conducted in order to comment on technique usefulness for field quality assurance and quality control of field-installed bonded anchor materials.

7.1 Anchor Pullout Test Results

Six bonding materials from various chemistries and manufacturers were used for the evaluation of AASHTO TP-84 [4]. Supplemental short-term tests were conducted with variation in hole drilling and anchor installation direction to investigate the influence of installation direction on the performance of adhesive anchors. Additional short-term tests were also conducted to study the temperature effects on adhesive anchoring systems. For these tests, the performance of a material recommended by the manufacturer for use in cold weather applications was compared to materials recommended for typical installation conditions.

The following observations and recommendations can be concluded from this research.

AASHTO TP-84 Materials

- The SvTTF approach of AASHTO TP-84 [4] is very promising, though restrictions are recommended.
- The SvTTF approach can overestimate the long-term capacity of a material with large variation in results of short-term tests. Therefore, a maximum COV of 10% for short-term tests is recommended in order to proceed with the full SvTTF procedure.
- The extrapolation of four months of long-term data to a design life of 100 years should be further justified due to the inherent variability in material behavior and the

unknown effect of physical aging on bonding materials. Pending further study, a more conservative approach or required inspection of anchors at ages beyond ten times the four-month test protocol is recommended.

- Based on the limited bonding materials studied for this research project, epoxy materials presented the most reliable long-term load performance. The methyl methacrylate, ester-based and cementitious materials did not perform well; however, further research is needed to study a larger sampling of these material types.
- The test method has a slight inconsistency in how short-term data is reported. It is recommended that short-term tests be included in the SvTTF trend lines, and that they be plotted at actual time zero to be consistent with the reporting of long-term data. It is noted that the plotting at time zero makes minimal difference in results for materials meeting the maximum COV of 10% for short-term tests.
- Specific criteria should be provided when data can be excluded from results, such as specimens that fail while being loaded to their percentage of MSL for long-term testing and specimens that are noted to have incomplete curing.
- It is expected that new products will be developed with higher bond strengths than are now typical. The test procedure many not be able to ensure bond failures without violating the minimum embedment depths specified. Reducing embedment depths further may result in tests that are dominated by bond performance at the top and bottom of the anchor, which may not be representative of a typical embedment depth for an installed anchor.
- A precision and bias have not been established for this test method.

Installation Direction Testing

- It was found that horizontal installations resulted in a loss of capacity on the order of 10% of downward installed specimens for these materials and specimens.

Extreme In-Service Temperature Testing

- Material 7, a product recommended for use in cold temperature, exhibited excellent performance in extreme cold-temperature testing, while both Material 1B and Material 2, materials recommended for typical installation temperatures, had severely reduced capacities when tested at temperatures lower than their recommended installation temperatures, even though they were installed and cured within the recommended range.
- Materials 1B, 2, and 7 were influenced not just by temperature occurring during the installation, but through the service life of the anchor. Therefore, it is important to consider the service life temperature of post-installed adhesive anchors as well as the installation temperature.

7.2 Polymer Characterization Testing

In this investigation, polymer characterization testing was conducted on six adhesive anchor materials at varying cure times and cure temperatures. The polymer tests included FTIR and DSC testing of each material. The intent of this research was to provide recommendations on the application of FTIR testing to be used as a quality assurance and quality control technique for post-installed adhesive anchoring systems and DSC testing to provide additional information regarding a material's thermal properties.

The following observations and recommendations can be concluded from this research.

- FTIR is expected to be a useful tool for quality assurance and quality control of adhesive anchor materials. The method can be used to verify that the adhesive was properly mixed at the site and to verify consistency of a product from batch to batch.
- It is recommended that samples to be used for FTIR testing be cast as thin disks approximately 1.5 inches (38.1 mm) in diameter and 0.03 inch to 0.05 inch (0.762 mm to 1.27 mm) thick. It is recommended best practice to apply a single cure temperature and cure time to all sample disks for consistency. The research team recommends a curing temperature of 74°F (23°C) and cure time of 7 days.
- DSC testing is most useful at determining the glass transition temperature of a material. This can be useful in assessing materials that may have lower performance at elevated temperatures that may occur in the field.

7.3 Implementation

The following recommendations are made for implementation of post-installed anchorage to concrete based on the results of this project. These have been developed in discussion with the Technical Committee associated with this project.

- Current prohibition of structural applications for adhesive anchors per MassDOT Engineering Directive E-10-001 "Guideline for the use of Adhesive Anchors" [16] shall be continued. Research under Task Order # 12-7, "Performance of Adhesive and Cementitious Anchorage Systems" (this project), has not provided evidence to contradict FHWA Technical Advisory 5140.30, "Use and Inspection of Adhesive Anchors in Federal-Aid Projects," which "strongly discourages" the use of adhesives for these applications [16].

- Cementitious (grout-based) post-installed anchors shall also be prohibited for structural applications listed as prohibited in MassDOT Engineering Directive E-10-001, "Guideline for the use of Adhesive Anchors" [16].

For approval of adhesive anchors, the following must be submitted by the manufacturer for review by MassDOT. Approved materials that will be on MassDOT's Qualified Construction Materials List may only be used in permitted structural

applications as defined by MassDOT Engineering Directive E-10-001, "Guideline for the use of Adhesive Anchors" [16].

- All material documentation shall be separately submitted for approval for use on threaded rod or reinforcing bar applications.

- Materials shall be certified per ICC-ES AC308 [13] cracked and uncracked concrete testing, with the following additional criteria.

    - Materials must also be certified per optional testing for "sensitivity to freeze/thaw conditions" and "sensitivity to installation direction."

    - Materials shall have a maximum COV of 10% for short-term "reference testing" performed as part of the ICC-ES AC308 [13] certification. Results from "reference testing" and COV shall be provided by the manufacturer to MassDOT as part of the materials approval process.

    - When applicable per ICC-ES AC308 (13), "tension at decreased installation temperature" ICC-ES AC308 certification results shall not decrease by more than 10% from "reference testing." Materials shall have a maximum COV of 10% for "tension at decreased installation temperature" test results. Results verifying the comparison and coefficient of variation shall be provided by the manufacturer to MassDOT as part of the materials approval process.

    - Manufacturer shall submit test data from an additional 5 tests. Testing shall be similar to "reference testing," with the following exception. After curing, test specimens shall be conditioned and tested at ambient temperature of 0^{o}F (-18^{o}C). Specimens shall be conditioned at the test temperature for a minimum of 24 hours prior to testing. Results shall not decrease by more than 10% from "reference testing." Materials shall have a maximum COV of 10% for these reduced temperature test results. Results verifying the comparison and coefficient of variation shall be provided by the manufacturer to MassDOT as part of the materials approval process.

- When providing anchor capacity data for use in design, the Manufacturer shall provide the factors of safety referenced to the ICC-ES AC308 [13] certified "reference testing" results. All results shall be referenced to Load and Resistance Factor design criteria.

- Manufacturer shall provide data (value and plot of heat flow versus temperature) certifying the glass transition temperature from the **<u>initial cycle</u>** of Differential Scanning Calorimetry (DSC) testing (ASTM E1356-08(2014) [30]). No initial thermal program or pre-treatment of the specimen is allowable (Section 10.2 is NOT appropriate). Material shall exhibit a minimum T_m of 125^{o}F (52^{o}C) and T_f of 120^{o}F (52^{o}C). Any signs of material thermal degradation shall be reported and not occur at temperatures less than 125°F (52°C). Samples shall be cured at ambient conditions of 70°–80°F (21°–27°C) for a period not to exceed seven days prior to DSC testing.

- Manufacturer shall submit results from Fourier Transform Infrared Spectroscopy (FTIR) testing of a sample disk of cured adhesive material for use as reference data for comparison to as-delivered products. Specimen thickness shall be 0.03–0.05 in. (0.8–1.3 mm). Specimens shall be cured and maintained at a constant ambient temperature of 74°F (23°C) prior to testing. FTIR testing shall occur at seven days from initiation of cure. Updated data for current material lot number shall be submitted annually in order to maintain acceptance on MassDOT's Qualified Construction Materials List.

Installation of adhesive anchors must satisfy the following requirements.

- All installations of horizontally or overhead post-installed adhesive anchors shall be performed by personnel certified for such installations per the American Concrete Institute (ACI)-Concrete Reinforcing Steel Institute (CRSI) adhesive anchor certification.

- Adhesive anchors installation temperatures must be within the allowable range certified by the manufacturer. "Installation temperatures" are defined as the maximum and minimum ambient temperatures occurring over the entire cure time as provided by the manufacturer for the minimum installation temperature. Installation temperatures are restricted to between 40°F (4.4°C) and 90°F (32.2°C), unless more restrictive temperatures are published by the manufacturer.

Further study is recommended in the following areas.

- Adhesive post-installed anchors rely predominantly on bond strength for long-term tensile resistance. These anchor types have inherent variability in performance, and the effect of long-term physical aging on bonding materials is not well documented for currently marketed products. Further study on aging effects is warranted.

- Cementitious post-installed anchors rely predominantly on grout strength. Further study to evaluate the long-term tensile resistance of these materials is recommended, and the materials should not be used for this application until proof of performance can be established through a certification process.

- The SvTTF approach of AASHTO TP-84 [4] is very promising as a tool to predict anchor tensile capacity as a function of design life, though if it is to be implemented, restrictions are recommended per this report. ICC-ES AC308 [13] certification with a factor of safety of two applied would be conservative for 100-year design life for the materials with good performance in this test program. Use of the SvTTF approach would allow for design that more directly includes the time that the anchor is loaded in tension, which could lead to more accurate design. However, without implementation at the national level through FHWA or ACI, it is not recommended that an individual DOT require this testing.

8.0 Appendix: Concrete Batch Specifications

Table A.1: Concrete batch 1 specifications

Date of pour:	12/12/2014
Time Started:	14:10 hr
Quantity:	1.5 yd³
Water added:	12 gal

Mix Specifications								
	3/4"MIX	**SAND**	**SLAG**	**CEM - 1**	**WATER**	**AIR 250**	**100 XR**	**MR-WR**
MIX:	1870	1205	170	510	34.5	3.5	-	34
TRM:	0	0	0	0	0	0	-	0
MST:	0.50 %M	5.0 %M	-	-	-	-	-	-
TGT:	2819	1903	255	765	19	5	-	51
UNIT:	Lb	Lb	Lb	Lb	Gl	Oz	-	Oz
1:	2880	1940	245	790	16	6	-	52
M:	-	-	-	-	-	-	-	-

Concrete Properties			
Slump:			
Air Content:			
Unit Weight:			
28-Day Compressive Strength:	5190 psi	=	6.9 kpa

*Additional water was inlcuded in the batch; however, the exact amount was not recorded.
** Concrete properties are not available at this time.

Table A.2: Concrete batch 2 specifications

Date of pour:	8/3/2015
Time Started:	9:40 hr
Quantity:	2 yd³
Water added:	20 gal

Mix Specifications								
	3/4"MIX	**SAND**	**SLAG**	**CEM - 1**	**WATER**	**AIR 250**	**100 XR**	**MR-WR**
MIX:	1870	1205	170	510	34.5	3.5	0	34
TRM:	0	0	0	0	0	0	0	0
MST:	1.0 %M	3.3 %M	-	-	-	-	-	-
TGT:	3778	2492	340	1020	40	7	0	68
UNIT:	Lb	Lb	Lb	Lb	Gl	Oz	Oz	Oz
1:	3740	2520	330	1080	38	8	0	69
M:	-	-	-	-	-	-	-	-

Concrete Properties	
Slump:	6 in
Air Content:	5 %
Unit Weight:	143.3 lb/ft³
28-Day Compressive Strength:	5506 psi
241-Day Compressive Strength:	5933 psi

Table A.3: Concrete batch 3 specifications

Date of pour:	11/11/2015
Time Started:	8:00 hr
Quantity:	2 yd^3
Water added:	15 gal

Mix Specifications

	3/4"MIX	SAND	SLAG	CEM - 1	WATER	AIR 250	100 XR	MR-WR
MIX:	1870	1100	170	510	34.5	3.5	0	34
TRM:	0	0	0	0	0	0	0	0
MST:	0.5%M	3.2%M	-	-	-	-	-	-
TGT:	3759	2273	340	1020	43	7	0	68
UNIT:	Lb	Lb	Lb	Lb	Gl	Oz	Oz	Oz
1:	3740	2300	340	1010	43	8	0	69
M:	-	-	-	-	-	-	-	-

Concrete Properties

Slump:	7 in
Air Content:	7 %
Unit Weight:	143.1 lb/ft^3
28-Day Compressive Strength:	4728 psi
141-Day Compressive Strength:	5228 psi

Table A.4: Concrete batch 4 specifications

Date of pour:	5/3/2016
Time Started:	8:50 hr
Quantity:	2 yd³
Water added:	4 gal

Mix Specifications								
	3/4"MIX	**SAND**	**SLAG**	**CEM - 1**	**WATER**	**AIR 250**	**100 XR**	**MR-WR**
MIX:	1870	1205	170	510	35.5	3	-	34
TRM:	0	0	0	0	0	0	-	0
MST:	-	-	-	-	-	-	-	
TGT:	3778	2529	340	1020	42	6	-	68
UNIT:	Lb	Lb	Lb	Lb	Gl	Oz	-	Oz
1:	3800	2520	350	1050	42	7	-	69
M:	-	-	-	-	-	-	-	-

Concrete Properties	
Slump:	4 in
Air Content:	3.5 %
Unit Weight:	148 lb/ft³
28-Day Compressive Strength:	5321 psi
220-Day Compressive Strength:	5717 psi

Table A.5: Concrete batch 5 specifications

Date of pour:	5/27/2016
Time Started:	12:30 hr
Quantity:	2 yd³
Water added:	15 gal

Mix Specifications								
	3/4"MIX	**SAND**	**SLAG**	**CEM - 1**	**WATER**	**AIR 250**	**100 XR**	**MR-WR**
MIX:	1870	1205	170	510	35.5	3.2	-	34
TRM:	0	0	0	0	0	0	-	0
MST:	0.5%M	3.7%M					-	
TGT:	3759	2503	340	1020	43	6	-	68
UNIT:	Lb	Lb	Lb	Lb	Gl	Oz	-	Oz
1:	3780	2520	435*	980	41*	6	-	69
M:	-	-	-	-	-	-	-	-

Concrete Properties	
Slump:	5 in
Air Content:	5.5 %
Unit Weight:	148.6 lb/ft³
28-Day Compressive Strength:	4628 psi
84-Day Compressive Strength:	4742 psi

Table A.6: Concrete batch 6 specifications

Date of pour:	10/5/2016
Time Started:	8:15 hr
Quantity:	2 yd^3
Water added:	5 gal

Mix Specifications							
	SAND	**3/4'' TRAP**	**SLAG**	**CEM-1**	**WATER**	**MR-WR**	**AIR 250**
MIX:	1205	1870	170	510	35.5	34	4.6
TRM:	0	0	0	0	0	0	0
MST:	3.3 %M	0.3 %M	-	-	-	-	-
TGT:	2492	3749	340	1020	40	68	9
UNIT:	LB	LB	LB	LB	GL	OZ	OZ
1:	2540	3900	350	995	40	69	10
M:							

Concrete Properties	
Slump:	4 in
Air Content:	5.4 %
Unit Weight:	146.4 lb/ft^3
28-Day Compressive Strength:	5836 psi

9.0 References

[1] ACI. *Qualification of Post-Installed Adhesive Anchors in Concrete (ACI 355.4).* American Concrete Institute, Farmington Hills, MI, 2011.

[2] Cook, R. A., E. P. Douglas, T. Davis, and C. Liu. *NCHRP Report 757: Long-Term Performance of Epoxy Adhesive Anchor Systems.* Transportation Research Board, Washington, D.C., 2013.

[3] Cook, R. A., E. P. Douglas,T. M. Davis, and C. Liu. *NCHRP Report 639: Adhesive Anchors in Concrete under Sustained Load.* Transportation Research Board, Washington, D.C., 2009.

[4] AASHTO. *Standard Method of Test for Evaluation of Adhesive Anchors in Concrete (TP-84).* American Association of State Highway and Transportation Officials, Washington, D.C., 2010.

[5] NTSB. *Highway Accident Report: Ceiling Collapse in the Interstate 90 Connector Tunnel Boston, Massachusetts, July 10, 2006*. National Transportation Safety Board, Washington, D.C., 2007.

[6] ACI Committee 318. *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (318R14).* American Concrete Institute, Farmington Hills, MI, 2014.

[7] Eligenhausen, R., W. Fuchs, and B. Mayer. Loadbearing Behavior of Anchor Fastenings in Tension. *Betonwerk & Fertigteil-Technik* (Wiesbaden), No. 12, 1987, pp. 826–832.

[8] Fuchs, W., R. Eligenhausen, and J. Breen. Concrete Capacity Design (CCD) Approach for Fastening to Concrete. *ACI Structural Journal,* Vol. 92, 1995, pp. 73–94.

[9] Cook, R., J. Kunz, W. Fuchs, and R. Konz. Behavior and Design of Single Adhesive Anchors under Tensile Loading in Uncracked Concrete. *ACI Structural Journal,* Vol. 95, No. 1, 1998, pp. 9–26.

[10] Zamora, N., R. Cook, R. Konz, and G. Consolazio. G. Behavior and Design of Single, Headed and Unheaded Grouted Anchors under Tensile Load. *ACI Structural Journal,* 2003, pp. 220–230.

[11] ASTM. *Standard Test Methods for Strength of Anchors in Concrete Elements (ASTM E488).* ASTM International, West Conshohocken, PA, 2010.

[12] ASTM. *Standard Test Method for Testing Bond Performance of Bonded Anchors (ASTM E1512)*. ASTM International, West Conshohocken, PA, 2007.

[13] ICC-ES. *Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements (AC308)*. ICC Evaluation Services Incorporated, Whittier, CA, 2013.

[14] Cook, R. and J. Burtz. *Design Guidelines and Specifications for Engineered Grouts.* Florida Department of Transportation, Tallahassee, FL, 2003.

[15] James, R., C. De la Guardia, and C. McCreary. Strength of Epoxy-Grouted Anchor Bolts in Concrete. *Journal of Structural Engineering,* Vol. 113, No. 12, 1987.

[16] MassDOT. *Engineering Directive E-10-001*. MassDOT, Boston, MA, 2010.

[17] ASTM. *Standard Test Method for Tensile, Compressive and Flexural Creep and Creep-Rupture of Plastics (ASTM D2990)*. ASTM International, West Conshohocken, PA, 2009.
[18] ASTM. *Standard Specification for Packaged Dry, Hydraulic-Cement Grout (Nonshrink) (ASTM C1107).* ASTM International, West Conshohocken, PA, 2013.
[19] Conrad, R. Tests of Grouted Anchor Bolts in Tension and Shear. *ACI Journal, 1967,* pp. 725–728.
[20] ACI Committee 318. *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (318R14).* American Concrete Institute, Farmington Hills, MI, 2002.
[21] Subramanian, N., and R. Cook. Behavior and Design of Grouted Anchors. *Indian Concrete Journal,* 2004, pp. 14–21.
[22] Rodriguez, M., D. Lotze, Y. Zhang, R. Klinger, and H. Graves. Dynamic Behavior of Tensile Anchors to Concrete. *ACI Structural Journal,* Vol. 98, No. 4, pp. 511–524, 2001.
[23] ASTM. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM C39).* American Society for Testing and Materials, West Conshohocken, PA, 2012.
[24] Gulmine, J. V. Polyethelen Characterizations by FTIR. *Polymer Testing,* 2002.
[25] Zaikov, G. E., ed. *Trends in Molecular and High Molecular Science*. Nova Science Publishers, New York, NY, 2004.
[26] Achilias, D. S. Cure Kinetics of Two Epoxy Systems with Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (DSC). *Journal of Macromolecular Science,* Vol. 49, No. 8, 2012.
[27] Pavia, D. L. *Introduction to Spectroscopy*. Brooks/Cole Publishers, Belmont, CA, 2009.
[28] Dannenberg, H.. Determination of Cure and Analysis of Cured Epoxy Resins. Symposium on Cure in Thermosetting Resins, 1956.
[29] Pike Technologies. *Application Note 0503: Analysis of Cured Epoxy Adhesives by ATR / FTIR.* https://www.piketech.com/skin/fashion_mosaic_blue/application-pdfs/AN_0503_Cured_Epoxy_MIRacle.pdf. Accessed July 21, 2017.
[30] ASTM. *Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry (ASTM E1356-08).* ASTM International, West Conshohocken, PA, 2014.