Performance of Adhesive and Cementitious Anchorage Systems

Mirna Mendoza

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PERFORMANCE OF ADHESIVE AND CEMENTITIOUS ANCHORAGE SYSTEMS

A Thesis Presented

by

MIRNA G. MENDOZA

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

May 2017

Civil and Environmental Engineering
PERFORMANCE OF ADHESIVE AND CEMENTITOUS ANCHORAGE SYSTEMS

A Thesis Presented
by
MIRNA G. MENDOZA

Approved as to style and content by:

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Scott Civjan, Chair

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Richard N. Palmer, Department Head
Civil and Environmental Engineering
DEDICATION

This work is dedicated to my loving family, who always encourages me to go on every adventure, especially this one.
ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Scott Civjan, for his unwavering support and mentorship throughout this project.

I am very grateful to all of the professors of the Structural Engineering and Mechanics group at UMass whose classes and guidance were invaluable to my education.

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ABSTRACT

PERFORMANCE OF ADHESIVE AND CEMENTITIOUS ANCHORAGE SYSTEMS

MAY 2017

MIRNA G. MENDOZA, B.S., UNIVERSIDAD DIEGO PORTALES

M.S.C.E. UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Scott A. Civjan

Post-installed anchoring systems are used extensively in Massachusetts Department of Transportation (MassDOT) projects due 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 thesis was to provide guidance on the use of anchoring systems to MassDOT. This research project evaluated the behavior of adhesive and cementitious bonded anchoring systems per the Stress-versus-Time-to-Failure 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 were also conducted in order to comment on technique usefulness for field quality assurance/quality control of field installed bonded anchor materials.
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CHAPTER 1
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) Statewide 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, 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.

Figure 1-1: Types of Anchor Systems (Cook, 2003)
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 which 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]. ACI 355.4 [2] 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 [2].
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 [1]. 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 Report 639 [3] and NCHRP 757 [1]. 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 [2] 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 a pass/fail criteria based on extrapolating displacement data. Revisions to ACI 355.4 [2] to include similar testing have also been proposed. The succeeding report, [1], expanded on the research by investigating additional environmental parameters that can affect bond strength.

1.2 Motivation for the Study

Post-installed systems are used extensively in Massachusetts Department of Transportation (MassDOT) projects due 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 into 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 amount 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 which was reported by the manufacturer to have poor long-term load characteristics [5]. In response
to the failure, NTSB recommended to the Federal Highway Administration (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, 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.

Figure 1-2: I-90 Tunnel Ceiling Collapse Due to Adhesive Anchor Failure, (NTSB, 2007, pg. 1)

1.3 Research Objectives

The purpose of this investigation is to provide guidance on the use of anchoring systems to MassDOT. This investigation evaluates 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 will assess 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 will be conducted in order to comment on supplemental methods which 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 involves 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 were 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 is 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 which can be linked to many performance parameters.
CHAPTER 2
BACKGROUND

This chapter presents an overview of the background of existing behavior models and design of bondedanchoring systems as well as the applicable current test standards applicable to post-installed bonded anchor systems. A complete literature review regarding post-installed bonded anchoring systems was presented by Droesch [6].

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 [7] 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.
Figure 2-1: Potential Failure Modes of Bonded Anchors (Zamora et al., 2003). Authorized Reprint from ACI Structural Journal Vol. 100 No. 2

2.1.1 Concrete Design Capacity (CCD) Model

The CCD model was developed by Eligenhausen (1987) [8] and was first compared with existing ACI standards by Fuchs (1995) [9]. 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 [7].

\[
N_b = k\lambda_a \sqrt{f'_c h_{ef}}^{1.5} \tag{Eq. 1}
\]

Where,

\[N_b = \text{Basic concrete breakout strength in tension of a single anchor in cracked concrete, lbs}\]

\[k = \text{Coefficient for basic concrete breakout strength in tension (24 for cast-in-place anchors, 17 for mechanical post-installed anchors)}\]

\[f'_c = \text{Specified compressive Strength of concrete, psi}\]

\[h_{ef} = \text{Effective anchor embedment depth, inch}\]
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) [10] and is summarized by Zamora (2003) [11] and Cook et al. (2013) [1]. 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. This model is defined per Equation 2.
Figure 2-3: (a) Hyperbolic Tangent Stress Distribution; (b) Uniform Bond Stress Distribution (Cook et al, 2013). Authorized Reprint from the Transportation Research Board.

\[ \bar{N}_\tau = \bar{\tau} \pi d h_{ef} \]  
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 [1]:
• 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.

![Stress Distribution along Length of Adhesive Anchor](image)

**Figure 2-4: Stress Distribution along Length of Adhesive Anchor for** \( h_{ef}/d_o = 8.0 \)
(Cook et al., 2013). Authorized Reprint from the American Society of Civil Engineers (ASCE).

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).

\[
N_u \leq \varphi N_{bond} \quad \text{Eq. 3}
\]

Where,
- \( N_u \) = factored tension load, lbs
- \( \varphi \) = capacity reduction factor
- \( N_{bond} = \tau' \pi d h_{ef} \)
- \( \tau' \) = nominal bond stress, psi
- \( d \) = anchor diameter, in
- \( h_{ef} \) = embedment depth, in
The nominal bond strength ($\tau'$) is the 5% lower fractile of mean bond strength modified by a series of reduction factors ($\alpha$) 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.

\[ \tau' = \tau_k \alpha_1 \alpha_2 \alpha_3 \]  

Eq. 4

Where,

$\tau'$ = 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 (2003) [11] presents 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 ($\tau$) for the grout/steel interface failure mode and a bond stress of ($\tau_o$) 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 break out cone. Failure of the bond at the grout/concrete interface can be
predicted by Equation 5, [11]. Failure of the grout is not mentioned in the literature, however, it is a possible failure mode that should be further investigated.

$$\bar{N}_\tau = \tau_o \pi_o d \ h_{ef}$$  \hspace{1cm} \text{Eq. 5}

Where,

- $\bar{N}_\tau$ = mean failure load, lbs
- $\tau$ = 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.


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 which 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) [12] and AASHTO TP-84 [4] require a minimum of five anchors to be tested and their results averaged in order to determine the MSL.


ASTM E1512 (2007) [13] provides testing procedures for assessing the effects of bond strength under factors such as: elevated temperature, fire, moisture, freeze/thaw cycles. This standard is similar to ASTM E488 (2010) [12], 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 [1]. 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) [1].

The last 20 days (20 data points) from the test are used to construct a logarithmic trend line using a least square’s 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) [1]. ASTM E1512 [13] 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) [14] 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) [2].

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

ACI 355.4 (2011) [2] is similar to ASTM E1512 (2007) [13] 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) [2] 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) [2] for long-term tests is as follows:

- The projected displacement at ten 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 [4]

This proposed test method differs from the long-term test procedure of ACI 355.4 (2011) [2] and ASTM E1215 (2007) [13] 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%-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 a SvTTF semi-log plot and a linear trendline 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) [2] 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) [2]. At this time it is unclear whether ACI or AASHTO will adopt this test procedure.
CHAPTER 3
TEST METHODS AND MATERIALS

This 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.

3.1 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 below.

- 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)
3.1.1 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 according to the provisional standard, a minimum of five short-term tests were initially conducted and their results averaged in order to determine the mean static load (MSL) of the material. Subsequently, ten long-term tests were performed at two different load levels, 60%-70% of MSL and 70%-80% of MSL. A minimum of five anchors were tested per load level, with exceptions as noted. A Displacement vs. 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 3-1. The results from both the short-term and long-term tests were plotted on a Stress vs. Time-to-failure (SvTTF) graph and a linear trendline was 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 3-1: Example Displacement vs. Time Graph for Long-Term Tests

All short-term and long-term tests were confined tests completed at a temperature range of 110°F-120°F (43°C-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 the adhesive as allowed by AASTHTO 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

### 3.1.2 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 which 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 two of the tests in each series were installed and drilled in the downward direction in order to verify that results were similar to previous short-term testing. The results of these control tests are not included as part of the short-term test results of the material due to differences in the age of the epoxy at the time of testing, though comparisons will be 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
3.1.3 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 Material 1B, 2 and 7 can be found in Table 3-1.

Table 3-1: Installation Temperature Ranges

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>MIN. CONCRETE TEMPERATURE (°F)</th>
<th>MAX. CONCRETE TEMPERATURE (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>23</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>110</td>
</tr>
<tr>
<td>7</td>
<td>14</td>
<td>104</td>
</tr>
</tbody>
</table>

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 3-1. Testing temperatures were chosen
between 0°F and 120°F (-18°C and 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 20°F (-7°C) and the sample block at ambient temperature was placed inside. Hourly electrical resistance readings were taken from the embedded thermistors to determine the time necessary for the block to reach the designated temperature.

Figure 3-2 shows 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; being conditioning of specimen to the final testing temperature

• Days 5-6: Continue conditioning to final testing temperature

• Day 7: Conduct short-term tests at testing temperature

![Resistance vs. Time Plot of Sample Concrete Block in Freezer](image)

**Figure 3-2: Resistance vs. Time Plot of Sample Concrete Block in Freezer**

### 3.1.4 Polymer Characterization Testing

Polymer characterization testing of six of the bonding materials studied during this investigation (Materials 1, 1B, 2, 3, 4 and 7) were conducted in order to comment on technique usefulness for field quality assurance/quality control of field installed bonded anchor materials. Only products which 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 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. DSC testing has also 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 on site. 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.
3.2 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.

3.2.1 Concrete

A standard MassDOT 4000 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 of this thesis.

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 seven 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 require 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 time the embedment depth.

Approximately 45 specimens were cast per batch of concrete along with fifteen 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 [15] in a Forney FX 500 compression machine. Figure 3-3 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.

![Figure 3-3: (a) Sample Concrete Test Specimens during Initial Seven Day Cure; (b) Sample Test Specimens at 28 Day Cure](image_url)

3.2.2 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 rod.

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.

### 3.2.3 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 3.1. All products were stored in an air conditioned space in order to store the materials within the temperature range specified by the manufacturer.

### 3.3 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.
3.3.1 Conditioning Prior to Drilling

AASHTO TP-84 [4] requires all concrete specimens to stabilize at a temperature between 65°F and 85°F (18°C and 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 conditions as shown in Figure 3-4.

![Conditioning of Specimens Prior to Drilling](image)

Figure 3-4: Conditioning of Specimens Prior to Drilling

3.3.2 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 and a 0.89 inch (22.61 mm) diameter hole for Material 6. All test specimens were drilled in a downward direction, with the exception of later specimens that were used to evaluate the drilling and installation directions. These specimens required a horizontal drilling direction as will be later noted. For downward
drilling applications, a drilling stand was used to ensure verticality while drilling downward as shown in Figure 3-5(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 3-5(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.

Figure 3-5: (a) Downward Drilling of Specimens; (b) Horizontal Drilling of Specimens
3.3.3 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 and/or water jet, 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 3-2.
Table 3-2: Hole Cleaning Procedure for All Materials

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>HOLE CLEANING PROCEDURE</th>
</tr>
</thead>
</table>
| 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) |

3.3.4 Anchor Installation

All anchors were installed in accordance with the 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.
Therefore, an alternative testing method was adopted for this product. Several trial installations were conducted to ensure that consistent results were obtained.

3.3.4.1 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 according to the 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 so as to allow the anchor to reach the appropriate embedment depth and support vertical placement during curing as shown in Figure 3-6. The adhesive was delivered into the hole using the manufacturer recommended dispensing tool and mixing nozzle. The hole was filled to approximately two-thirds its depth prior to immediately inserting the anchor. The anchor was rotated in the 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.
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 its depth, as seen in Figure 3-7(a) and the anchor was immediately inserted into the filled hole, Figure 3-7(b). The anchor was installed such 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 so as to allow a steel confining plate to bear flat against the surface of the concrete for testing.
3.3.4.2 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 where 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 which 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 manufacturer’s recommendations. Therefore, this modified installation method was considered acceptable.

The hammer glass capsule can be seen in Figure 3-8. The anchor installation set-up for this capsule format adhesive can be seen in Figure 3-9.

Figure 3-8: Adhesive in Glass Capsule Format
Figure 3-9: Installation Set-Up for Adhesive in Glass Capsule Format; (a) Glass capsule inserted in drilled hole; (b) Wood placed over capsule; (c) Wood secured to test specimen

3.3.4.3 Adhesive in Cementitious Capsule Format

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 1 to 2 minutes, or until the material stopped releasing bubbles. The soaked capsule was then placed into the hole, Figure 3-10(b), and cut to the required length. The anchor rod was placed inside the capsule, Figure 3-10(c), and hammered into the hole using a 20 pound hammer, Figure 3-10(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.
Figure 3-10: (a) Cementitious capsule; (b) Insertion of capsule into clean hole; Insertion of Anchor Rod into capsule; (d) Hammering of anchor into hole

3.4 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 required by AASHTO TP-84 [4]. The chamber was powered by commercial heaters which were automated to maintain the internal specimen temperature between 110°F (43°C) and 120°F (49°C). Figure 3-11(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, seen in Figure 3-11(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.

![Figure 3-11: Environmental Conditioning Chambers](image)

3.5 Test Components

3.5.1 Short-Term Test Apparatus

The short-term test apparatus conforms to the requirements of ASTM E488 [12] and NCHRP Report 757 [1]. A maximum load 40.00 kips (178.00 kN) was assumed when designing the test apparatus. The short-test assembeled inside the testing chamber can be seen in Figure 3-12. Plans for the test apparatus can be seen in Figure 3-13.
First, a PTFE (Polytetrafluoroethylene) 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 are distanced so as to not interfere with the anchor as it fails. 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 secured with a heavy hex nut and washer on both ends. The loading rod was carefully aligned so as to be positioned directly above the anchor rod and reduce eccentricities during loading, although it is not possible to be exact with the test apparatus and led to some visual non-alignment under full load.
Figure 3-13: Short-Term Test Apparatus Section A-A
Figure 3-14: Short-Term Apparatus Section B-B
3.5.2 Long-Term Test Apparatus

Long-term tests conform to AASHTO TP-84 [4] and NCHRP 757 [1]. Three long-term test setups were on loan from the University of Florida and were used to conduct trial tests. An additional 20 test set ups were manufactured to complete the long-term testing for this project. The long-term setup assembled inside of the chamber can be seen in Figure 3-15. Plans for the apparatus can be seen in Figure 3-17 and Figure 3-18.

![Diagram of Long-Term Test Apparatus]

**Figure 3-15: Long-Term Test Apparatus**

The anchor rod passes 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 is placed to that includes a top and bottom plate that contain a set of Standard Car Truck Company D2 inner and D2 outer springs used to maintain long-term load. The small spring (D2 Inner) fits inside the large spring (D2 Outer) when used in parallel and are wound in opposite directions to avoid torsion during loading. The nominal properties of the springs as are as follows: large springs are 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 are 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/in (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 spring calibration is shown in Figure 3-16. It was found that the springs had a stiffness of 12.56 kip/in (22.00 kN/cm). The springs are housed in a two piece spring retainer unit. The loading rod is secured to the top of the non-rigid coupler with an ASTM A194 2H heavy hex nut and passes 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 3-16: Example Spring Calibration
Figure 3-17: Long-Term Test Apparatus Section A-A
LONG-TERM TEST SETUP

(SECTION B-B)

Figure 3-18: Long-Term Test Apparatus Section B-B
3.5.3 Loading Rod

The loading rod was designed to have a greater capacity 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)).

3.5.4 Non-Rigid Coupler

A steel non-rigid coupler is used to connect the anchor rod to the loading rod. This coupler has a 0.69 inch (17.5 mm) diameter hole at the bottom where the anchor rod passes through and a 1.00 in (25.40 mm) diameter hole at the top where the loading rod passes through. Both the anchor rod and the loading rod are 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 is 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 is 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.

3.5.5 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 in (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 is done to allow for a more consistent measurement of bond failure.
3.5.6 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 polytetrafluoroethylene (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.

3.5.7 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.

3.6 Test Procedure

The test procedures of AASHTO TP-84 [4] consist of two types of tests, short-term and long-term. Short-term tests were initially conducted to determine the MSL of the system and long-term tests are subsequently conducted at various percentages of MSL. In accordance with AASHTO TP-84 [4], all tests must be confined tests performed at the environmental conditions of 110°F-120°F (43°C- 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.

3.6.1 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 was 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) were 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 vs. 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.

3.6.2 Long-Term Test Procedure

To begin a long-term test per AASHTO TP-84 [4], a tensile load not exceeding of 5% of MSL is initially applied in order to bring all members into full bearing. The load was subsequently increased at constant load rate which allows the desired long-term load to be reached within 2 ± 1 minutes. Anchors were tested at two different load levels, 60%-70% MSL and 70%-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 (percent 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 secures 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 is reported as the load on the anchor, though if losses were excessive the spring was re-compressed per the above 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].

3.7 Instrumentation

3.7.1 Temperature and Relative Humidity

Air temperature and relative humidity inside of 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 take 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 of the allowable environmental condition temperatures, the time was discounted from the total testing time reported for the specimen.

3.7.1 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 can be seen in Figure 3-19. A thin glass slide was placed underneath each transducer prior to testing to provide a smooth surface for the LVDT to rest on.

![Figure 3-19: Linear Potentiometers Attached to Steel Bar](image)
3.7.2 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 percent MSL values of each anchor at failure.

3.8 Data Management

3.8.1 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 timestamp, chamber temperature and relative humidity, concrete temperature, load (for static tests only) and anchor displacement.
3.8.2 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 test, 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 re-started. When this occurred sampling temporarily proceeded at a higher rate than that listed above.
CHAPTER 4
ANCHOR PULLOUT TEST RESULTS

This chapter includes the results of the anchor pullout tests conducted at UMass. Only those specimens which failed through the pullout of the anchor have been reported.

4.1 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**

\[ M - D_1/H_1 - D_2/H_2 - \# \]

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 - #

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

4.2 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 vs. Displacement graphs for the short-term tests of each material are presented in Figure 4-1 to Figure 4-9, all of which presented a bond failure.

4.2.1 Material 1

Material 1, an epoxy adhesive with amine hardener, presented consistent short-term results seen in Figure 4-1. An MSL of 19.17 kip (85.27 kN) and coefficient of variation (COV) of 5% was 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. Although data for theses initial
short-term tests were not collected, they provide additional confidence in the reliability of this material’s short-term performance.

Figure 4-1: Material 1 Short-Term Tests: Load vs. Displacement

*Only load reading recorded. Displacement data point based on average displacement results.
4.2.2 Material 1B

Material 1B, an epoxy adhesive with amine hardener, presented consistent short-term results seen in Figure 4-2. An MSL of 20.10 kip (89.41 kN) and COV of 7% was 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 4-2: Material 1B Short-Term Tests: Load vs. Displacement](image)
4.2.3 Material 2

Material 2, an epoxy adhesive with amine hardener, presented consistent short-term results seen in Figure 4-3. An MSL of 18.33 kip (81.54 kN) and COV of 5% was 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 4-3: Material 2 Short-Term Tests: Load vs. Displacement
4.2.4 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 can be seen in Figure 4-4. An MSL of 16.45 kip (73.17 kN) and COV of 14% was 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 4-5.
Figure 4-4: Material 3 Short-Term Tests: Load vs. Displacement

Figure 4-5: Material 3 Adhesive Change in Color during Installation; (a) Bright adhesive color after disposing of first strokes as indicated by manufacturer; (b) Duller shade of adhesive with color streaks during installation
4.2.5 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 seen in Figure 4-6. An MSL of 10.65 kip (47.37 kN) and COV of 24% was 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 strength. In on-site 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 also indicated the wide variability of this materials which was shown by the remaining four tests.

Due to electrical problems with the data acquisition system encountered during the testing 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 test 04-S-03 and 04-S-05 represent the lapses in time during which load readings were not available.
Figure 4-6: Material 4 Short-Term Tests: Load vs. Displacement

*Excluded from results.
4.2.6  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 can be seen in Figure 4-7. An MSL of 6.76 kip (30.07 kN) and COV of 31% was 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 4-7: Material 5 Short-Term Tests: Load vs. Displacement

4.2.7  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 test 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 can be seen in Figure 4-8.

Test Series 1 of 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 110°F-120°F (43°F-49°F) inside the testing chamber. Under these conditions, an MSL of 3.88 kip (17.26 kN) and COV of 43% was 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 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 110°F-120°F (43°F-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 with an increased cure time and embedment depth.

Test Series 3 of 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 re-testing 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 short-term tests were 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 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 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 confirms that the material can be used with threaded rod 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.

![Graph showing load vs. displacement for Material 6 short-term tests](image)

**Figure 4-8: Material 6 Short-Term Tests: Load vs. Displacement**

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Statistical Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Series 1</strong></td>
<td>MSL: 3.88 kip&lt;br&gt;Std. Dev: 1.68kip&lt;br&gt;COV: 43%</td>
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<td><strong>Test Series 2</strong></td>
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<tr>
<td><strong>Test Series 3</strong></td>
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<td><strong>Test Series 4</strong></td>
<td>MSL: 9.43 kip&lt;br&gt;Std. Dev: 2.34kip&lt;br&gt;COV: 25%</td>
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4.2.8 Material 7

Material 7, a urethane methacrylate resin with dibenzoylperoxide hardener, presented consistent short-term results seen in Figure 4-9. An MSL of 17.42 kip (77.49 kN) and COV of 4% was 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 4-9: Material 7 Short-Term Tests: Load vs. Displacement](image)

4.2.9 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 4-1. This analysis includes the MSL, standard deviation, coefficient of variation and \( \alpha_{COV} \) adjustment factor for those materials not meeting the requirements on coefficient of variation stipulated in Chapter 10 of ACI 355.4 [2]. Section 10.4.2 of this standard prescribes a maximum limit of 15% on the coefficient of variation for short-term
reference tests. If a tests series exceeds this allowable threshold, a reduction of $\alpha_{COV}$ is taken on the bond stress value. This reduction factor is calculated in accordance with Equation 6.

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

Where:

$v_{test, x}$ : Sample coefficient of variation for test series $x$ equal to the mean divided by the sample standard deviation, percent

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

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>MSL (kip)</th>
<th>STD. DEV. (kip)</th>
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<th>$\alpha_{COV}$</th>
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</table>

*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 coefficient of variation (Material 1B COV = 7%; Material 1 COV = 5%, Material 2 COV = 5%, Material 7=4%) and did not require a reduction factor ($\alpha_{COV}$) 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 Material 1B, 1 and 2 during short-term testing, the COV is less than the maximum limit of 15% prescribed by ACI 355.4 [2], 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 that 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 [2]. For cases which exceed this threshold, a reduction must be taken on the
bond stress in the form of $\alpha_{COV}$. 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. The short-term testing of Material 6 showed a significantly larger deformation of the anchor as it approached its final capacity (Figure 5 through 8). These anchors deformed from 0.40 inches (10.16 mm) to 1.00 inch (25.4 mm) at failure, values which 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, it is not specified when the results from a test may be omitted from reporting. Therefore, it was up to the research team 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.

4.3 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 vs. Time-to-failure (SvTTF) graph and a linear trend line is drawn through each data point. The SvTTF graph created of each material can be found in Figure 4-10 to Figure 4-15. In these plots, two different trendlines 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 [1]. Each trend line is projected to a design life of 100 years.

Table 4-2 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 4-2: Summary of AASHTO TP-84 Tests

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>TEST TYPE</th>
<th>TP-84 REQUIRED TESTS</th>
<th>COMPLETED TESTS</th>
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<tr>
<td>1</td>
<td>Short-Term</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Long-Term (60%-70% MSL)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Long-Term (70%-80% MSL)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Short-Term</td>
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<td>5</td>
</tr>
<tr>
<td></td>
<td>Long-Term (60%-70% MSL)</td>
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<td>5</td>
</tr>
<tr>
<td></td>
<td>Long-Term (70%-80% MSL)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
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<td>5</td>
</tr>
<tr>
<td></td>
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<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Long-Term (70%-80% MSL)</td>
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<td>5</td>
</tr>
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<td>5</td>
</tr>
<tr>
<td></td>
<td>Long-Term (70%-80% MSL)</td>
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<td>2&lt;sup&gt;1&lt;/sup&gt;</td>
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<tr>
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<td>8&lt;sup&gt;2&lt;/sup&gt;</td>
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<tr>
<td></td>
<td>Long-Term (70%-80% MSL)</td>
<td>5</td>
<td>0&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>1</sup>No further testing was recommended due to poor material performance

<sup>2</sup>Long-Term tests were loaded to a displacement of 0.10 inch (2.54 mm)
4.3.1 Material 1

The SvTTF graph of Material 1 can be seen in Figure 4-10. When short-term and long-term data are included in the trendline, 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 trendline, the 50 year and 100 year capacities of the material are 57% MSL and 56% MSL, respectively.

Figure 4-10: Material 1 SvTTF Graph
4.3.2 Material 2

The SvTTF graph of Material 2 can be seen in Figure 4-11. When short-term and long-term data are included in the trendline, 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 trendline, the 50 year and 100 year capacities of the material are 51% MSL and 49% MSL, respectively.

Figure 4-11: Material 2 SvTTF Graph
4.3.3 Material 3

The SvTTF graph of Material 3 can be seen in Figure 4-12. When short-term and long-term data are included in the trendline, 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 trendline, the 50 year and 100 year capacities of the material are 59% MSL and 58% MSL, respectively. Tests loaded outside of the allowable load range of 60%-80% MSL were not included in the trendlines of the SvTTF graph.

As noted previously, Material 3 presented higher variability in short-term test results than Materials 1 and 2. This led to flatter slope in the trendline 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, 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 which showed significantly more inconsistent short-term capacities. When initiating long-term tests, it was difficult to predict the actual percent 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 4-12 is an example of an adhesive with scatter in long-term

data due to a high coefficient of variation in short-term tests that the authors feel is beyond the limit for potential application of the test method.

Figure 4-12: Material 3 SvTTF Graph
4.3.4 Material 4

The SvTTF graph of Material 4 can be seen in Figure 4-13. When short-term and long-term data are included in the trendline, 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 trendline, the 50 year and 100 year capacities of the material are 33% MSL and 31% MSL, respectively. Due to the poor results, long-term testing of this material was ended after the completion of seven long-term tests.

Figure 4-13: Material 4 SvTTF Graph
4.3.5 Material 5

The SvTTF graph of Material 5 can be seen in Figure 4-14. Due to the wide scatter of in 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 exhibited and even larger COV in short-term testing (Material 4 COV = 24%, Material 5 COV = 31%).

Figure 4-14: Material 5 SvTTF Graph
4.3.6 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 percent 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 at 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 can be seen in Figure 4-15. When short-term and long-term data are included in the trendline, 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 trendline, 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 4-8 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 percent 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 described in Section 0. 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 4-8) 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 6 that large variations in results of short-term testing can result in an unrealistic trend line. The trendline 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 percent 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 4-15: Material 6 SvTTF Graph
4.3.7 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 required a series of short-term and long-term tests in order to predict the acceptable load capacity of an adhesive anchoring system under a specific long-term load (percent 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 COV in short-term testing leading to wide variability in results under long-term load since the percent of MSL does not correlate well with the percent of the individual anchor short-term capacity. Similar results can be seen in SvTTF graphs brought forth in NCHRP Report 757 [1] for the testing of adhesive A in a Standard DOT mix (see Figure 67 of the 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 trendlines. 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 for results from the 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 [2]. 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
3-1, the long-term time to failure initiates after initial loading. However, SvTTF plots
reported in NCHRP Reports [3], [1] 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 2 to 3 minute short-term test duration,
though it was found that the difference is minimal for well performing materials. Figure
4-16 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
to from 48% MSL and 46% MSL to 50% MSL and 48% MSL, respectively.
Figure 4-16: Material 1 Modified SvTTF Graph: Short-Term Tests Plotted at Time Zero

The SvTTF graphs of Material 1 (Figure 4-10) and Material 2 (Figure 4-11) 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 [1] (see Figures 73 and 74 of the 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 [1] for the testing of Adhesive B and Adhesive C. Three long-term tests were excluded from the SvTTF plot for Adhesive B and 5 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 included 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 [1], with each trendline is projected to a design life of 100 years. The results showed that the inclusion of the short-term test results in the trendline of material led to a more conservative load prediction at a design life of 100 years and is recommended by the authors.

4.4 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 Materials 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 4-17(a) and Figure 4-17(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 vs. Displacement graphs of each test series used to calculate the short-term capacity of each anchor be found in Figure 4-18 for Material 1B and Figure 4-18: Material 1B, Installation Direction: Load vs. Displacement for Material 2. A summary of the average short-term load capacity of the materials tested under various drilling and installation directions can be seen in Figure 4-20. Further details regarding the specifications of each test can be found in Table 4-3.

Figure 4-17: (a) Downward Orientation; (b) Horizontal Orientation
4.4.1 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 this material 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 this material 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 be related to the fact that downward drilling produces a hole which 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 aid 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 was 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 4-18: Material 1B, Installation Direction: Load vs. Displacement

Figure 4-19: Material 2 Installation Direction: Load vs. Displacement
Figure 4-20: Summary of Installation Direction Results
<table>
<thead>
<tr>
<th>Test Name</th>
<th>Load (kip)</th>
<th>Average Load (kip)</th>
<th>Standard Deviation</th>
<th>CoV</th>
<th>Material 1B (Horizontal)</th>
<th>Material 2 (Downward)</th>
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<tr>
<td>02-H-H-01</td>
<td>20.45</td>
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<td>19.82</td>
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<td>0.20</td>
<td>0.01</td>
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<td>DOWNWARD</td>
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<td>0.20</td>
<td>0.01</td>
<td>HORIZONTAL</td>
<td>DOWNWAD</td>
</tr>
<tr>
<td>1B-D-H-08</td>
<td>16.12</td>
<td>17.94</td>
<td>2.25</td>
<td>0.13</td>
<td>HORIZONTAL</td>
<td>DOWNWAD</td>
</tr>
<tr>
<td>1B-D-D-09</td>
<td>18.74</td>
<td>18.43</td>
<td>0.33</td>
<td>0.01</td>
<td>HORIZONTAL</td>
<td>DOWNWAD</td>
</tr>
<tr>
<td>1B-D-D-10</td>
<td>19.20</td>
<td>19.43</td>
<td>0.28</td>
<td>0.01</td>
<td>HORIZONTAL</td>
<td>DOWNWAD</td>
</tr>
</tbody>
</table>

Table 4-3: Installation Direction Testing Program
4.5 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 can be found in Figure 4-21. The test types named in this figure are defined per the nomenclature defined in Section 5.1 for extreme in-service temperature tests. Further detail regarding each test can be found in Table 4-4 for Material 1B, Table 4-5 for Material 7 and Table 4-6 for Material 2.

4.5.1 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 references 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-80°F (21°C-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 the tested at ambient conditions of 70°F-80°F (21°C-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-120°F (43°C-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 maintained 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 4-21: Summary of Extreme In-Service Temperature Test Results
<table>
<thead>
<tr>
<th>TEST NAME</th>
<th>LOAD (kip)</th>
<th>STD. DEV. (kip)</th>
<th>COV</th>
<th>MIX</th>
<th>INSTALLATION</th>
<th>TESTING</th>
<th>TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B-30-30-A-01</td>
<td>21.02</td>
<td>5</td>
<td>8-Jul-16</td>
<td>12-Jul-16</td>
<td>30°F</td>
<td>30°F</td>
<td>1B-30-30-A-01</td>
</tr>
<tr>
<td>1B-30-30-A-02</td>
<td>16.33</td>
<td>6</td>
<td>8-Jul-16</td>
<td>12-Jul-16</td>
<td>30°F</td>
<td>70°F - 80°F</td>
<td>1B-30-A-A-01</td>
</tr>
<tr>
<td>1B-30-30-H-01</td>
<td>17.92</td>
<td>5</td>
<td>8-Jul-16</td>
<td>12-Jul-16</td>
<td>30°F</td>
<td>30°F</td>
<td>1B-30-30-H-01</td>
</tr>
<tr>
<td>1B-30-30-H-02</td>
<td>17.12</td>
<td>5</td>
<td>8-Jul-16</td>
<td>12-Jul-16</td>
<td>30°F</td>
<td>30°F</td>
<td>1B-30-30-H-02</td>
</tr>
<tr>
<td>1B-30-30-H-03</td>
<td>18.10</td>
<td>5</td>
<td>8-Jul-16</td>
<td>12-Jul-16</td>
<td>30°F</td>
<td>30°F</td>
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<tr>
<td>1B-30-30-H-01</td>
<td>17.92</td>
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<td>30°F</td>
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<td>30°F</td>
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<tr>
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<td>5</td>
<td>20-Oct-16</td>
<td>24-Oct-16</td>
<td>30°F</td>
<td>30°F</td>
<td>1B-30-30-H-03</td>
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<tr>
<td>1B-30-30-30-01</td>
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<tr>
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<td>30°F</td>
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<td>30°F</td>
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<td>11.77</td>
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<td>25°F</td>
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</tr>
<tr>
<td>1B-25-25-0-03</td>
<td>11.02</td>
<td>6</td>
<td>10-Nov-16</td>
<td>14-Nov-16</td>
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<td>25°F</td>
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</tr>
<tr>
<td>1B-20-20-A-01</td>
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<td>15-Jul-06</td>
<td>19-Jul-16</td>
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<td>20°F</td>
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<tr>
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<td>20°F</td>
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</tr>
<tr>
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<td>20°F</td>
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<td>25-Jul-16</td>
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<td>20°F</td>
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</tr>
<tr>
<td>1B-20-20-H-03</td>
<td>17.93</td>
<td>5</td>
<td>21-Jul-16</td>
<td>25-Jul-16</td>
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<td>20°F</td>
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</tr>
<tr>
<td>1B-20-20-20-01</td>
<td>19.90</td>
<td>6</td>
<td>18-Aug-16</td>
<td>22-Aug-16</td>
<td>20°F</td>
<td>20°F</td>
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<td>25-Aug-16</td>
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<td>20°F</td>
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<td>1B-20-20-20-03</td>
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<td>6</td>
<td>25-Aug-16</td>
<td>29-Aug-16</td>
<td>20°F</td>
<td>20°F</td>
<td>1B-20-20-20-03</td>
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</table>

**Courtesy of Rachel Wang. Further information on results will be published in future Masters thesis.**

Table 4-4: Material 1B, Extreme In-Service Temperature Test Results
<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>INSTALLATION TEMP.</th>
<th>CURING TEMP.</th>
<th>TEST NAME</th>
<th>LOAD (kip)</th>
<th>AVERAGE LOAD (kip)</th>
<th>STD. DEVI.</th>
<th>COV</th>
<th>LOAD TEMP.</th>
<th>TEST NAME</th>
<th>INSTALLATION TEMP.</th>
<th>CURING TEMP.</th>
<th>LOAD TEMP.</th>
<th>AVERAGE LOAD (kip)</th>
<th>STD. DEVI.</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
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<td>20°F</td>
<td>110°F - 120°F</td>
<td>0°F</td>
<td>20.55</td>
<td>0.72</td>
<td>0.03</td>
<td>0°F</td>
<td>18.56</td>
<td>1.03</td>
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<td>0°F</td>
<td>17.90</td>
<td>1.34</td>
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</tr>
<tr>
<td>7</td>
<td>20°F</td>
<td>20°F</td>
<td>110°F - 120°F</td>
<td>0°F</td>
<td>21.13</td>
<td>0.09</td>
<td>0.00</td>
<td>0°F</td>
<td>17.18</td>
<td>1.18</td>
<td>0.05</td>
<td>0°F</td>
<td>17.59</td>
<td>1.67</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*Courtesy of Rachel Wang. Further information on results will be published in future Masters thesis.*
<table>
<thead>
<tr>
<th>Test Name</th>
<th>Load (kip)</th>
<th>Average Load (kip)</th>
<th>STD. Dev.</th>
<th>CoV</th>
<th>Mix</th>
<th>ASTM</th>
<th>Material</th>
<th>Extreme Service Temperature Test Results</th>
</tr>
</thead>
<tbody>
<tr>
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<td>19.63</td>
<td>20.01</td>
<td>0.40</td>
<td>0.02</td>
<td>9</td>
<td>25°F</td>
<td>110°F - 120°F</td>
<td></td>
</tr>
<tr>
<td><strong>02-H-H-H-02</strong></td>
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<td>20.01</td>
<td>0.41</td>
<td>0.04</td>
<td>9</td>
<td>25°F</td>
<td>110°F - 120°F</td>
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</tr>
<tr>
<td><strong>02-25-25-0-01</strong></td>
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<td>10.02</td>
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<td></td>
</tr>
<tr>
<td><strong>02-25-25-0-02</strong></td>
<td>10.82</td>
<td>10.47</td>
<td>0.41</td>
<td>0.04</td>
<td>9</td>
<td>0°F</td>
<td>25°F</td>
<td></td>
</tr>
<tr>
<td><strong>02-25-25-0-03</strong></td>
<td>10.56</td>
<td>10.02</td>
<td>0.40</td>
<td>0.04</td>
<td>9</td>
<td>0°F</td>
<td>25°F</td>
<td></td>
</tr>
</tbody>
</table>

*Courtesy of Rachel Wang. Further information on results will be published in future Masters thesis.*

Table 4-6: Material 2, Extreme In-Service Temperature Test Results.
CHAPTER 5
POLYMER CHARACTERIZATION TESTS

This chapter summarizes the results and findings of the polymer characterization testing of six adhesive products through Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (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/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/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.
5.1 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 [16].

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 amongst the most frequently used curing agents [17]. 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 which 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 [18]. Adhesive anchoring products which 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 which 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).
5.2 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 [19]. 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 1-2 microns [19]. 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 [20].

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 non-stick 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 non-stick 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 non-stick 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 5-1.

![Figure 5-1: (a) Delivery of adhesive onto non-stick wax paper; (b) Use of steel finishing trowel to prepare disk](image-url)
Figure 5-2 shows the completed sample disks prior to final cure and conditioning. Samples for DSC testing were also prepared in accordance with this method.

![Completed Sample Disks](image)

**Figure 5-2: 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 which 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.

### 5.3 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 also cured at a constant temperature of 50°F, 104°F and 500°F for three days. Figure 5-3 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.

![Images of curing samples at different temperatures](image)

**Figure 5-3:** (a) Curing of Samples at 50°F; (b) Curing of Samples at 74°F; (c) Curing of Samples at 104°F

### 5.4 Testing Procedure

#### 5.4.1 FTIR

After a sample completed its designated cure time, an FTIR test was completed at the University of Massachusetts Amherst Polymer Science and Engineering Department using a Perkins Elmer Spectrum 100 instrument. Each test was conducted between a wavenumber range of 4000 cm\(^{-1}\) and 650 cm\(^{-1}\) for a duration of 4 scans and a resolution of 4.00. 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 which 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 is 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 is 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 [19]. 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 5-4. 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 exceed values of at least 80% transmittance.

Figure 5-4: FTIR Test of Epoxy Sample
5.4.2 DSC

DSC testing was conducted for all materials after completion of a seven day cure at 74F. Each test was completed at the University of Massachusetts Amherst Polymer Science and Engineering Department using a TA Instruments Q200 Series instrument. All tests and results were plotted on a Heat Flow vs. Temperature graph.

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

- Step 1: Heat to 250 °C at a rate of 10 °C/min
- Step 2: Cool to 0 °C at a rate of 10 °C/min
- Step 3: Heat to 250 °C at a rate of 10 °C/min

![Figure 5-5: (a) Preparation of sample for DSC testing in pressing device; (b) DSC Testing Instrument](image)
5.5 Polymer Characterization Test Results

This section presents the FTIR test results conducted at the University of Massachusetts 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 4000 cm\(^{-1}\) and 650 cm\(^{-1}\). Articles such as, [16] and [21], regarding the study of epoxy materials with FTIR suggest that spectral comparisons of data are more significant below a wavenumber of 2000 cm\(^{-1}\), also known as the fingerprint region. For the FTIR results presented in Figure 5-6 to Figure 5-17, all data of the spectra has been provided for completeness, however, the region above a wavenumber of 2000 cm\(^{-1}\) has been shaded in order to highlight the fingerprint region.

5.5.1 FTIR Testing Results with Varying Temperature

FTIR testing was conducted for Material 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 5-6 to Figure 5-11.

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 5-6: Material 1 FTIR Results with Varying Temperatures

Figure 5-7: Material 1B FTIR Results with Varying Temperatures
Figure 5-8: Material 2 FTIR Results with Varying Temperatures

Figure 5-9: Material 3 FTIR Results with Varying Cure Temperatures
Figure 5-10: Material 4 FTIR Results with Varying Cure Times

Figure 5-11: Material 7 FTIR Results with Varying Temperatures
5.5.2 FTIR Test Results with Varying Cure Times

FTIR testing was conducted for Material 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 graphs of each material. The results of FTIR tests with varying cure times are shown in Figure 5-12 to Figure 5-17.

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 seven 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 work day.
Figure 5-12: Material 1 FTIR Results with Varying Cure Times

Figure 5-13: Material 1B FTIR Results with Varying Cure Times
Figure 5-14: Material 2 FTIR Results with Varying Cure Times

Figure 5-15: Material 3 FTIR Results with Cure Varying Times
Figure 5-16: Material 4 FTIR Results with Varying Cure Times

Figure 5-17: Material 7 FTIR Results with Varying Cure Times
5.5.3 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 can be seen in Table 5-1. The Heat Flow vs. Temperature graph for each material can be found in Figure 5-18 to Figure 5-19.

Table 5-1: Glass Transition Temperatures Recorded from DSC Tests

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>Tg (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>131</td>
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<tr>
<td>1B</td>
<td>122</td>
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<tr>
<td>2</td>
<td>133</td>
</tr>
<tr>
<td>3</td>
<td>131</td>
</tr>
<tr>
<td>4</td>
<td>113</td>
</tr>
<tr>
<td>7</td>
<td>113</td>
</tr>
</tbody>
</table>
Figure 5-18: Material 1, DSC Test Results

Figure 5-19: Material 1B, DSC Test Result
Figure 5-20: Material 2, DSC Test Result

Figure 5-21: Material 3, DSC Test Result
Figure 5-22: Material 4, DSC Test Result

Figure 5-23: Material 7, DSC Test Result
5.6 Polymer Characterization Tests Analysis of Results

5.6.1 FTIR Testing

In other studies regarding the analysis of cured epoxy adhesives, such as [16] and [21], 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 5-24 shows the FTIR results of Material 1 directly rationed to equal a transmittance of 68% at a wavenumber of 1027 cm\(^{-1}\). This peak was chosen as it was the greatest peak in the fingerprint region prior to normalizing data (Figure 5-6). Next, all spectra were shifted so as to have the same initial transmittance at wavenumber 2000 cm\(^{-1}\), as shown in Figure 5-25. 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 5-24: Material 1 FTIR Results with Varying Cure Temperatures, Rationed Spectra

Figure 5-25: Normalized Material 1 FTIR Results with Varying Cure Temperatures
5.6.2 DSC Testing

It can be observed from the glass transition temperatures reported in Table 5-1 that Material 7 and Material 4 had lowest the recorded glass transition temperature during the first heating cycle, 113°F. This temperature is within the testing temperature range of 110°F-120°F at which short-term reference tests were conducted. As was reported in Chapter 5, Section 5.1.1 of this report, Material 4 exhibited poor short-term performance with an MSL of only 10.65 kip and a coefficient of variation 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 program 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 a supplemental tool in analyzing the performance of adhesive materials.
CHAPTER 6
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 on the use of anchoring systems to MassDOT. 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/quality control of field installed bonded anchor materials.
### 6.1 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 over-estimate 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 materials 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 trendlines 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. Specifically, specimens which fail while being loaded to their % MSL for long-term testing and specimens which 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 has 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.

- Material 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.
6.2 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/quality control technique for post-installed adhesive anchoring systems and DSC testing to provide additional information regarding a material’s thermal properties.

- FTIR is expected to be a useful tool for quality assurance/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-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 teams 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.
### APPENDIX:

**CONCRETE BATCH SPECIFICATIONS**

Table A-1: Concrete Batch 1 Specifications

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<tbody>
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<tr>
<td>Quantity:</td>
<td>1.5 yd³</td>
</tr>
<tr>
<td>Water added:</td>
<td>12 gal</td>
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</tbody>
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#### Mix Specifications

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<tr>
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<th>3/4&quot;MIX</th>
<th>SAND</th>
<th>SLAG</th>
<th>CEM - 1</th>
<th>WATER</th>
<th>AIR 250</th>
<th>100 XR</th>
<th>MR-WR</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIX:</td>
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<td>1205</td>
<td>170</td>
<td>510</td>
<td>34.5</td>
<td>3.5</td>
<td>-</td>
<td>34</td>
</tr>
<tr>
<td>TRM:</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
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<td>-</td>
</tr>
</tbody>
</table>

#### Concrete Properties

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

*Additional water was included 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**

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<th>WATER</th>
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<td>170</td>
<td>510</td>
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<td>3.5</td>
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<td>-</td>
<td>-</td>
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</tbody>
</table>

**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

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<td>Quantity:</td>
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## Mix Specifications

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<th>WATER</th>
<th>AIR 250</th>
<th>100 XR</th>
<th>MR-WR</th>
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<td>1100</td>
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<td>1010</td>
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<td>M:</td>
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## Concrete Properties

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<td>7 in</td>
</tr>
<tr>
<td>Air Content:</td>
<td>7 %</td>
</tr>
<tr>
<td>Unit Weight:</td>
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<tr>
<td>28-Day Compressive Strength:</td>
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<tr>
<td>141-Day Compressive Strength:</td>
<td>5228 psi</td>
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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 |

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<th>SLAG</th>
<th>CEM - 1</th>
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<td>170</td>
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<td>Lb</td>
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<td>Oz</td>
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<tr>
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<td>28-Day Compressive Strength:</td>
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<td>220-Day Compressive Strength:</td>
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<td>Water added:</td>
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### Mix Specifications

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<th>MR-WR</th>
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<td>0</td>
</tr>
<tr>
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<td>0</td>
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<td>0</td>
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<td>TGT:</td>
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<td>43</td>
<td>6</td>
<td>-</td>
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<td>UNIT:</td>
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<td>Lb</td>
<td>Lb</td>
<td>Lb</td>
<td>Gl</td>
<td>Oz</td>
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<td>980</td>
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<td>-</td>
<td>69</td>
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<td>M:</td>
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</table>

### 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**

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<td>Water added:</td>
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</tr>
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<td><strong>SLAG</strong></td>
<td>170</td>
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<tr>
<td><strong>CEM-1</strong></td>
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<td><strong>WATER</strong></td>
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<td><strong>MIX</strong></td>
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<tr>
<td><strong>TRM</strong></td>
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<tr>
<td><strong>MST</strong></td>
<td>3.3 %M</td>
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<td><strong>TGT</strong></td>
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<tr>
<td><strong>UNIT</strong></td>
<td>1LB</td>
</tr>
<tr>
<td><strong>I:</strong></td>
<td>2540</td>
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<tr>
<td><strong>M</strong>:</td>
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<table>
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<tr>
<th><strong>Concrete Properties</strong></th>
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<td>Slump:</td>
<td>4 in</td>
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<tr>
<td>Air Content:</td>
<td>5.4 %</td>
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<tr>
<td>Unit Weight:</td>
<td>146.4 lb/ft³</td>
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<tr>
<td>28-Day Compressive Strength:</td>
<td>5836 psi</td>
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REFERENCES


[7] ACI 318 (2014), Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (318R-14), Farmington Hills, MI: American Concrete Institute.


