Creep Behaviour of Post-Installed Adhesive Anchors under Various Sustained Load Levels and Environmental Exposures

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

This thesis describes an experimental study on the long-term creep behaviour of adhesive anchors under sustained tensile loads in combination with different environmental exposures. A comprehensive background and literature review is presented, focusing on various bond stress models for adhesive anchors, factors affecting their bond behavior, and an overview of available testing standards and evaluation criteria. The experimental program comprises of 82 test specimens. The specimens consist of a cylindrical shaped concrete block of 300 mm (12 inch) in diameter and 200mm (8 inch) in depth, with 15M (No. 5) deformed steel bar post-installed to an embedment depth of six times the bar diameter or 125mm (5 inch). Three types of adhesives were used for anchor installation: Type-A a fast setting two component methyl methacrylate adhesive, Type-B a fast setting two part epoxy adhesive, and Type-C a standard set two part epoxy adhesive.

The study is divided into four phases. Phase I consists of 27 static pullout tests to determine the yield strength (f_y) and the maximum tensile capacity of each anchor system under three exposure conditions. Phase II and Phase III consist of 36 specimens tested under sustained load levels of 40%f_y (32kN) and 60%f_y (48kN) under normal laboratory conditions (room temperature) and moisture exposure, respectively. Phase IV consists of 9 specimens tested under sustained load with a load level of 40%f_y (32kN) with exposure to freeze/thaw cycling. All sustained load tests lasted for a period of at least 90 days.

The results of the static pullout testing showed that specimens with epoxy based adhesive exhibited stronger bond strength, forcing the anchor to fail by rupture prior to bond failure. Under sustained load testing, specimens with standard set epoxy based adhesive showed insignificant creep displacement under room conditions, however, when exposed to moisture noticeable creep displacements were recorded. Specimens with both fast setting epoxy and methyl methacrylate based adhesives showed higher creep displacements under environmental exposure (moisture, freeze/thaw) versus those kept at room temperature.

Displacement data from creep testing were analysed and projected over a service life span of 50 years for room temperature exposure, and for 10 years for moisture and freeze/thaw exposures. Based on the analysis results, the service life of different anchor systems was estimated. An integrated qualification and testing protocol is proposed for the creep behavior of adhesive anchors under various environmental exposures.

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Dedication

To my wife, Mona, and to our five months old beautiful daughter, Maya

To my parents, thank you for everything.

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Notation

a,b = constants evaluated by regression analysis.

d= anchor diameter (mm).

d_o= drilled hole diameter (mm).

h_c= height of concrete cone (mm).

h_{ef}= effective anchor embedment depth (mm).

f_c= concrete compressive capacity (MPa).

K = a statistically determined coefficient based on the 5 percent fractile, number of tests, and confidence to be used for design.

N_{adh} = tension load corresponding to loss of adhesion between the adhesive and the concrete, (kN).

N_u= ultimate predicted strength of anchor (kN).

P_y= load corresponding to yielding of the anchor (kN).

P_u= ultimate tensile load capacity from static pullout test.

t = time corresponding to total recorded displacement (hours).

COV= coefficient of variation.

Δ_{lim} = limiting displacement corresponding to $N_{adh.}$

$\Delta_{t=0}$ = initial displacement recorded under sustained load (mm).

λ= Stiffness characteristic of the adhesive anchor system (mm^{-1}).

τ= bond stress (MPa).

τ'= design value for uniform bond stress (MPa).

τ_o= bond stress evaluated at hole diameter (MPa).

ψ_c= modification factor for bond area.

$\Delta(t)$ = total displacement recorded in the test at time t (mm).

Chapter 1

Introduction

1.1 Problem Description

Adhesive-bonded anchors are increasingly used as structural fasteners for connections to hardened concrete. However, because of their reliance on chemical and mechanical bond, adhesive anchors are uniquely susceptible to a number of potentially adverse factors. The long-term performance over the expected service life of such anchors has been a focus of the research community over the past couple of years.

Curing time of adhesive products is rapid, which makes them ideal for situations requiring a quick set. Different adhesive (epoxies, polyesters, or vinylesters) products can be used to install anchors. Structural adhesives are mainly polymer-based, and like all polymers, their stiffness is time dependent. If a load is applied suddenly, the epoxy responds like a hard solid. But if that load is then held constant, the molecules within the polymer may begin to rearrange and slide past one another, causing the adhesive to gradually deform in a process called creep. As the deformation increases, it becomes irreversible and eventually leads to damage accumulation and failure. This process can also be affected by other aspects of the in-service environment, such as the presence of moisture, freeze-thaw cycles, and/or elevated temperatures.

On July 10, 2006 a suspended ceiling section of the Interstate 90 (I-90) connector tunnel in Boston, MA, collapsed crushing a car and fatally injuring one of its occupants. The suspended ceiling in the collapsed section was comprised of concrete panels connected to steel hangers suspended from the tunnel concrete ceiling by an adhesive anchor system consisting of stainless steel anchor rods embedded in epoxy. The National Transportation Safety Board's (NSTB) investigation has determined that the ceiling collapse was probably triggered by creep failure of the epoxy adhesive anchors used to hold the ceiling in place. Major safety issues identified in this accident include insufficient understanding among designers and builders of the nature of adhesive anchoring systems and lack of standards for the testing and pre-qualification of adhesive anchors in sustained tensile load applications.

Although adhesive anchors are used extensively in practice, they have not yet been incorporated in design codes. The American Concrete Institute ACI 318 (2008) building code includes design provisions for anchorages using cast-in-place and post-installed mechanical anchors but does not include design provisions for adhesive anchors. This may be due to lack of information about the long-term behaviour of adhesive-bonded anchors.

Moisture absorption is known to have detrimental effects on the tensile behaviour of adhesives, however, none of the current evaluation criteria account for the effects of in-service moisture on the long-term creep behaviour of adhesive anchors. This research study investigates the long-term creep behaviour of adhesive anchors under sustained tensile loads as well as the long-term durability of such anchors.

1.2 Objectives and Scope

The objective of this research study is to evaluate the performance of epoxy- and acrylic-based adhesive anchor systems commonly used in the industry. The study focuses on the creep performance of these anchor systems under sustained tensile loads and on the tensile capacity after exposure to different environmental conditions. These objectives are pursued experimentally with various research tasks. A sufficient number of tests will be conducted to examine the performance of such anchors, and assist in evaluation and propose modification to existing testing protocols to prequalify the anchors. This project will increase our knowledge regarding the long-term performance of adhesively-bonded anchors and provide practicing engineers with an evaluation and a testing protocol for adhesive anchors.

1.3 Thesis Outline

Chapter 2 gives background and literature review on adhesive anchors. Chapter 3 describes the experimental program, while Chapter 4 summarizes the test results. Chapter 5 presents the data analysis and testing protocol. Finally Chapter 6 gives the conclusion and recommendations. Appendix A and Appendix B present plots of the projected displacement based on 90 and 42 days of test data, respectively.

Chapter 2

Background

The demand for more flexibility in the planning, design and strengthening of concrete structures has resulted in an increased use of fastening systems. This chapter presents a comprehensive background and literature review on anchor systems for concrete.

2.1 Types of anchoring systems

Anchor fastenings to concrete can be divided into two main categories: cast-in place and post-installed anchors. Cast-in-place anchors are installed by first connecting them to the formwork prior to pouring concrete. A cast-in-place anchor is typically composed of a headed steel bolt or stud. The main load transfer mechanism is keying or bearing, which is the direct transfer of load from the anchor into the concrete by bearing forces in the same direction of loading the anchor (Collins et al. 1989, Fuchs et al. 1995). Possible failure mechanisms are yield and fracture of the anchor shank, or the formation of a concrete breakout cone. Extensive testing has been performed on cast-in-place anchors and design models have been developed to accurately predict their behaviour (ACI 318-05, Appendix D).

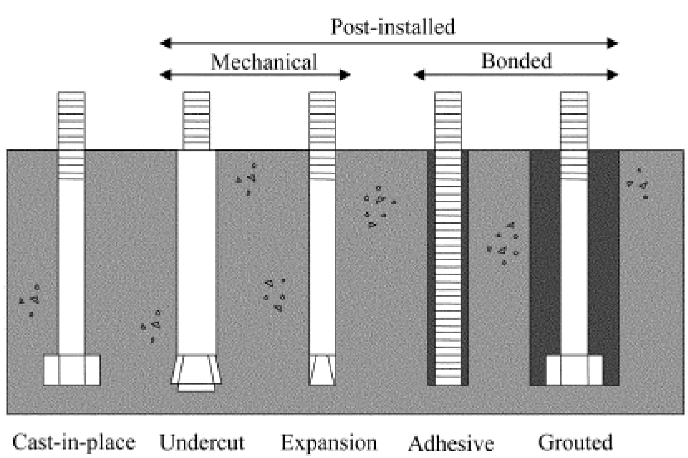


Figure 2.1 – Types of anchors

Post-installed anchors offer more flexibility and their use is now common. They are either mechanical or bonded anchors. Post-installed bonded anchors include both adhesive anchors and grouted anchors. An adhesive anchor can be either an unheaded threaded rod or a deformed reinforcing bar that is inserted into hardened concrete in a predrilled hole that is typically 10 to 25 percent larger than the diameter of the anchor. These anchors are bonded into the hole using a two-part structural adhesive consisting of a resin and a curing agent to bind the concrete and steel together.

2.2 Types of structural adhesives

Adhesives are commonly available as two-component systems that might require or not require user mixing. The resin component is commonly labeled as component A and the curing agent/catalyst is labeled as component B. The curing time of adhesive products is rapid, which makes them ideal for situations requiring a quick set. Different products can be used to install adhesive anchors. These products can be polymers (epoxies, polyesters, or vinylesters) or hybrid systems. Collins et al. (1989) classified the adhesive types as follows:

- Epoxy adhesives are synthetic compounds of epoxy resin cross linked by a curing agent; they possess a long shelf time, high durability, and are almost shrinkage free. Heat is generated during the reaction between the resin and curing agent (exothermic reaction), the generated heat is essential for the curing process of epoxy polymers (thermosetting polymers).
- Polyester adhesives are a thermosetting plastic. However, due to the difference in chemical properties and a faster exothermic reaction between the polyester resin and the catalyst, polyester adhesives have a shorter curing time than epoxy adhesives. Polyester adhesives have short shelf time, a tendency to self polymerize at high temperature, and degrade under ultraviolet light.

- Vinylester adhesives are a thermosetting plastic, and they fall in between epoxy and polyester adhesives in terms of curing time, shelf time, sensitivity to ultraviolet exposure, and tendency to self polymerize.

2.3 Load transfer mechanism of adhesive anchors

When the resin and curing agent undergo an exothermic reaction, it results in the formation of a polymer matrix that binds the anchor and the concrete together. Adhesive anchors are typically installed in clean dry holes to attain maximum bond strength. Because of their reliance on chemical and mechanical bond, adhesive anchors are uniquely susceptible to a number of potentially adverse factors. Conditions that cause these factors can occur during installation and throughout the service life of the anchor (Collins et al. 1989, Cook and Konz 2001, Cook et al. 1998).

Unlike pre-installed/cast-in anchors, the load transfer mechanism from the adhesive anchor to the concrete is by one of two mechanisms: mechanical interlock and bond in the anchor/adhesive interface, and chemical binding of the adhesive to the concrete along the entire embedded depth of the anchor, Figure 2.2. Load transfer depends on the strength of the anchor-adhesive and adhesive-concrete bond as well as how much the adhesive impregnates the surrounding concrete (Eligenhausen et al. 2007, Collins et al. 1989, Cook et al. 1998, McVay et al. 1996).

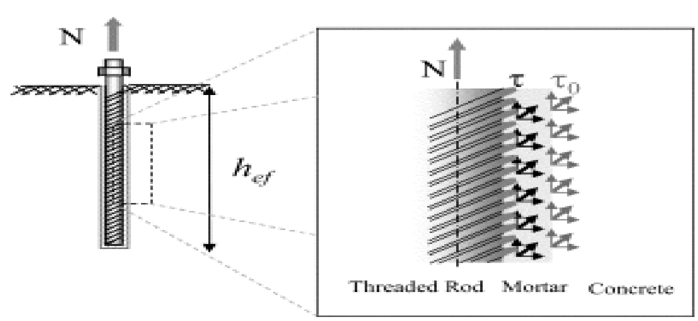


Figure 2.2 – Load transfer mechanism for adhesive anchors, Eligenhausen et al. (2007)

Typical failure modes for post-installed adhesive anchors are: concrete cone breakout, anchor pullout/bond failure, combined cone-bond failure, or shank fracture/anchor rupture, shown in Figure 2.3.

Variation between these failure modes mainly depends on the embedment depth. For a very small embedment depth, concrete cone breakout is more commonly observed. Typically as the embedment depth increases the mode of failure varies. For deeper embedment depth a combined mode of failure of concrete cone breakout and bond failure is often observed. Bond failure can be either at the concrete-adhesive interface, the adhesive-anchor interface, or both. For very deep embedment depth the bond strength increases and the anchor reaches its development depth causing the anchor itself to rupture (Cook et al. 1998). Figure 2.3 presents the different failure modes for adhesive anchors.

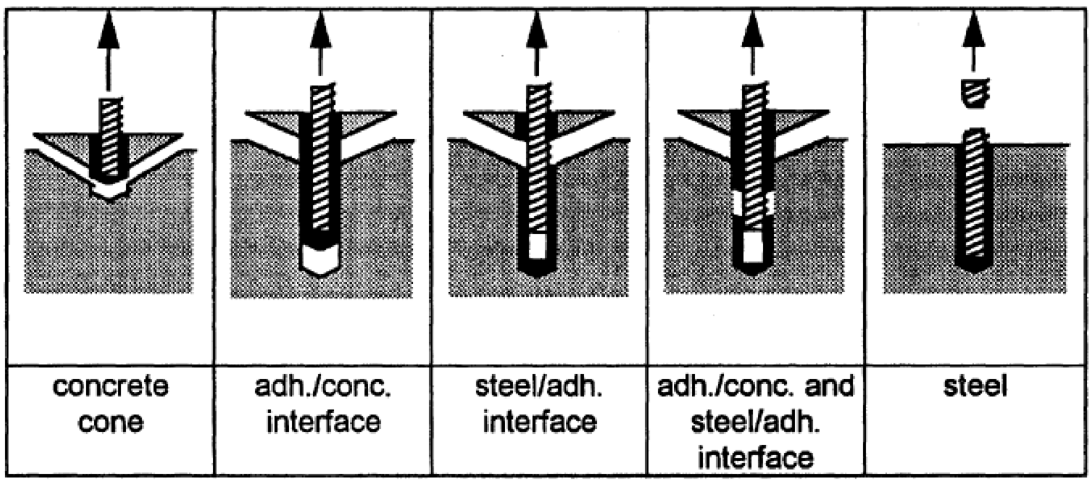


Figure 2.3 – Failure modes for post-installed adhesive anchors, Cook and Konz (2001)

For a combined cone-bond failure, Cannon et al. (1981) reported failure initiation by cone failure, subsequently Luke et al. (1985) reported that the failure initiated due to bond failure followed by cone failure by monitoring the surface displacement close to the anchor as well as the free end displacement. Collins et al. (1989) concluded that combined cone-bond failure is initiated simultaneously by bond and cone failure. This is in line with the results reported by (McVay et al. 1996, Cook et al. 1993).

McVay et al. (1996) conducted an elastoplastic finite element analysis on single adhesive anchors. This analysis revealed that the tension zone at the anchor-adhesive interface below the concrete surface initiates the failure. As the tension zone propagates with load towards the surface it causes the concrete and adhesive to expand, increasing the confinement, and thus increasing the shear resistance within the adhesive layer. This shear resistance weakens as the tension zone reaches the surface and the anchor fails.

2.4 Bond models for adhesive anchors

Adhesive anchors are used extensively in practice but have not yet been incorporated in design codes. ACI 318 Building Code (2008), for example, includes Appendix D as design provisions for anchorages using cast-in-place and post-installed mechanical anchors but does not include design provisions for adhesive anchors.

Various models for predicting the ultimate tensile capacity for adhesive anchors are available in the literature, Cook et al. (1998).

2.4.1 Concrete cone model

This model was derived for a single adhesive and a constant embedment depth to diameter ratio, and is valid for h_{ef}/d ratio of nine. The model accounts only for a concrete cone failure, since it only takes into account the concrete strength. The concrete cone model is expressed as the following equation:

$$N_u = 0.92 h_{ef} \sqrt[2]{f_c} \qquad \text{Eq. 2.1}$$

2.4.2 Bond Stress Model

Bond stress models are based on uniform or elastic bond stresses. The ultimate load based on the elastic bond stress model is given by equation (2.2), while that based on the uniform bond stress is given by equation (2.3):

$$N_u = \tau \pi d_o \left[\frac{\tanh(\lambda h_{ef})}{\lambda} \right] \qquad \text{Eq. 2.2}$$

$$N_u = \tau \pi d h_{ef} \qquad \text{Eq. 2.3}$$

For a low embedment depth the term in the bracket in equation (2.2) yields to h_{ef}, while for a deeper embedment depth it is smaller than h_{ef} indicating no direct proportionality between the embedment depth and the anchor strength (Cook et al. 1998, Nilson 1972, Cook 1993). Prediction from the two bond models are almost identical for shallower embedment depths, Figure 2.4

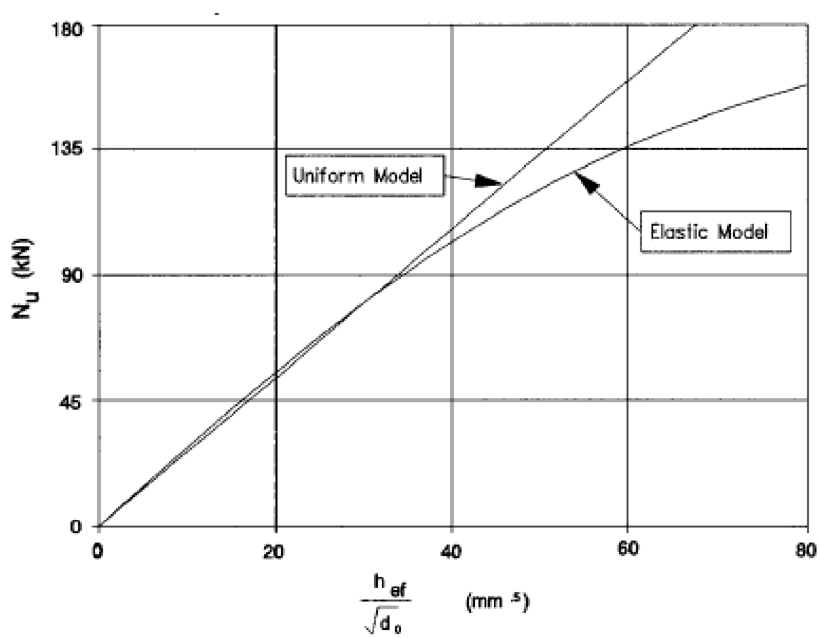


Figure 2.4 – Comparison of bond stress models, Cook (1993)

2.4.3 Bond models neglecting the shallow concrete cone

Cook et al. (1993) presented a model for the ultimate load from an adhesive anchor based on neglecting the concrete cone. The assumed effective embedment depth does not include the depth where a concrete cone is expected to occur. Thus the effective embedment depth equals the actual embedment depth minus $3d_b$. This model is given by equation (2.4):

$$N_u = \tau \pi d(h_{ef} - 3d) \qquad \text{Eq. 2.4}$$

2.4.4 Cone models with bond models

This model utilizes the concrete cone formula for a shallow embedment, and the uniform bond stress for a deeper embedment. This was based on an assumption that a concrete cone failure governs at a shallow embedment.

2.4.5 Combined cone/bond models

This model assumes a concrete cone failure for shallow embedment depth, and a combined cone and bond failure for deeper depth. First the depth of the concrete cone (h_c) is calculated using equation (2.4), and compared to the effective depth (h_{ef}). If the calculated cone height (h_c)is bigger than the effective embedment (h_{ef}), a cone failure is assumed, and the ultimate load is calculated using equation (1). Otherwise the ultimate load is computed using a combined failure mode given by equation (2.6), Cook (1993).

$$h_c = \frac{\tau \pi d}{1.84\sqrt{f_c}} \qquad \text{Eq. 2.5}$$

$$N_u = 0.92 h_c^2 \sqrt{f_c} + \tau \pi d (h_{ef} - h_c) \qquad \text{Eq. 2.6}$$

2.4.6 Two interface bond model

This model computes the ultimate load of an adhesive anchor based on whether the failure occurred at the steel/adhesive interface, or the adhesive/concrete interface. Equation (2.7) is used in case of a steel/adhesive interface failure, where the ultimate load would rely on the anchor diameter, embedment depth, and bond strength. Equation (2.8) is used in case of adhesive/concrete interface failure, where the concrete strength is added to the formula. The drawback of this model is that it is difficult to distinguish at which the interface the failure occurs (Cook and Konz 2001, Cook et al. 1998).

$$N_u = \tau \pi d h_{ef} \qquad \text{Eq. 2.7}$$

$$N_u = \tau_o \pi d_o h_{ef} \sqrt{\frac{f_c}{f_{c,low}}}$$ Eq. 2.8

McVay et al. (1996) proposed the use of a uniform bond stress model after conducting a numerical and experimental study on single adhesive anchors. The experimental study focused on unconfined pullout tests involving one threaded bar diameter (16mm), four embedment depths (76, 102, 127 and 152mm), and using one adhesive. The numerical study involved an elastoplastic finite element modeling. The proposed model is given by equation (2.9).

$$N_u = \tau_{avg} \pi d h_{ef}$$ Eq. 2.9

Where τ_{avg} is obtained from experimental data

Cook et al. (1998) examined the previously published design models for single adhesive anchors in comparison to the worldwide adhesive anchor data base maintained for ACI committee 355. The data base was filtered to include only threaded or reinforcing bar anchors with a minimum edge distance equal to the embedment depth, installed in clean, dry, and brushed holes. The result of the comparison to the ACI 355 data base indicated that the uniform bond stress model provides the best fit to the data. The authors proposed a design model that incorporated an adjustment factor into the uniform bond stress model to account for the concrete strength, given by equation (2.10).

$$\phi_b N_{n,bond} = \phi_b \tau' A_b \Psi_c$$ Eq. 2.10

where:

$$A_b = \pi d h_{ef}$$

$$\tau' = \tau_{f_c=20MPa}(1 - kCOV)$$

2.5 Factors affecting adhesively bonded joints

Messler (2004) states that the main deficiency of structural adhesives is their sensitivity/intolerance to elevated temperature. Water has a significant effect on the adhesive, especially when combined with elevated temperatures (Bowditch 1996). In warm moist environments, adhesives typically would absorb water and swell until they become in equilibrium with their environment. However, when additional load is applied causing further stress, the adhesive would continue to deform decreasing the stress until reaching a new equilibrium, a phenomena known as stress relaxation. A decrease in strength caused by stress relaxation is detrimental for most adhesives, (Hand et al. 1991).

Feng et al. (2005) studied the effects of temperature on the durability and viscoelastic behaviour of two types of adhesives through a series of tension, water absorption, and creep tests. The tension test were conducted in accordance to ASTM-D638, and the results showed that an elevated testing temperature has detrimental effect on the tensile modulus of the epoxy adhesive, (Figure 2.5). This indicates that the mechanical properties of adhesives deteriorate severely with increased temperatures.

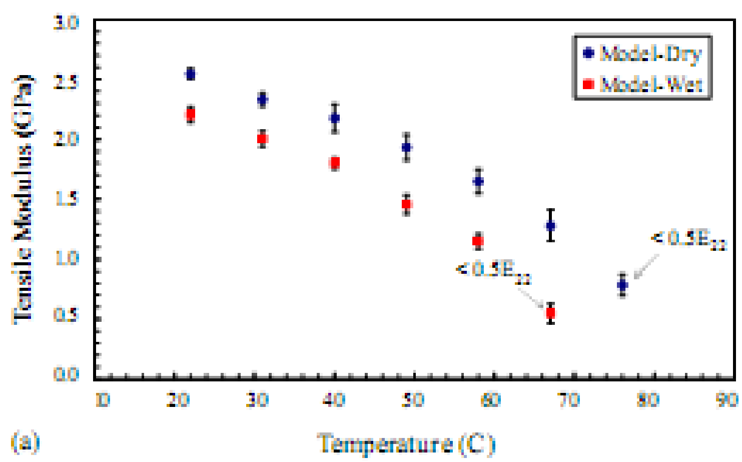


Figure 2.5 – Tensile modulus of model epoxy as a function of temperature (Feng 2005)

Tu and Kruger (1996) studied the effects of water immersion and curing temperature on the bond strength of epoxy bonded concrete specimens. The specimens consisted of two half cylindrical concrete blocks bonded using two two-part cold cured epoxy adhesives. After the specimens were immersed in water for 135 days, the specimens were tested to determine the bond strength at the adhesive interface. These results were compared to specimens that were air cured for 7 days. Figure 2.6 compares the bond strength of air cured specimens for 7 days, versus that of specimens submerged in water. The detrimental effect of water absorption is significant. The authors explain that since concrete has 10-40% volumetric fraction of voids and capillary pores, water can diffuse through those voids having access to the adhesively bonded joint. This may cause the irreversible bond line swelling and displacement of the adhesive, and as a result weakening of the bond strength.

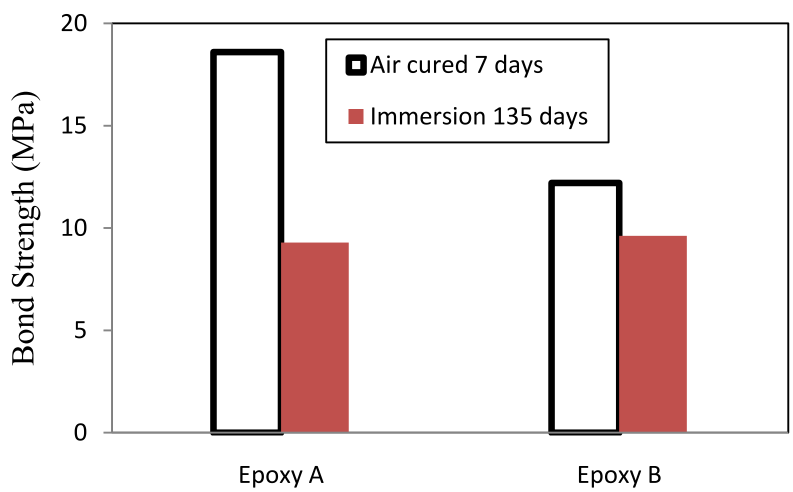


Figure 2.6 – Bond strength are long term water immersion for epoxy bonded hardened-to-hardened concrete at 20^{o}C (Tu and Kruger 1996)

2.6 Factors affecting bond behaviour of adhesive anchors

Cook et al. (1992) investigated the load-deflection behaviour of grouted and adhesive anchors through a series of static, fatigue, and impact tension tests. Based on that study, the authors found that the installation orientation for paste-like adhesives had no effect on the anchor behaviour, concluding that the extent to which the adhesive impregnated the concrete inside the hole is not simply a function of the viscosity. However, Cook (2009) states that vertically inclined or overhead application proves difficult to fully fill the hole with the adhesive as it will tend to run out of the hole. Thus causing voids within the bond area that significantly reduce the bond strength of the adhesive.

Ammann (1992) studied the effect of moisture and elevated temperature on the creep behaviour of two types of adhesives: epoxy acrylate (vinylester) and unsaturated polyester. The vinylester resin with hardener and quartz granules showed a minor increase of displacement after submerging the test specimens in water compared to the polyester resin, Figure 2.7. Elevated temperature had a significant effect on both types of adhesive anchors, Figure 2.8.

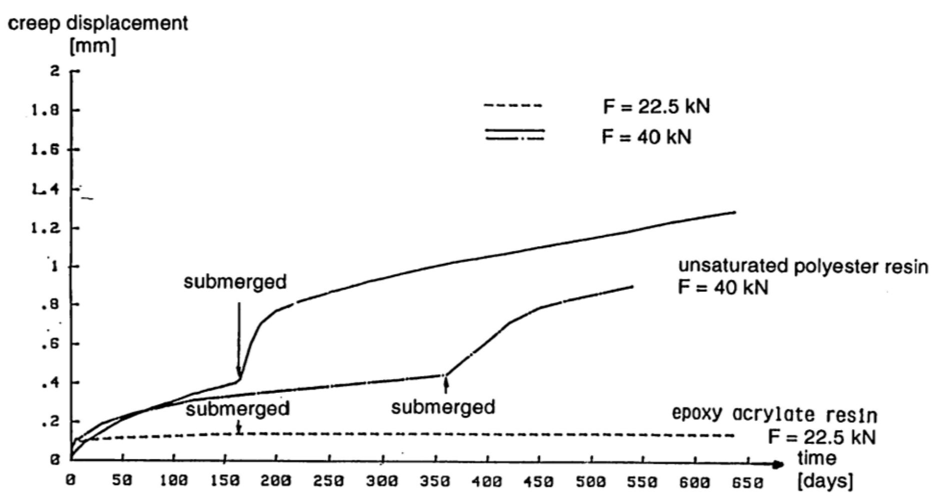


Figure 2.7 – Creep behaviour of adhesive anchors when submerged in water (Ammann 1992)

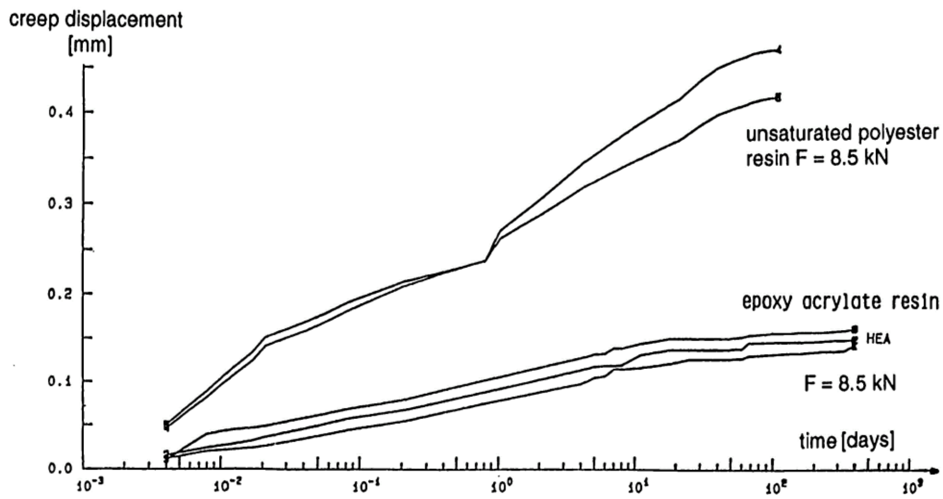


Figure 2.8 – Creep behaviour of adhesive anchors at elevated temperature (Ammann 1992)

Cook et al. (1996) found that the exposure to elevated temperatures (typically during the summer months) substantially decreases the tensile bond capacity of resins, in particular organic resins. Although different products respond differently, the detrimental effect of elevated temperature on the tensile bond capacity of adhesive anchors is evident from Figure 2.9.

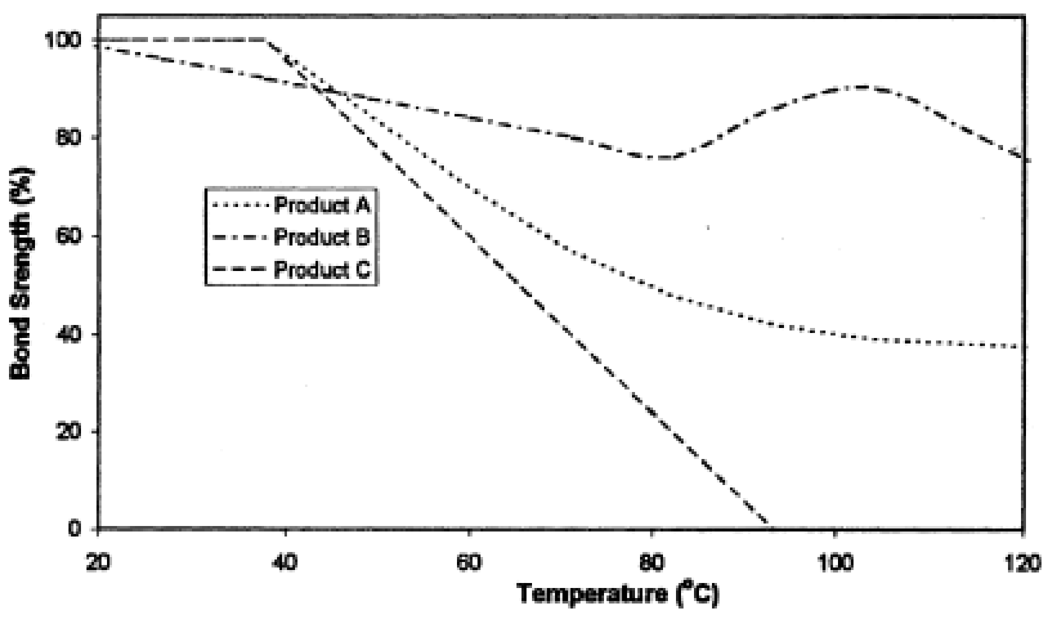


Figure 2.9 – Effect of elevated temperature on the bond strength of adhesives (Cook et al. 1996)

Higgins and Klingner (1998) tested the effect of UV exposure and acid rain wetting and drying on the bond strength of a single adhesive anchor. The study revealed that UV exposure had no significant impact on the tensile behaviour of adhesives anchors. Specimens subjected to acid rain wetting and drying were tested when the adhesive dried and it was found to have no significant effects. The authors concluded that although hydrolysis can degrade the stiffness and strength of structural adhesive, the effects are reversible if subjected only for short exposure periods; however, for long-term exposure the effects could be detrimental.

Cook and Konz (2001) experimentally investigated the sensitivity of 20 adhesive products to various installation and service conditions through 765 tests. Installation factors examined included variations in the condition of the drilled hole, concrete strength, and concrete aggregate. Service conditions considered included a short-term cure and loading at elevated temperature. A baseline for the relative bond strength was determined through testing specimens with anchors installed in clean dry holes, fully cured (7 day curing period), and loaded in room temperature ($25^{o}C \pm 6^{o}C$). For anchors installed in damp and wet holes, their average relative bond strength was 77% and 43% of their respective baseline, with an average coefficient of variation of 23% and 27% respectively. Anchors installed in unclean holes had an average relative bond strength of 71% of their baseline with 20% average coefficient of variation. A total of 300 specimens were evaluated for the effect of the concrete compressive strength on the bond strength of adhesive anchors. Although individual adhesives showed a linear trend of increasing bond strength and concrete compressive strength, a consistent relationship was not observed among all types of adhesives. Specimens installed in concrete with river gravel aggregate showed a 39% increase in average relative bond strength with a coefficient of variation of 18% over their respective baseline in concrete with limestone aggregate. In terms of service conditions, adhesive anchors subjected to a short term cure (24 hours cure time) achieved an average relative bond strength of 88% with a 14% coefficient of variation of their baseline with 7 days curing period. Adhesive anchors subjected to an elevated temperature of $43^{o}C$

exhibited a 5% increase in their average relative bond strength with a 21% coefficient of variation over the baseline.

Therefore, although general trends might be observed within adhesive groups of similar chemical composition, making predictions based on chemical formulation might prove unreliable. In their study, Cook and Konz (2001) evaluated 20 adhesive types (14 of which were epoxy adhesives and six were ester adhesives) based on chemical grouping. They observed that the average bond strength of epoxy adhesives was more than double that of ester adhesives; however, the coefficient of variation between products within each chemical group was greater than 20%.

Meline et al. (2006) evaluated the creep performance of epoxy adhesive anchor systems with epoxy-coated steel rebar at an elevated temperature. Three different epoxy adhesive brands were used in this investigation. They were Simpson Strong-Tie SET22, Red Head Epcon Ceramic 6, and Covert Operations CIA-Gel 7000. A total of 15 creep specimens were used (5 specimens for each type of epoxy adhesive). A sustained creep load of 40% of the average ultimate static load was applied to the test specimens for 42 days at 43.3°C ± 1.65°C (110°F ± 3°F). The creep displacements at 600 days were extrapolated and it was found that both SET22 and Ceramic 6 failed to satisfy the ICBO-AC58 (2005) requirements. On the other hand, the CIA-Gel 7000 adhesives satisfied the ICBO-AC58 (2005) requirements.

2.7 Creep of adhesive anchors

Structural adhesives, being viscoelastic by nature, exhibit a time-dependent behaviour that greatly affects their long-term load bearing capacity and durability (Feng et al. 2005). If a load is applied suddenly, the adhesive responds elastically, but if that load is held constant for an extended period of time, the chains within the polymer begin to rearrange and slide past one another. This causes the adhesive to gradually deform in a process called creep. As the deformation increases, it becomes irreversible and eventually leads to damage accumulation and failure. A typical creep behaviour of adhesives is presented in Figure

2.10. This process can also be affected by other aspects of the operating environment, such as the presence of moisture or freeze-thaw cycles.

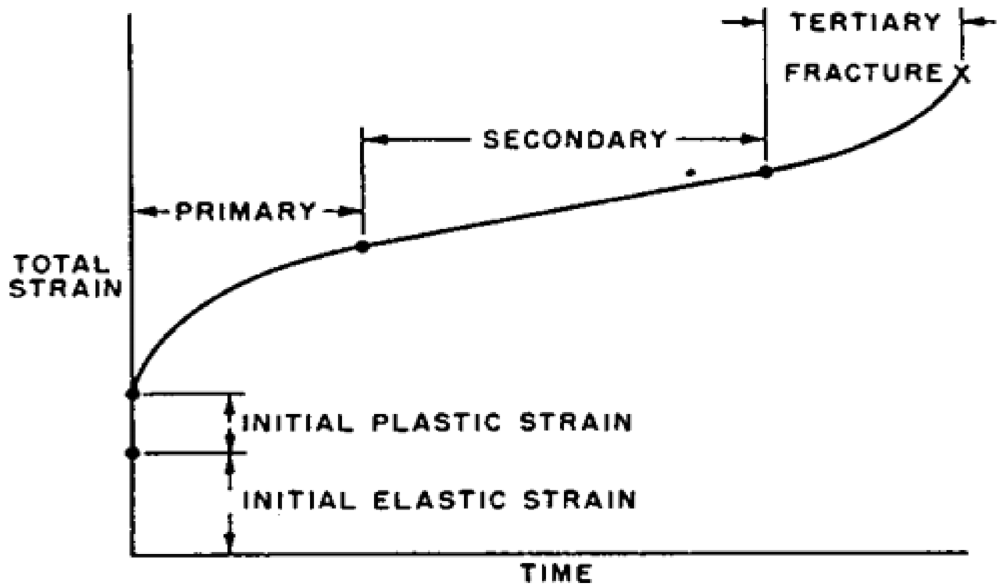


Figure 2.10 – Typical creep behaviour (ASTM D2990-09)

2.8 Adhesive anchors testing and evaluation standards under sustained load

This section provides an overview for the available testing standards and evaluation criteria that are widely adopted by the design community. ASTM E 488-96 1976 (2003) and ASTM E 1512-01 1993 (2007) are the testing standards that form the basis of current evaluation criteria.

2.8.1 ASTM E 488-96 Standard test methods for strength of anchors in concrete and masonry elements

Section 8 of ASTM E 488-96 1976 (2003) covers the static testing procedure to determine the tensile strength of post-installed and cast-in-place anchors in concrete and masonry structures. This standard adopts an unconfined test setup for the static pullout strength. A minimum of five specimens per anchor size shall be tested to determine an average tensile strength. For purpose of acquiring statistical data a minimum number of specimens *n* is required (Table 2.1).

Table 2.1 – Sample size requirement, (ASTM E488-96)

Coefficient of variation, %	Minimum test sample size, (*n*)
Up to12	5
12 to 15	10
>15	30

ASTM E 488-96 1976 (2003) specifies the use of a LVDT device or equivalent with an accuracy of at least 0.025mm for anchor displacement measurements. The anchors should be initially loaded with a seating load of 5% of the expected ultimate capacity to final loading. The final load is applied at either a continuous load rate (25-100% of the maximum load/minute, total test duration of 1-3 minutes) or an incremental load rate with a maximum increment not exceeding 15% of the maximum load, and held between load increments constant for 2 minutes. Load is increased up to failure or a load at a specified maximum displacement.

2.8.2 ASTM E1512-01 Standard testing methods for testing bond performance of bonded anchors

ASTM E 1512-01 1993 (2007) covers a variety of tests for evaluating the performance of post-installed adhesive anchors (steel reinforcing bars in concrete and masonry structures) under installation and in-service conditions. Structural members and measuring equipment are described in ASTM E 488-96 1976 (2003). Specimens are constructed using concrete with river gravel or crushed rock aggregate, and should have a compressive strength of 20 ± 3 MPa, and be cured for a minimum of 28 days. Specimens are conditioned to 24°C±5°C prior to anchor installation, and anchors are cured for 7±5days prior to testing, static tension tests should be conducted in accordance with ASTM E 488-96 1976 (2003).

Section 7.4.8 of (ASTM E 1512-01 1993 (2007)) describes the requirements for the creep testing;

- The sustained load is 40% of the average ultimate load determined by a static tension test. Static tension tests are conducted at a temperature of 24°C±5°C to determine the average ultimate load. Results that are less than 85% of the average are excluded and the average load recalculated.

- Static tension tests at an elevated concrete temperature of 43°C are conducted to determine the average displacement at the ultimate tension load. Displacement values greater than 115% of the average are excluded and the average load recalculated. That average is used as a limiting displacement to which the projected displacement from the sustained load testing is compared.

- Creep tests at an elevated concrete temperature of 43°C are conducted with a thermocouple embedded in the concrete to monitor the temperature. Specimens are preloaded with 5% of the sustained load prior to zeroing the equipment. A final sustained load is applied and the initial elastic displacement is recorded within 3 minutes of loading. The load is maintained for a minimum of 42 days, during which the displacement is monitored hourly for the first six hours and daily thereafter. The total displacement at 42 days is projected to 600 days using a logarithmic trend line, using the square fit thorough at least the data from the last 20 days (a minimum of 20 data points). The projected displacement at 600 days is compared to the average displacement at the ultimate load determined from the static tension tests at an elevated concrete temperature.

2.8.3 ICC ES-AC58 Acceptance criteria for adhesive anchors in concrete and masonry elements

ICC ES-AC58 was developed by the International Code Council Evaluating Services, Inc. (ICC-ES) to provide manufacturers with means of qualifying their products. AC58 was first issued in 1995, reapproved in 2005, and recently replaced by ICC-ES AC308. AC58 (2005) presents a non-mandatory creep testing method for adhesive anchors, however, if anchors are not tested for creep they are prohibited from use under sustained load.

AC58 (2005) adopts the general testing procedure from ASTM E 488-96 1976 (2003) and ASTM E 1512-01 1993 (2007) with minor differences in the conditioning temperature and temperature tolerances (Cook 2009). For the creep evaluation, AC58 (2005) follows the same procedure for total displacement projection as that presented in ASTM E 1512-01 1993 (2007), however, in addition to comparing the logarithmically projected displacement at 600 days to the average static displacement at ultimate tension at elevated concrete temperature, AC58 sets an upper displacement limit of 0.3mm.

2.8.4 ICC-ES AC308 Acceptance criteria for post-installed adhesive anchors in concrete elements

ICC Evaluation Service, Inc. issued an acceptance criterion for post-installed adhesive anchors in concrete elements (AC308) in June, 2006 and it was re-approved in November of 2009. This report was intended for the development, evaluation and recognition of the use of adhesive anchors in concrete, and has replaced AC58 (2005). ICC ES-AC308 (2009) in that it offers a comprehensive testing and evaluation protocol for adhesive anchors. Evaluation of creep performance is mandatory in AC308 unlike in its preceding document, AC58.

Section 8 of AC308 presents a wide range of reliability tests aimed at evaluating the behaviour of an anchoring system in normal and adverse conditions. Section 8.17 describes the testing procedure for sensitivity to a freeze/thaw effect, while section 8.18 presents a testing procedure for the sensitivity to sustained loading under standard and elevated temperatures.

Sustained load testing is carried out for a minimum duration of 42 days. The recommended displacement monitoring rate is:

- Every 10 min for the first hour,
- Every hour for the next 6 hours,

- Every day for the next 10 days, and
- Every 5 to 10 days thereafter.

Section 11.12 of AC308 presents the assessment procedure for sustained load behaviour for adhesive anchors. At the end of the test duration the total displacement is projected to 50 years for the standard temperature, and to 10 years for elevated temperature. A displacement projection is done for the test data using the Findley Power Law equation:

$$\Delta(t) = \Delta_{t=0} + a.t^{b} \qquad \text{Eq.2.11}$$

The mean extrapolated displacement is then compared and shall not exceed the limiting mean displacement calculated in section 11.3.4. The mean limiting displacement is determined from static pullout tests, and taken to be the load at which loss of adhesion occurs. Loss of adhesion is characterized by a significant change in stiffness as reflected in an abrupt change in the slope of load-displacement curve (AC308).

2.8.5 ACI 355.Y Draft criteria "Qualification of post-installed adhesive anchors" V.5.0

ACI committee 355 is currently balloting a draft document for the qualification of post-installed adhesive anchors ACI355.Y. Once approved, this document is expected to be included in the ACI318 2010 code, and to replace ICC ES-AC308. Testing procedures for sensitivity to sustained loading at standard and elevated long-term temperatures presented in ACI 355.Y are essentially the same as those in AC308 with minor modifications to the testing temperature and sustained load calculation at long-term temperatures, (Cook 2009).

2.8.6 Stress versus time to failure test method

ASTM D2990-09 is the testing standard for the creep-rupture of plastics under different stress levels, where failure is defined by the initiation of tertiary creep for specimens that do not fail catastrophically. The test data is used to create a stress versus time-to-failure curve, Figure 2.11. Similarly, ASTM D4680 is used for adhesive wood-to-wood, joints where time to failure data is collected at various stress levels as a percentage of the mean static strength of the joint. This data is used to formulate a linear regression of log of stress over log of time to failure, producing a stress versus time-to-failure envelope for the joint.

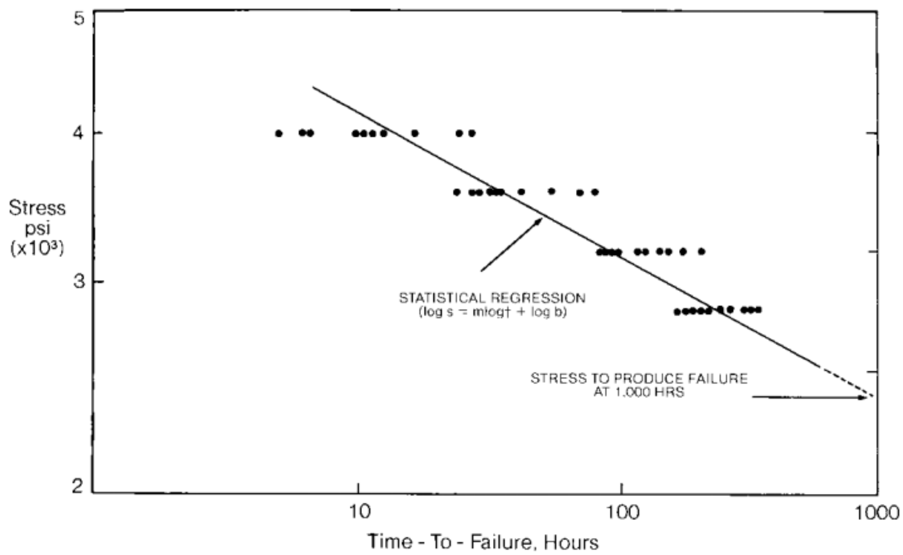


Figure 2.11 – Logarithmic stress versus time-to-failure curve (ASTM D4680-09)

Cook (2009) proposed two possible testing methods for adhesive anchors under sustained loads for AASHTO. The first method is based on AC308 and ACI 355.Y but with a modification of the sustained load level to 60% of the static capacity. The advantage of this method is that it is a widely used standard in the industry. The main disadvantage of this method is that it is based on a pass/fail criterion using a mathematically projected displacement and thus will not allow an accurate assessment of different adhesive products.

The second test method proposed by Cook (2009) is the stress versus time-to-failure method, which aims at developing product specific time-failure charts or tables. The charts will be created based on three testing series; the first series will include five specimens tested under confined static loading to determine the mean static strength. Series two and three would include three specimens each, tested to failure under sustained load levels of 85% and 75% of the mean static load (series one). Failure is defined by the initiation of tertiary creep. Specimens tested under a 75% stress level that do not fail within 3000 hours will be stopped and considered as failed providing a conservative data point. A least squares trendline is constructed through the data points on a log scale and extended linearly to the x-axis, Figure 2.12. The advantages of this method are that it allows for the incorporation of existing test data based on ICC ES-AC308 into the stress versus time-to-failure curves and removes the uncertainty accompanied with the projected displacement and the mathematical extrapolation, as well as it allows manufacturers to qualify their products beyond a simple pass/fail criterion.

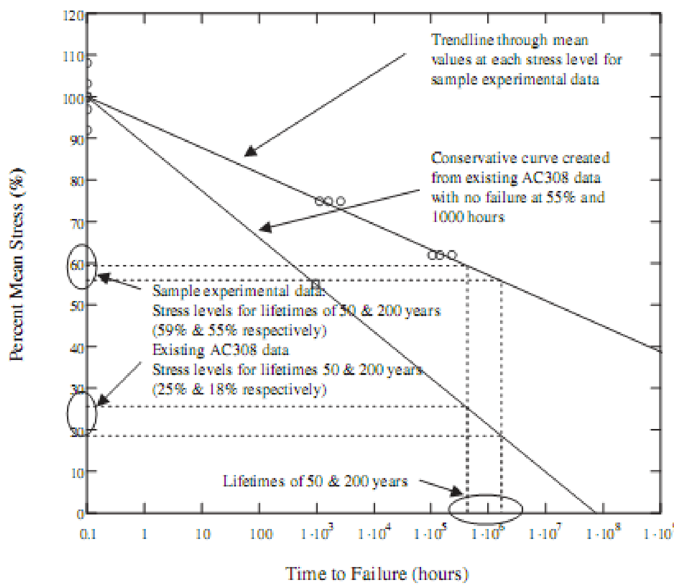


Figure 2.12 – Sample stress versus time-to-failure curve (Cook 2009)

2.9 Summary

This chapter presented an overview of the background and a literature review of the use of adhesively bonded anchors. The effects of adverse environmental conditions on the behaviour of adhesive were noted evident. The long term behaviour of post-installed adhesive anchors under various environmental exposure conditions lacks experimental data and needs to be vigorously investigated. This research study aims to contribute to filling this gap in our current knowledge.

Chapter 3

Experimental Program

3.1 General

The experimental program was divided into four different phases intended to evaluate the tensile behaviour of adhesive anchors under sustained load in various environmental conditions. The environmental conditions considered included testing at an ambient temperature (normal condition), moisture exposure, and freeze-thaw cycles to assess the long-term durability of the adhesive anchors. Three types of adhesives (commonly used by MTO) were considered: fast setting acrylic based adhesive (Type-A), fast setting epoxy based adhesive (Type-B), and a standard setting epoxy based adhesive (Type-C). Three specimens are tested for each type of testing. This chapter provides information on the specimen preparation, test setup, instrumentation and test procedure. Table 3.1 gives a summary of the test program.

Table 3.1 – Test matrix

Phase/Conditions		Type-A	Type-B	Type-C
Phase I : static testing	Room temperature (Series I-1)	3	3	3
	Moisture exposure (Series I-2)	3	3	3
	Freeze-thaw cycles (Series I-3)	3	3	3
Phase II : Creep testing under normal conditions	Sustained load = 40% ultimate (Series II-1)	3	3	3
	Sustained load = 60% ultimate (Series II-2)	3	3	3
Phase III : Creep testing under moisture exposure	Sustained load = 40% ultimate (Series III-1)	3	3	3
	Sustained load = 60% ultimate (Series III-2)	3	3	3
Phase IV : creep testing under freeze-thaw cycles	Sustained load = 40% ultimate	3	3	3
*numbers denote # of specimens tested		24	24	24

3.2 Description of test phases

Four different test phases were performed, as shown in Table 3.1. The tests were performed in accordance with ASTM E 488-96, ASTM E 1512-01, and ICC-ES AC308 2006(2009).

3.2.1 Phase I: Static tests

A total of 27 specimens are tested to failure in 3 series, to study the effect of various environmental exposure conditions on the ultimate static bond strength. These tension tests served as references for the other creep and durability tests in the study. The tensile tests were used to establish the static bond resistance of the anchor systems. The displacement of the anchor relative to the concrete surface during testing was recorded and the mode of failure was examined. An average ultimate load was determined for each series based on the test results of three specimens.

3.2.2 Phase II: Creep tests under normal conditions

Two series of 9 specimens each were tested to evaluate the performance of adhesive anchors under sustained tensile loads in an ambient temperature. Series II-1 and Series II-2 are subjected to a sustained load of (32kN and 42kN) 40% and 60% of the yield strength of the anchor; these load levels represent service loads used by MTO. Creep tests continued for 90-100 days. A preload not exceeding 5% of the sustained creep load was applied before zeroing of the displacement transducer readings. Then the remainder of the sustained creep load was applied. The displacement versus time data was recorded and the displacement data was then extrapolated to estimate the time at which failure will occur (beyond the range of the test duration). Following creep testing, the specimens were tested in tension to failure and the residual strength of these specimens was determined.

3.2.3 Phase III: Creep tests under moisture exposure

A total of 18 specimens were tested. This phase was aimed at evaluating the effect of moisture absorption on the bond behaviour of adhesive anchors. Moisture absorption can have a significant effect on the properties of epoxy adhesives. Series III-1 and Series III-2 were subjected to a sustained load of (32kN and 42kN) 40% and 60% of the yield strength of the anchor while being exposed to moisture by ponding. These sustained loads were maintained for a minimum of 90 days. The specimens were tested in tension in the same manner as specimens of Series I. The strength loss due to moisture absorption was determined for the three different adhesives employed.

Phase IV: Creep tests under freeze-thaw exposure

Nine specimens were tested to evaluate the effect of freeze-thaw cycles on the creep behaviour of the adhesive bonded anchor. The freeze-thaw cycles were performed in accordance to CC-ES AC308. The top surface of the test specimen, within a 76 mm radius from the centre of the test anchor, was covered with tap water and a 12 mm depth was maintained throughout the test. During freezing and thawing, a tension load, 40% of the anchor yield strength was maintained. The freeze and thaw cycles were applied at a rate of 1 cycle per day. Each cycle consists of 8 hours of thawing at a temperature of +20±2^{o}C and 16 hours of freezing at a temperature of -20±2^{o}C. The displacement is measured during the temperature cycles. After the completion of a minimum of 90 cycles, the specimens were tested to failure to determine the residual tensile strength and to evaluate the effect of the freeze-thaw cycles on such types of anchors.

3.3 Specimen Nomenclature

The specimen nomenclature consists of 4 symbols. The first part indicates the type of adhesive (A= Type-A, B = Type-B, C = TYPE-C). The second part indicates the environmental exposure (R = room temperature, M = moisture exposure, FT = freeze-thaw cycles in the presence of moisture), the third part indicates the sustained load level (0%, 40%, or 60% of the anchor's yield strength), and the fourth part indicates the specimen number.

3.4 Specimen Preparation

The test specimen consists of a concrete block and an adhesive anchor. The blocks are constructed using a standard MTO 30 MPa concrete mix and the anchors are 15M steel deformed bars. An embedment length of 125 mm, typically used by MTO, is used in all specimens. Anchors were installed in the concrete following the procedures suggested by the manufacturer.

3.4.1 Concrete Blocks

All concrete specimens were cylindrical in shape of approximately 300 mm (12 inch) in diameter and 200mm (8 inch) in height. The specimens were all poured from 30 MPa MTO concrete mix, Figure 3.1. The specimens were cured for 14 days. Concrete cylinders were also made for compressive testing. A set of 3 cylinders of size 4 inch by 8 inch were tested at the beginning and the end of each testing phase.

(a) Specimen concrete pouring (b) Concrete finishing

Figure 3.1 – Concrete blocks preparation

3.4.2 Anchor Installation

All anchors were 15M deformed steel bars that were installed to an embedment depth of approximately 125mm (5 inches). Three different adhesive materials (Type-A, Type-B and Type-C**)** were used for the anchor installation. A total of nine anchors were installed using each of the adhesive materials.

- Type-A: A fast setting two component methyl methacrylate adhesive, that comes prepackaged in a dual cartridge and is self mixed as the two components, that are simultaneously dispensed through a static mixing nozzle was used. The adhesive has a working time of 5.5 minutes and full cure time of 30 minutes at 27°C.

- Type-B: A fast setting high strength two component epoxy adhesive anchoring gel, supplied in a single cartridge with two compartments or in a dual cartridge, with a component ratio of A:B=1:1 was used. It has a working time of 6-8 minutes and a full cure time of 2 hours at 22^{o}C.

- Type-C: A standard set, high strength epoxy adhesive was supplied in a side-by-side adhesive refill pack. Components A and B are dispensed simultaneously through a static mixing nozzle. It has a typical cure time of 12 hours.

The 19 mm (0.75 inch) diameter holes for the rebar anchors were drilled using a rotary hammer drill, and then cleaned as per the manufacturer's instructions. They consist of a three step process: a blasting of compressed air, brush cleaning and then a final blast of compressed air, Figure 3.2. The adhesive material was then dispersed at the bottom of the drilled hole followed by inserting the anchor with a slow rotational motion to allow an equal distribution of the adhesive, and to avoid the formation of air pockets around the anchor. To insure that the anchors remained vertical, they were held in place by steel tripods until the adhesive was fully set, Figure 3.3. The full process of anchor installation was witnessed by a representative from each adhesive manufacturer.

(a) Hole drilling (b) Brush cleaning (c) Blasting of compressed air

Figure 3.2 – Drilled hole preparation prior to anchor installation

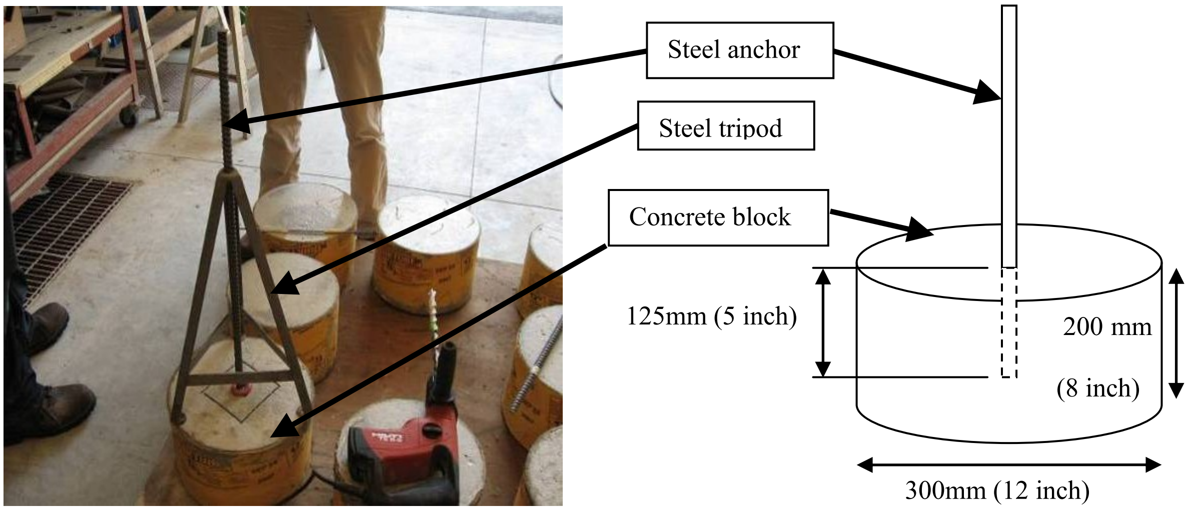


Figure 3.3 – Anchor installation

3.5 Creep Test Setup

3.5.1 Creep Frames

Two creep test setups were utilized to carry out the test phases. Each test setup consists of three sets of frames; each set was used to test three specimens of each adhesive material.

For the first creep setup a total of nine creep loading frames were fabricated. The loading system is designed to magnify a dead load through a series of lever arms with a magnification factor of 1:115, Figure 3.4. All 9 frames were calibrated to the required service loads of 32kN and 48kN prior to creep testing, using various combinations of dead loads while measuring the magnified tension load using a 50,000 lbs Futek-LTH500 load cell.

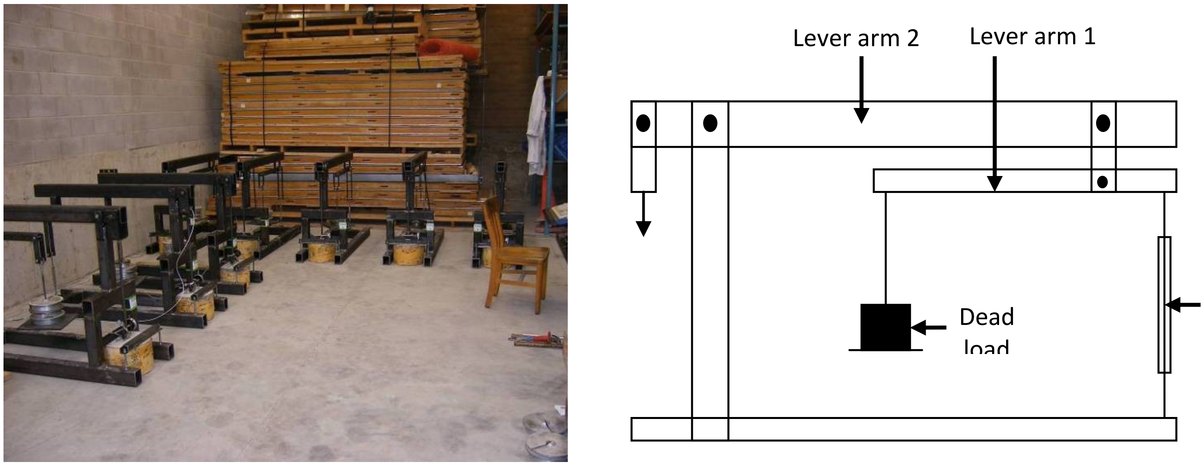


Figure 3.4 – Creep testing setup (1) for room temperature and moisture exposure

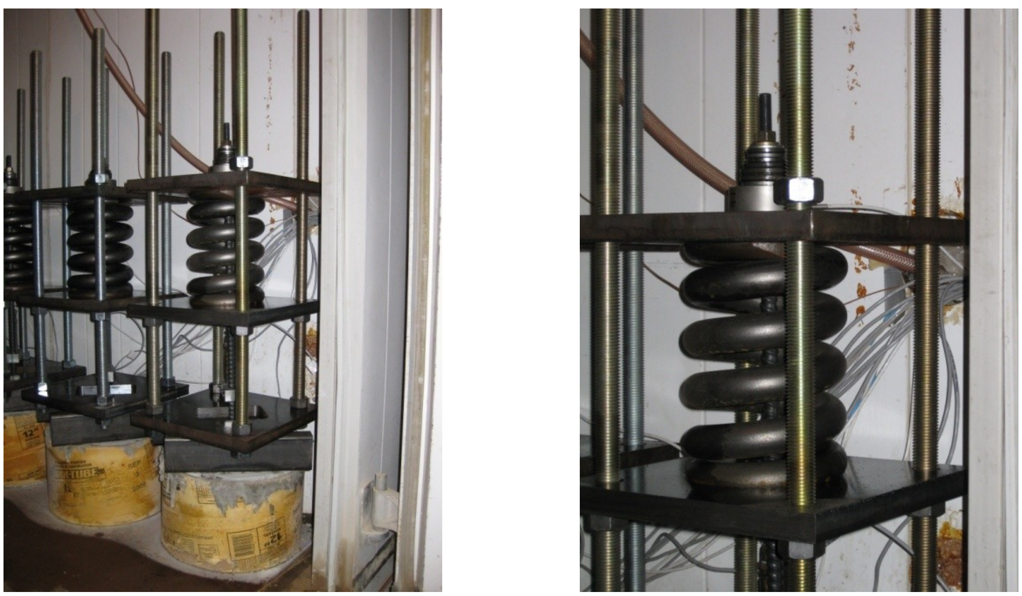


Figure 3.5 – Creep test setup (2) inside the environmental chamber for freeze/thaw exposure

The second creep setup had a total of 9 creep systems. The setup relied on the compression coil springs and a rod assembly to apply the sustained tensile load. The coil springs used had a capacity of 40kN at 1.5 inches of compression displacement, and are shown in Figure 3.5. The sustained loads were applied gradually transferring the required tensile load on the anchor over a period of 3-5 minutes per frame. The load was then maintained for minimum test duration of 90 days.

3.6 Instrumentation

A Scimetric Instruments System 200, Model 237 data acquisition system with a 12-bit resolution was used to continuously collect data from 9 displacement transducers, 3 load cells and a thermocouple over the test period. Macro Sensors HSE 750-500 DC-LVDTs with a 0.5″ stroke and non-linearity of +/- 0.10% of full-scale output (FSO) were used to measure the displacement. Measurements were collected every 5 minutes for the first hour, hourly for the next 24 hours, daily for the next 10 days and every 5 days thereafter, while the room temperature was monitored on hourly basis throughout the test duration. A backup power supply APC Smart-UPS 750 was used to account for any short term power blackouts. The instrumentation used is shown in Figure 3.6 and Figure 3.7.

Figure 3.6 – Creep testing instrumentation

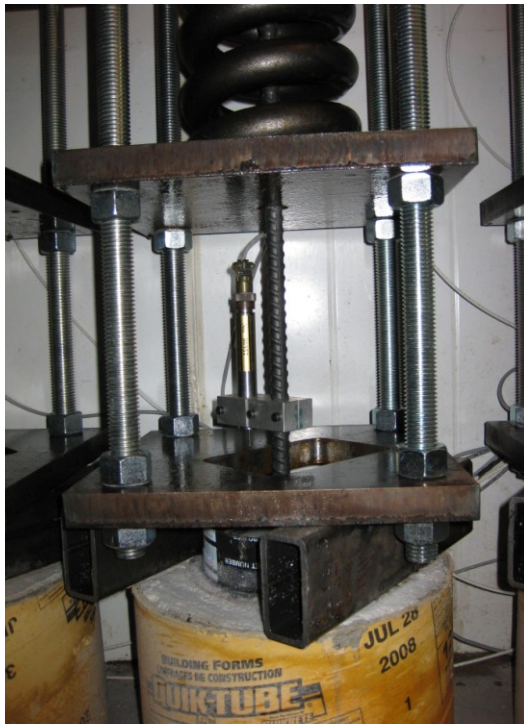


Figure 3.7 – Specimen under sustained load testing

3.7 Static Test Setup

3.7.1 Test setup and procedure

Pullout tests were carried out in a UniRoyal four post test frame, and were controlled by closed loop servo hydraulics, equipped with MTS controller-Flextest GT, a double ended MTS-244 actuator with a stroke of 500 mm (20 inches) and a capacity of 500 kN (112 Kips). The anchors were gripped using MTS-647 hydraulic wedge grips. The test was controlled using a MultiPurpose TestWare (MPT) environment with TestStar control software. A 1 inch thick steel plate with a 32 mm (1 ¼ inch) diameter center hole was placed on top of the concrete specimen for confinement of the concrete surface to avoid concrete cone failure. To ensure the load was uniformly distributed over the full surface area of the specimen, a thin layer of hydro-stone was applied between the steel plate and the concrete surface to ensure full contact. Figure 3.8 shows the static test setup.

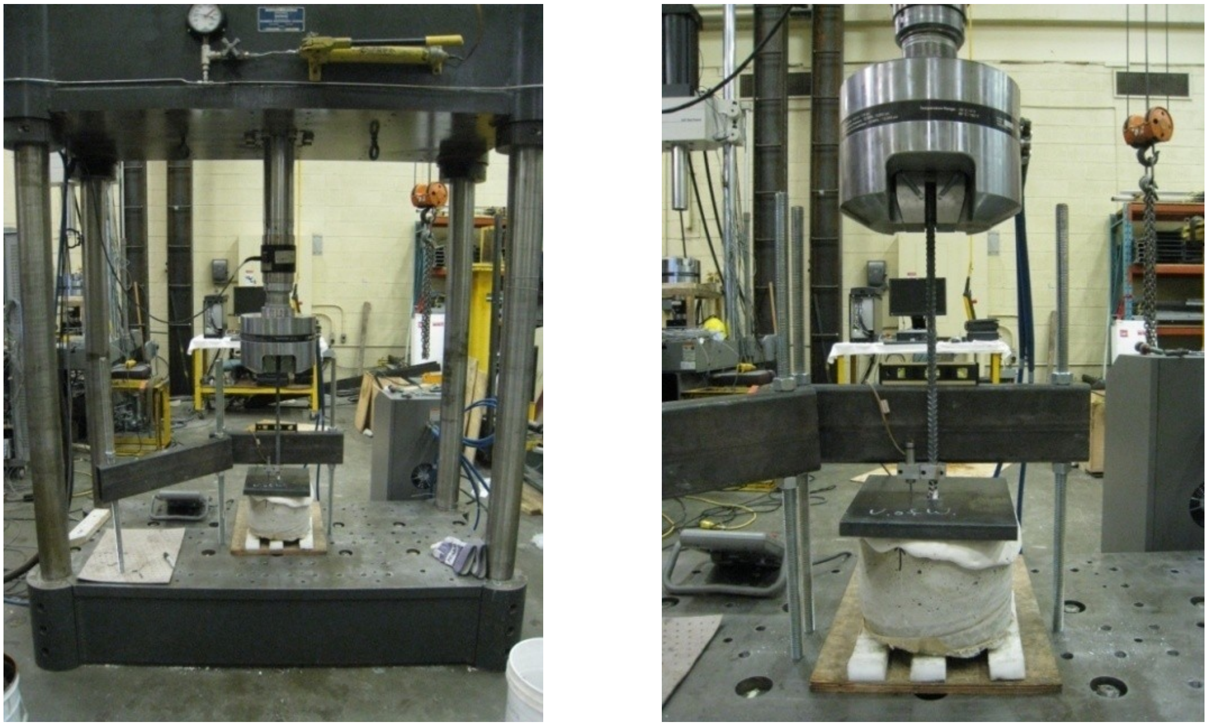


Figure 3.8-Static pullout testing setup

Each specimen was aligned in the machine with the steel rebar gripped by the actuator and the concrete block fixed to the lower table by two steel straps (6 inches deep HSS sections) held to the base of the testing frame by four threaded rods. The actuator was then moved upwards putting the anchor under tension. Load was applied as per ASTM-488, using the continuous load application method. A linear variable differential transformer (LVDT) was mounted using an aluminum bracket to the steel anchor to measure the displacement of the anchor relative to the top of the steel plate, while load measurements were taken from the test frame internal load cell.

Chapter 4

Experimental Results

4.1 General

This chapter presents the results of the static tests and creep tests on the three types of adhesives anchors embedded in concrete under various environmental exposures.

4.2 Static Test Results

The average concrete strength prior to of static testing was 44.14 +/- 0.82 MPa. The ultimate strength determined from the pullout testing was normalized by dividing the measured strength by the yield strength of the anchor. All specimens failed after the anchor had already yielded.

4.2.1 Specimens with a Type-A adhesive

The ultimate residual capacity for specimens with Type-A adhesive under room temperature drops with increasing sustained load level. However, when subjected to moisture exposure or freeze/thaw cycles the trend is inconsistent. The residual capacity for sustained load levels of40%f_y is almost equal to the static pullout tests baseline capacity, and drops for the sustained load level of 60%f_y. None of the three exposure conditions had an effect on the failure mode, with all 24 specimens failed by yielding of the anchor followed by bond failure.

Table 4.1 summarizes the static pullout test results for specimens with Type-A adhesive in room temperature tests. Moisture exposure had no significant effect on the ultimate capacity of the anchor with Type-A adhesive when compared to test at room temperature without moisture, while freeze/thaw cycles had a significant effect on the ultimate strength of the adhesive anchor. Table 4.2 summarizes the static pullout testing results for moisture and freeze/thaw exposures, while Figure 4.1 compares the normalized average ultimate and residual capacities.

Table 4.1 – Static pullout test results for specimens with Type-A a adhesive in room temperature

Specimen	$P_{y\text{-anchor}}$ (KN)	Ultimate Load (kN)		P_u/P_y		Failure Mode
		P_u	$P_{u\text{-avg}}$		Avg.	
A-R-0%-1	82	132	120.7	1.61	1.49	Yielding of the anchor followed by bond failure
A-R-0%-2	79	122		1.54		Yielding of the anchor followed by bond failure
A-R-0%-3	82	108		1.32		Yielding of the anchor followed by bond failure
A-R-40%-1	77	107	102.0	1.39	1.30	Yielding of the anchor followed by bond failure
A-R-40%-2	78	98		1.26		Yielding of the anchor followed by bond failure
A-R-40%-3	81	101		1.25		Yielding of the anchor followed by bond failure
A-R-60%-1	79	91.2	91.1	1.15	1.14	Yielding of the anchor followed by bond failure
A-R-60%-2	81	91		1.12		Yielding of the anchor followed by bond failure
A-R-60%-3	79	91.1		1.15		Yielding of the anchor followed by bond failure

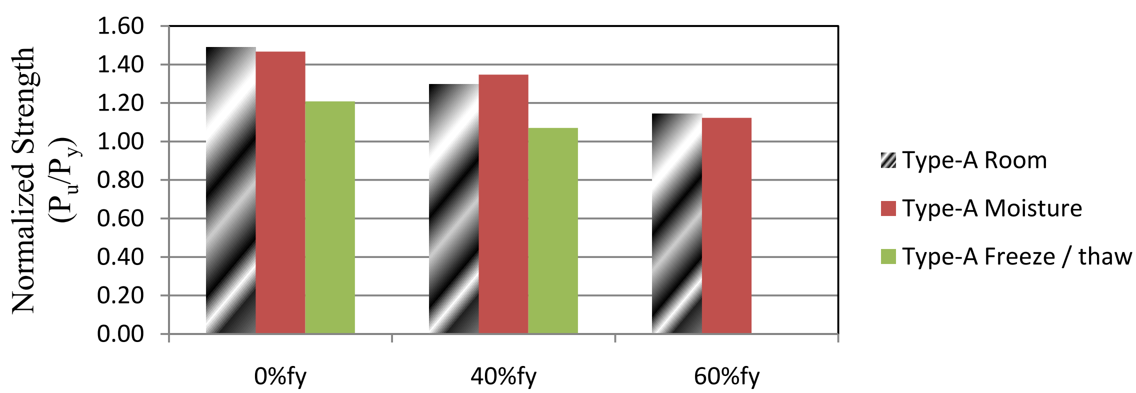


Figure 4.1 – Comparison of normalized ultimate and residual capacities for specimens with a Type-A adhesive

Table 4.2 – Static pullout test results for specimens with a Type-A adhesive under moisture and freeze/thaw exposures

Specimen	$P_{y\text{-anchor}}$ (KN)	Max. Load (kN)		P_u/P_y		Failure Mode
		P_u	$P_{u\text{-avg}}$		Avg.	
A-M-0%-1	91.8	127.8	131.7	1.39	1.47	Yielding of the anchor followed by bond failure
A-M-0%-2	94	145		1.54		Yielding of the anchor followed by bond failure
A-M-0%-3*	108	122.2		1.13		Yielding of the anchor followed by bond failure
A-M-40%-1*	80	131.1	134.8	1.63	1.35	Yielding of the anchor followed by bond failure
A-M-40%-2	96	131.1		1.37		Yielding of the anchor followed by bond failure
A-M-40%-3	107	142.2		1.33		Yielding of the anchor followed by bond failure
A-M-60%-1	100	118.3	113.9	1.18	1.12	Yielding of the anchor followed by bond failure
A-M-60%-2	N/A	N/A		N/A		Failed under sustained load testing
A-M-60%-3	103	109.5		1.06		Yielding of the anchor followed by bond failure
A-FT-0%-1	98	116.6	117.2	1.19	1.21	Yielding of the anchor followed by bond failure
A-FT-0%-2	97	122.7		1.26		Yielding of the anchor followed by bond failure
A-FT-0%-3	96	112.4		1.17		Yielding of the anchor followed by bond failure
A-FT-40%-1*	83	130	109.2	1.57	1.07	Yielding of the anchor followed by bond failure
A-FT-40%-2	102	106		1.04		Yielding of the anchor followed by bond failure
A-FT-40%-3	83	91.5		1.10		Yielding of the anchor followed by bond failure

4.2.2 Specimens with a Type-B adhesive

Increasing the sustained load level on specimens with a Type-B adhesive had no significant effect on the ultimate anchor capacity under room temperature and freeze/thaw cycles. However, there was a small decrease in the capacity of the anchor when a higher sustained load level was combined with a moisture exposure. Under the same sustained load level, specimens with a Type-B adhesive exhibited a significant decrease in capacity when exposed to moisture and freeze/thaw cycles in comparison to those tested at room temperature without moisture or freeze thawing.

Table 4.3 summarizes the static pullout test results for specimens with a Type-B adhesive at room temperature, while Table 4.4 summarizes the results under moisture and freeze/thaw exposures. A comparison of average normalized ultimate and residual capacities for specimens with Type-B adhesive under both load levels and all the 3 exposure conditions is presented in Figure 4.2.

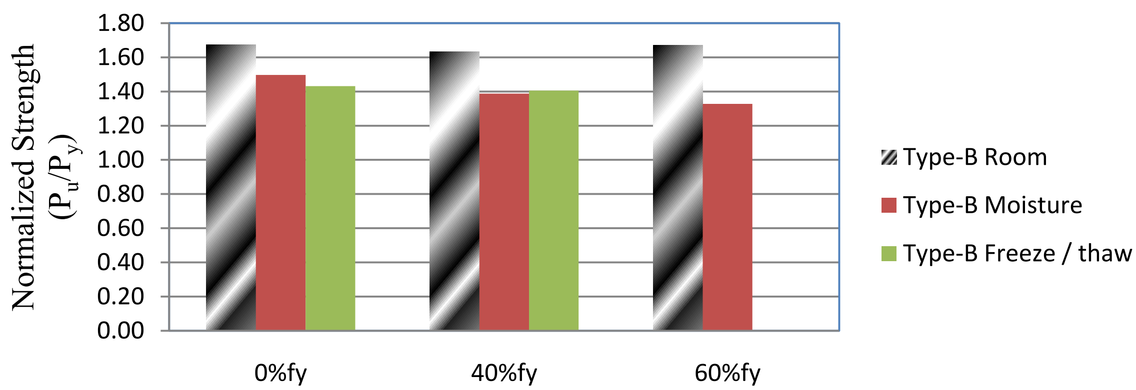


Figure 4.2 – Comparison of normalized ultimate and residual capacities for specimens with a Type-B adhesive

Table 4.3 – Static pullout test results for specimens with a Type-B adhesive in room temperature

Specimen	$P_{y\text{-anchor}}$ (KN)	Ultimate Load (kN)		P_u/P_y		Failure Mode
		P_u	$P_{u\text{-avg}}$		Avg.	
B-R-0%-1	79	133	133.3	1.68	1.67	Yielding of the anchor followed by anchor rupture
B-R-0%-2	80	133		1.66		Yielding of the anchor followed by anchor rupture
B-R-0%-3	80	134		1.68		Yielding of the anchor followed by concrete splitting
B-R-40%-1	79	126	124.3	1.6	1.63	Yielding of the anchor followed by bond failure
B-R-40%-2	79	132		1.67		Yielding of the anchor followed by anchor rupture
B-R-40%-3	N/A	115		N/A		Bond failure (anchor did not yeild)
B-R-60%-1	80	133.9	133.7	1.67	1.67	Yielding of the anchor followed by anchor rupture
B-R-60%-2	81	134.5		1.66		Yielding of the anchor followed by anchor rupture
B-R-60%-3	79	132.6		1.68		Yielding of the anchor followed by anchor rupture

Table 4.4 – Static pullout test results for specimens with a Type-B adhesive under moisture and freeze/thaw exposures

Specimen	$P_{y\text{-}anchor}$ (KN)	Ultimate Load (kN)		P_u/P_y		Failure Mode
		P_u	$P_{u\text{-}avg}$		Avg.	
B-M-0%-1	93.9	135.8	139.4	1.45	1.50	Yielding of the anchor followed by anchor rupture
B-M-0%-2	80	132.6		1.66		Yielding of the anchor followed by concrete split
B-M-0%-3	108	149.9		1.39		Yielding of the anchor followed by anchor rupture
B-M-40%-1	103	141.2	140.4	1.37	1.39	Yielding of the anchor followed by concrete split
B-M-40%-2	92	131.8		1.43		Yielding of the anchor followed by concrete split
B-M-40%-3	109	148.3		1.36		Yielding of the anchor followed by anchor rupture
B-M-60%-1	113	149.4	129.4	1.32	1.33	Yielding of the anchor followed by anchor rupture
B-M-60%-2	N/A	N/A		N/A		Failed under sustained load testing
B-M-60%-3	82	109.3		1.33		Yielding of the anchor followed by bond failure
B-FT-0%-1	98	144.9	126.8	1.48	1.43	Yielding of the anchor followed by bond failure
B-FT-0%-2	84	139.4		1.66		Yielding of the anchor followed by anchor rupture
B-FT-0%-3	83	96		1.16		Yielding of the anchor followed by bond failure
B-FT-40%-1*	82	132.2	130.5	1.61	1.41	Yielding of the anchor followed by concrete split
B-FT-40%-2	83	119.6		1.44		Yielding of the anchor followed by concrete split
B-FT-40%-3	102	139.7		1.37		Yielding of the anchor followed by concrete split

4.2.3 Specimens with a Type-C adhesive

The ultimate capacity of specimens with Type-C adhesive did not exhibit any effect of any of the these exposure conditions for the increasing sustained load levels. However, when subjected to a given sustained load level combined with moisture exposure or freeze/thaw cycles, a significant decrease in the ultimate capacity of the anchor compared to the specimens kept in room temperature was recorded. None of the three exposure condition had an effect on the mode of failure; all 24 specimens with Type-C adhesive failed by yielding of the anchor followed by anchor rupture.

Table 4.5 summarizes the static pullout test results for specimens with Type-C adhesive at room temperature, while Table 4.6 summarizes the results under moisture and freeze/thaw exposures. A comparison of average normalized ultimate and residual capacities for specimens with Type-C adhesive under both load levels and all the exposure conditions is presented in Figure 4.3.

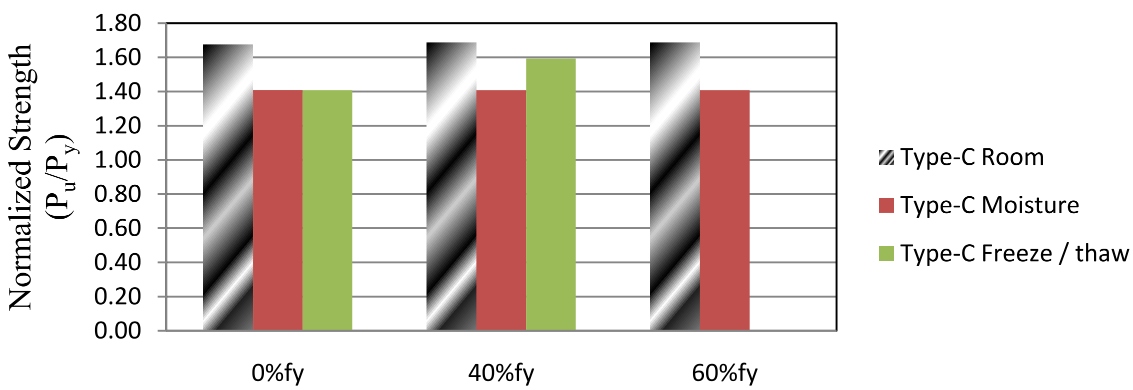


Figure 4.3 – Comparison of normalized ultimate and residual capacities for specimens with a Type-C adhesive

Table 4.5 – Static pullout test results for specimens with a Type-C adhesive in room temperature

Specimen	$P_{y\text{-anchor}}$ (KN)	Ultimate Load (kN)		P_u/P_y		Failure Mode
		P_u	$P_{u\text{-avg}}$		Avg.	
C-R-0%-1	77	129	131.7	1.68	1.67	Yielding of the anchor followed by anchor rupture
C-R-0%-2	79	133		1.68		Yielding of the anchor followed by anchor rupture
C-R-0%-3	80	133		1.66		Yielding of the anchor followed by anchor rupture
C-R-40%-1	78	133	134.3	1.71	1.69	Yielding of the anchor followed by anchor rupture
C-R-40%-2	80	135		1.69		Yielding of the anchor followed by anchor rupture
C-R-40%-3	81	135		1.67		Yielding of the anchor followed by anchor rupture
C-R-60%-1	79	134.4	134.9	1.70	1.69	Yielding of the anchor followed by anchor rupture
C-R-60%-2	81	135.7		1.68		Yielding of the anchor followed by anchor rupture
C-R-60%-3	80	134.5		1.68		Yielding of the anchor followed by anchor rupture

Table 4.6 – Static pullout test results for specimens with a Type-C adhesive under moisture and freeze/thaw exposures

Specimen	$P_{y\text{-anchor}}$ (KN)	Ultimate Load (kN)		P_u/P_y		Failure Mode
		P_u	$P_{u\text{-avg}}$		Avg.	
C-M-0%-1	108	149.6	144.0	1.39	1.41	Yielding of the anchor followed by anchor rupture
C-M-0%-2	96	143		1.49		Yielding of the anchor followed by anchor rupture
C-M-0%-3	103	139.3		1.35		Yielding of the anchor followed by anchor rupture
C-M-40%-1	94	133.3	138.4	1.42	1.41	Yielding of the anchor followed by anchor rupture
C-M-40%-2	107	149.1		1.39		Yielding of the anchor followed by anchor rupture
C-M-40%-3	94	132.9		1.41		Yielding of the anchor followed by anchor rupture
C-M-60%-1	82	133.2	144.2	1.62	1.46	Yielding of the anchor followed by anchor rupture
C-M-60%-2	108	149.3		1.38		Yielding of the anchor followed by anchor rupture
C-M-60%-3	109	150.2		1.38		Yielding of the anchor followed by anchor rupture
C-FT-0%-1	108	149.4	138.9	1.38	1.41	Yielding of the anchor followed by anchor rupture
C-FT-0%-2	94	133.7		1.42		Yielding of the anchor followed by anchor rupture
C-FT-0%-3	94	133.5		1.42		Yielding of the anchor followed by anchor rupture
C-FT-40%-1	96	142.9	138.1	1.49	1.59	Yielding of the anchor followed by anchor rupture
C-FT-40%-2	82	137.2		1.67		Yielding of the anchor followed by anchor rupture
C-FT-40%-3	83	134.2		1.62		Yielding of the anchor followed by anchor rupture

4.3 Creep Test Results

Sustained load test results showed a similar initial elastic displacement for all the anchors with the three adhesives tested under the various exposure conditions. However, the creep behaviour of the 3 types of adhesive anchors varied widely throughout the test duration.

4.3.1 Specimens with a Type-A adhesive

The effect of moisture exposure and cyclic freeze/thaw on the creep behaviour of specimens with aType-A adhesive is evident. The creep displacement was almost doubled when the specimens were subjected to moisture or freeze/thaw cycles. The highest creep displacement values were recorded under a load level of 60% f_y. Furthermore, when a load level of 60f_y was combined with a moisture exposure specimen A-M-60%-2 failed during the sustained load testing at the 30 day mark and this specimen exhibited the highest creep displacement value of all 15 specimens. Figure 4.4 to 4.8 present displacement versus time curves for specimens with Type-A adhesive under all exposure conditions and load levels. Figure 4.9 compares the total overall displacement values after 90 days for all specimens. Where R-40%f_y and R-60%f_y represent specimens tested in room temperature under sustained load levels of 40%f_y (32kN) and 60%f_y (48kN) respectively, M-40%fy and M-60%fy represent specimens tested in moisture exposure under sustained load levels of 40%f_y (32kN) and 60%f_y (48kN) respectively, and FT-40%f_y represents specimens tested under a sustained load level of 40%f_y (32kN) in cyclic freeze/thaw.

4.3.2 Specimens with a Type-B adhesive

Specimens with a Type-B adhesive under a sustained load level of 60% f_y exhibited an approximate by 50% increase in average overall creep displacement versus those tested under a load level of 40%f_y. On the other hand, inconsistent behaviours were recorded when anchors were subjected to the environmental exposure conditions. Exposure to freeze/thaw cycles in the presence of moisture appears to have little to no effect on the overall average creep displacement. However, exposing anchors with Type-B adhesive to moisture produced a widely varying response for the three specimens tested. A higher overall average creep displacement with an increasing rate of creep displacement with time was recorded at a sustained load level of 40% f_y. Under a sustained load level of 60% f_y combined with moisture exposure, a higher creep displacement were recorded and specimen B-M-60%-2 failed at the 10 day mark.

The displacement versus time curves for specimens with a Type-B adhesive under the three exposure conditions are shown in Figure 4.10 to 4.14. Figure 4.15 compares the maximum overall displacement at 90 days under the three exposure conditions and different sustained load levels.

4.3.3 Specimens with a Type-C adhesive

Specimens with a Type-C adhesive showed extremely consistent creep behaviour at an ambient temperature. No significant creep displacement was recorded under ambient temperature under either a sustained load level of 40% or 60% f_y, and only a slight increase in displacement when subjected to moisture. However, when subjected to freeze/thaw cycles under a sustained load level of 40%f_y, and to moisture exposure under a sustained load level of 60%f_y a significant variation in response was noticed, along with a substantial increase in creep displacement.

Figure 4.16 to 4.20 present displacement versus time curves for specimens with Type-C adhesive. Figure 4.21 compares the maximum overall displacement at 90 days under the three exposure conditions and different sustained load levels.

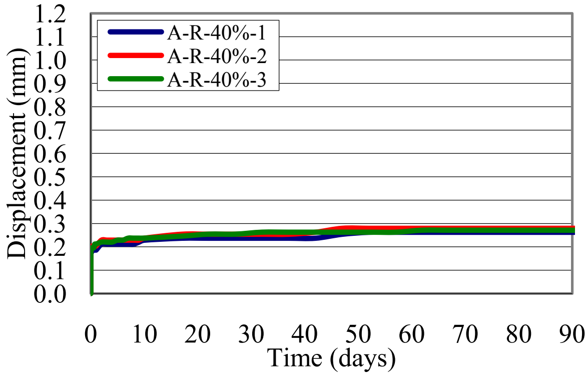


Figure 4.4 – Type-A adhesive under 40%fy in room temperature

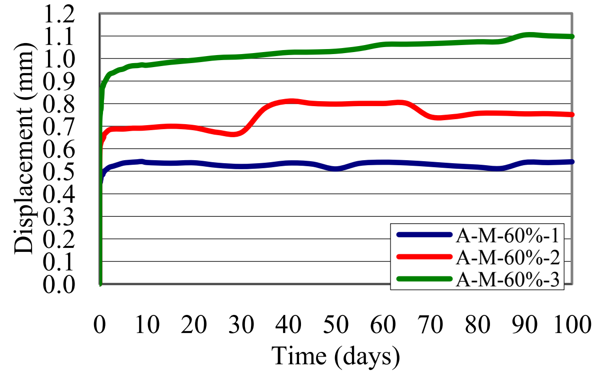


Figure 4.7 - Type-A adhesive under 60%fy in moisture exposure

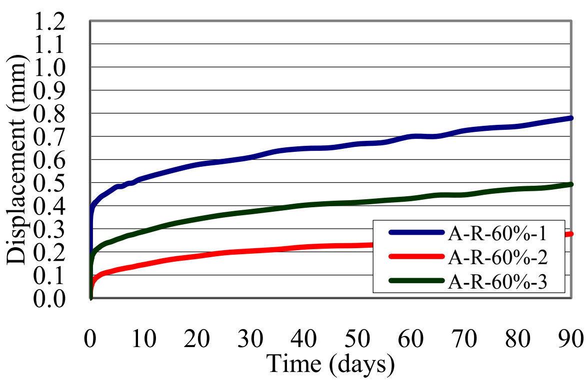


Figure 4.5 - Type-A adhesive under 60%fy in room temperature

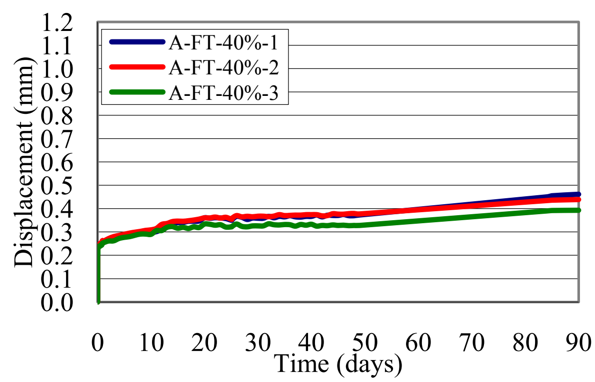


Figure 4.8 - Type-A adhesive under 40%fy in freeze/thaw cycles

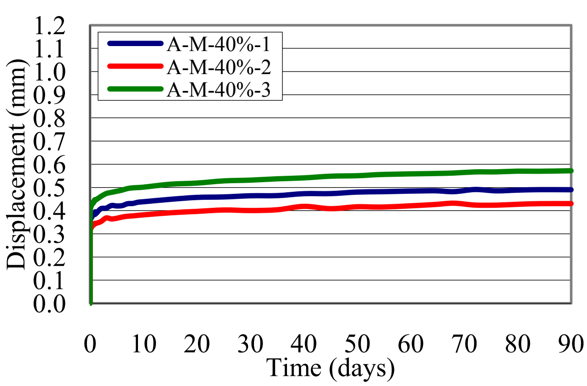


Figure 4.6 - Type-A adhesive under 40%fy in moisture exposure

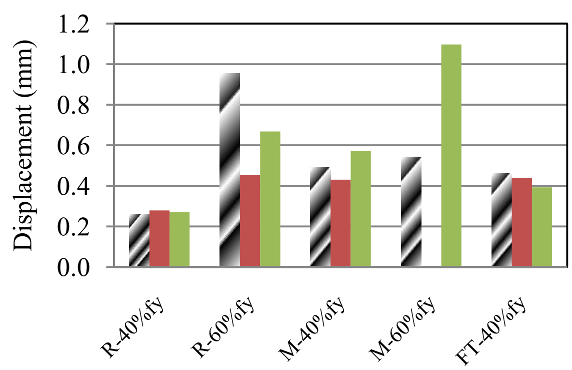


Figure 4.9 – Type-A adhesive overall displacement comparison at 90 days

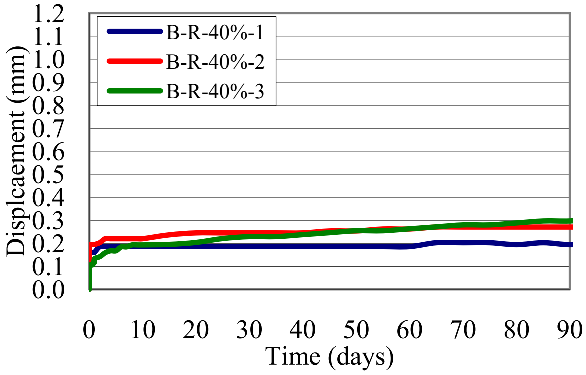


Figure 4.10 - Type-B under 40%fy in room temperature

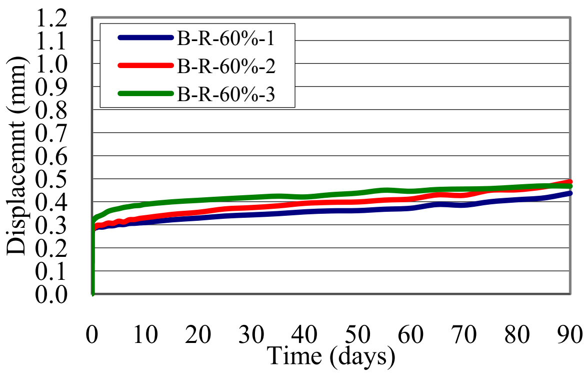


Figure 4.11 - Type-B under 60%fy in room temperature

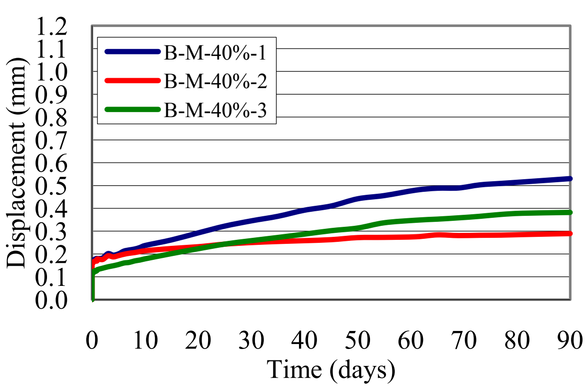


Figure 4.12 – Type-B under 40%fy in moisture exposure

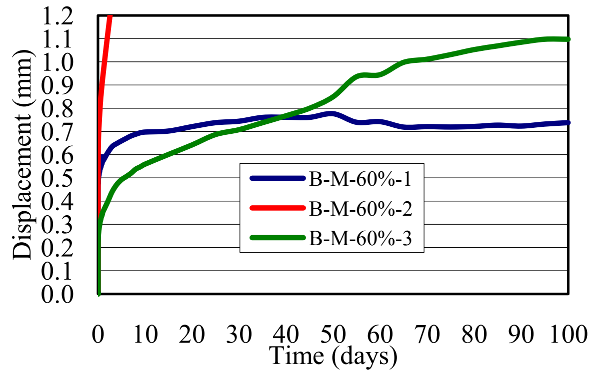


Figure 4.13 – Type-B under 60%fy in moisture exposure

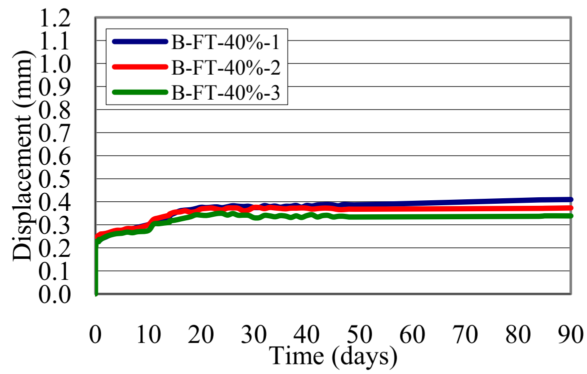


Figure 4.14 – Type-B under 40%fy in freeze/thaw cycles

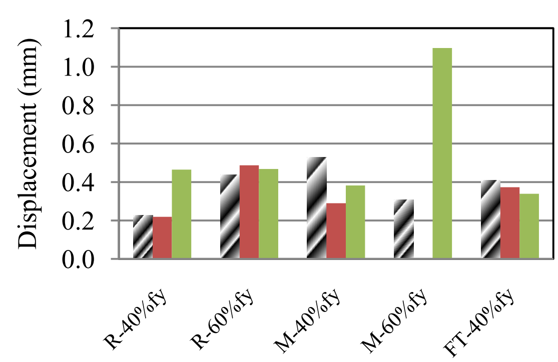


Figure 4.15 – Type-B overall displacement comparison at 90 days

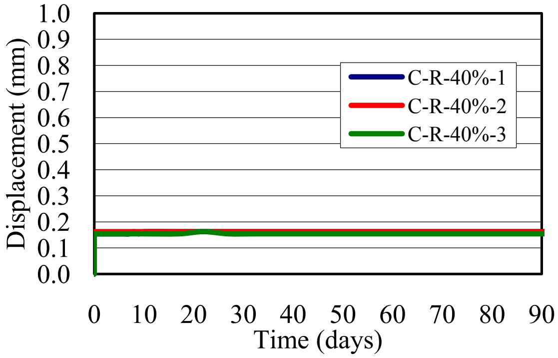


Figure 4.16 – Type-C under 40%fy in room temperature

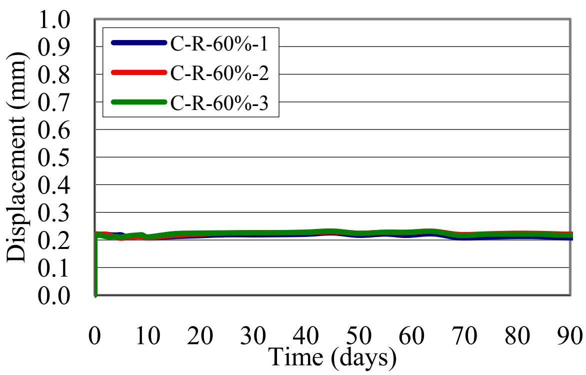


Figure 4.17 – Type-C under 60%fy in room temperature

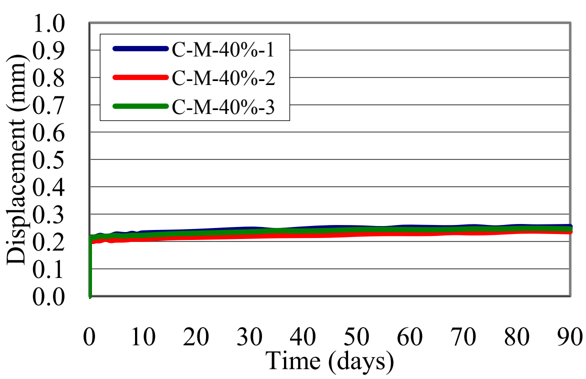


Figure 4.18 – Type-C under 40%fy in moisture exposure

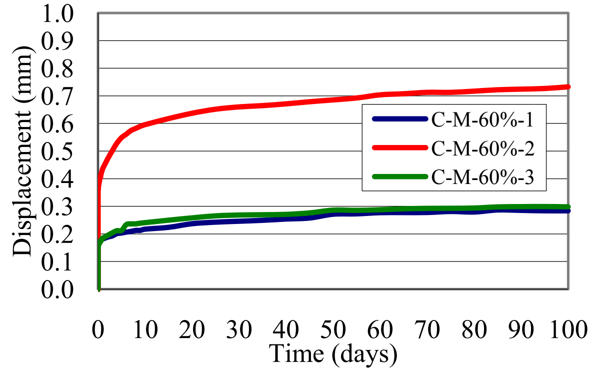


Figure 4.19 – Type-C under 60%fy in moisture exposure

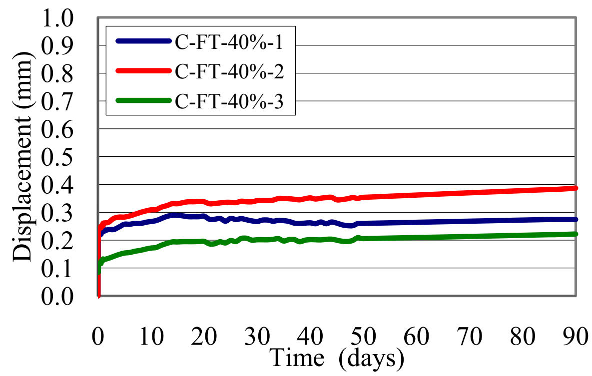


Figure 4.20 – Type-C under 40%fy in freeze/thaw cycles

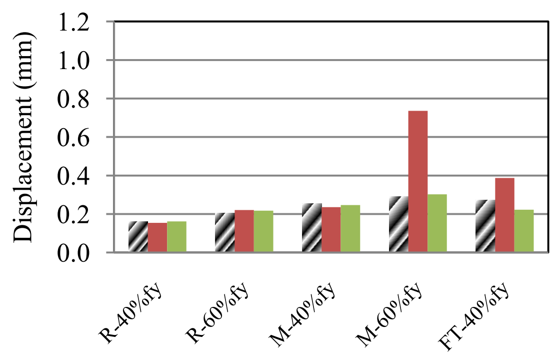


Figure 4.21 – Type-C overall displacement comparison at 90 days

Figure 4.22 compares the average creep displacement at 90 days for the three adhesive types. It is evident that Type-A adhesive exhibited the highest creep under exposures and load levels considered in this study.

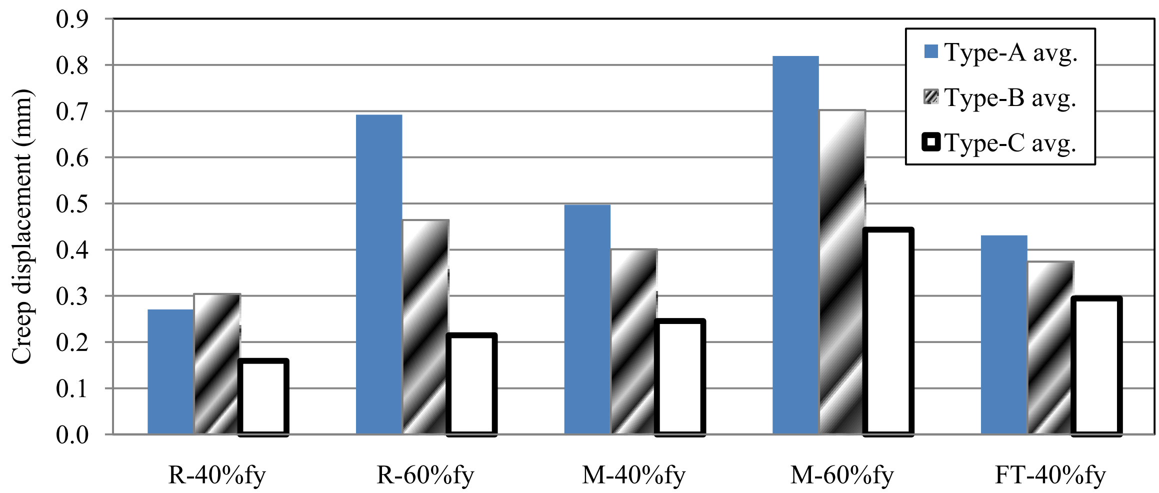


Figure 4.22 – Comparison of average total displacement at 90 days for specimens with the three adhesive types

Chapter 5

Discussion of Results and Proposed test protocol

5.1 Data analysis

Data analysis and a creep assessment were carried out in accordance with ICC-ES AC308 section 11.12 (2009), with RAW results presented in Chapter 4. The extrapolated total displacement including elastic, and creep displacement is determined by projecting a trend line over the service life of the adhesive anchor. The trend line is constructed from a minimum of the last 20 data points (not less than 20 days) of the creep test using the following equation.

$$\Delta(t) = \Delta_{t=0} + a.t^{b} \qquad \text{Eq. 5.1}$$

Where:

$\Delta(t)$ = total displacement recorded in the test at time t

$\Delta_{t=0}$ = initial displacement recorded under sustained load

t = time corresponding to total recorded displacement (hours)

a,b = constants evaluated by regression analysis.

After the trend line is determined, t is replaced with $t_{service}$ (the intended anchor service life), and the extrapolated estimated total displacement ($\Delta_{service}$) is calculated. For an anchor to be satisfactory the mean values of $\overline{\Delta}_{service}$ shall not exceed Δ_{lim} (mean displacement corresponding to loss of adhesion from tension tests, N_{adh}). Loss of adhesion is defined in section 11.3.4 of ES-ICC AC308 as a significant change in stiffness as reflected in an abrupt change in the slope of the static load-displacement curve of the anchor and is calculated according to the following procedure.

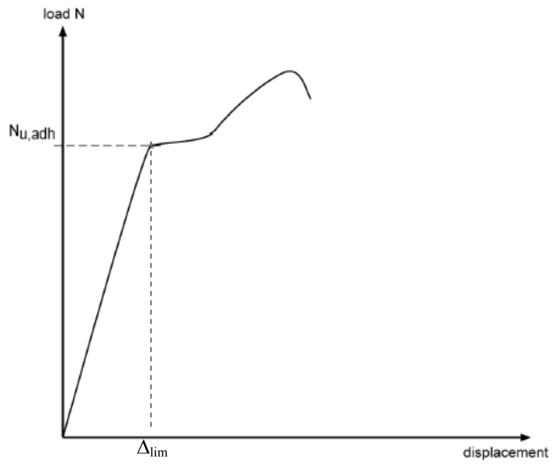
If a significant change in stiffness is identifiable by direct observation, then the loss of adhesion (N_{adh}) is taken as the load corresponding to that change, Figure 5.1(a) (ICC ES-AC308). In cases where the change cannot be observed, loss of adhesion is evaluated as follows:

1. Compute the tangent to the load-displacement curve at a load $N=0.3Nu$, where N_u is the ultimate load from tension tests. The tangent stiffness k_{tan} can be estimated as the secant stiffness between the origin of the load-displacement curve and the point defined by $0.3N_u$ and $\Delta_{0.3}$ as follows;

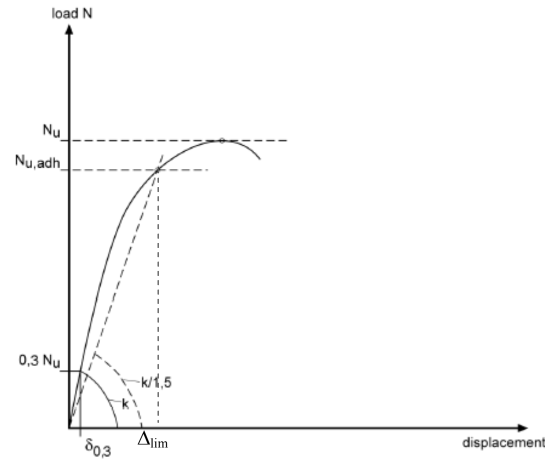
$$k_{tan} \simeq \frac{0.3N_u - N_{origin}}{\Delta_{0.3} - \Delta_{origin}} \qquad \text{Eq. 5.2}$$

   Where:
   $\Delta_{0.3}$ = anchor displacement at $N = N_{0.3}$

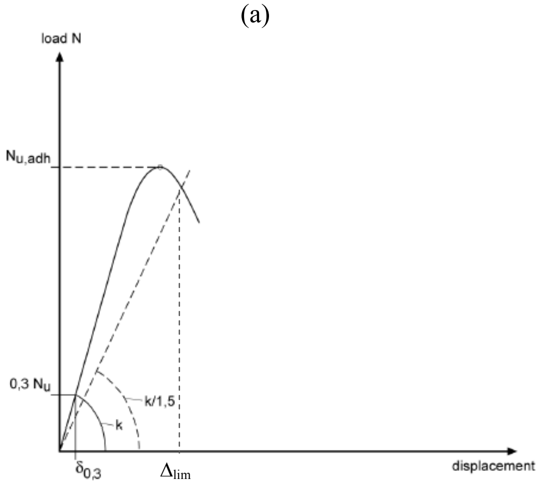
2. Multiply the tangent stiffness by 2/3.
3. Project a straight line from the origin of the load-displacement curve with a slope corresponding to the stiffness calculated.
4. The load N_{adh} corresponds to the point of intersection between the projected line and the measured load-displacement curve, Figure 5.1(b)
5. If point of intersection happens after the ultimate load, then N_{adh} shall be taken as the ultimate load, Figure 5.1(c)
6. If the displacement $\Delta_{0.3} \leq 0.05$ mm, the origin of the projected line shall be shifted to a point on the load-displacement curve given by 0.3 N_u and $\Delta_{0.3}$, Figure 5.1(d)



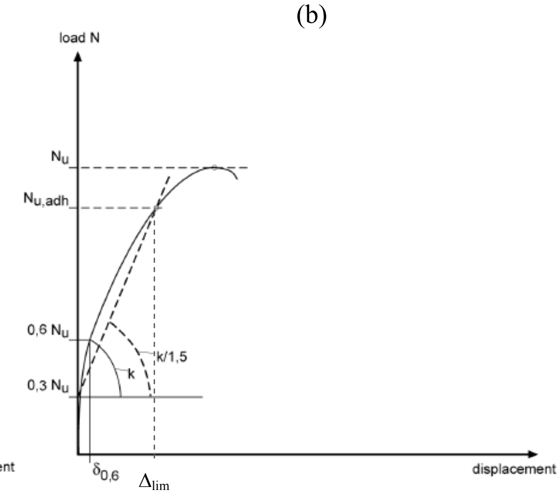
(a)



(b)



(c)



(d)

In this study an embedment depth of 125mm ($6d_b$) was used as representative of a typical embedment depth used in MTO applications. This embedment depth forced all anchors to yield prior to failure under tensile testing. As the anchor yields its cross section decreases along its length including the embedded length, in turn the adhesive expands to maintain contact with the anchor causing bond to start to fail; thus loss of adhesion was governed by the yield strength of the anchors, similar to the situation shown in Figure 5.1(a).

In order to normalize the variations in the yield strength of the steel rebars used in the adhesive anchors in this study, the loss of adhesion was considered to be the lesser of the actual yield strength of the steel bar or the theoretical yield strength for a grade 400 reinforcing bar, 80kN. The displacement corresponding to that load is determined and considered to be the limiting displacement (Δ_{lim}). The loss of Adhesion for each exposure condition is calculated based on the static pullout tests of each phase. Figure 5.2 shows a typical displacement versus time creep curve with the projected estimated displacement over time.

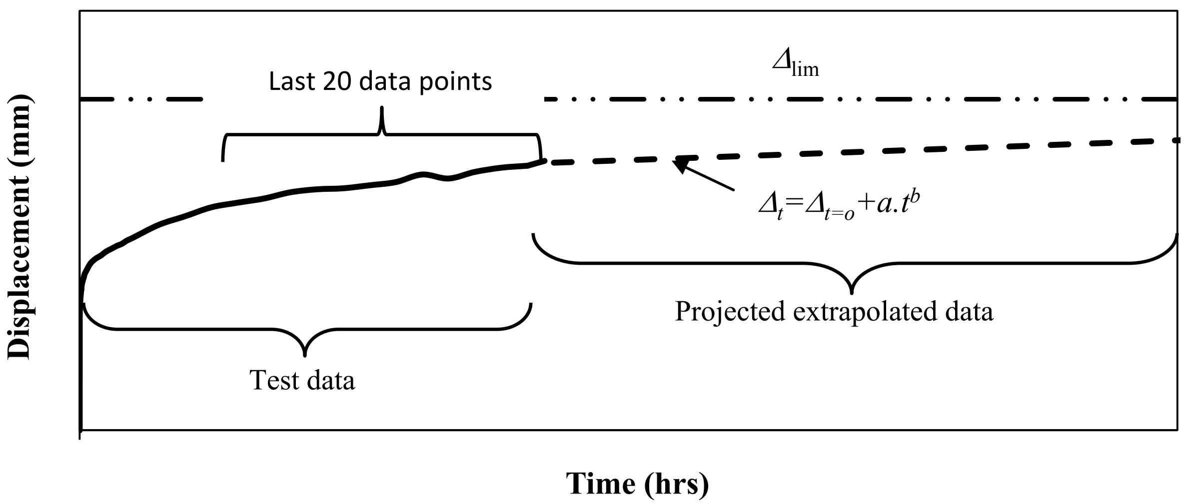


Figure 5.2 – Typical displacement projection versus time curve

ICC ES-AC308 specifies a minimum testing duration of 42 days, and uses the data from the last 20 days for a displacement projection. In this study a minimum testing duration of 90 days was used. For analysis and displacement projection purposes two data ranges where used. The first range complies with AC308, where the last 20 days of 42 days testing data were used for the displacement projection. The second range included the full 90 days of testing data, and used the displacement data from day 22 to 90 of the range for a displacement projection.

Table 5.1-5.3 summarize the data analysis for all the specimens with the extrapolated displacement estimates based on 42 days of test data, while Table 5.4-5.6 presents the analysis results based on 90 days of testing data. The results for all specimens were projected to periods of 10 and 50 years for room temperature conditions, and to a period of 10 years only for moisture and freeze/thaw exposures. Table 5.7-5.8 give a summary of the estimated condition of the anchors after 50 and 10 years of service.

Table 5.1 – Displacement projection summary for specimens with Type-A adhesive based on 42 days of displacement data

Specimen	$\Delta_{t=0}$ (mm)	By regression analysis: a	By regression analysis: b	Average: $\bar{\Delta}_{limit}$ (mm)	Δ_t (mm): 10 years	10 years: Average	50 years	50 years: Average
A-R-40%-1	0.161	0.0140	0.255	0.552	0.416	0.452	0.545	0.601
A-R-40%-2	0.178	0.0140	0.267		0.470		0.627	
A-R-40%-3	0.186	0.0120	0.278		0.470		0.630	
A-R-60%-1	0.179	0.2700	0.123	0.552	1.274	1.132	1.513	1.500
A-R-60%-2	0.185	0.0290	0.287		0.945		1.391	
A-R-60%-3	0.217	0.0760	0.223		1.179		1.594	
A-M-40%-1	0.349	0.0190	0.271	0.556	0.764	0.753		
A-M-40%-2	0.306	0.0180	0.255		0.634			
A-M-40%-3	0.385	0.0310	0.24		0.861			
A-M-60%-1	0.42	0.0720	0.074	0.556	0.587	N/A		
A-M-60%-2	0.412	N/A	N/A		FAILED DURING TESTING			
A-M-60%-3	0.548	N/A	N/A					
A-FT-40%-1	0.195	0.0640	0.145	0.552	0.528	0.481		
A-FT-40%-2	0.2	0.0670	0.138		0.522			
A-FT-40%-3	0.2	0.0710	0.087		0.391			

Table 5.2 – Displacement projection summary for specimens with Type-B adhesive based on 42 days of displacement data

		By regression analysis		Average	Δ_{t} (mm)			
Specimen	$\Delta_{t=0}$ (mm)	a	b	$\bar{\Delta}_{limit}$ (mm)	10 years		50 years	
						Average		Average
B-R-40%-1	0.160	0.0060	0.236		0.248		0.289	
B-R-40%-2	0.194	0.0020	0.505	0.586	0.821	0.638	1.606	1.111
B-R-40%-3	0.097	0.0120	0.363		0.844		1.437	
B-R-60%-1	0.267	0.0040	0.434		0.826		1.390	
B-R-60%-2	0.262	0.0090	0.395	0.586	1.068	0.915	1.785	1.468
B-R-60%-3	0.308	0.0130	0.328		0.851		1.229	
B-M-40%-1	0.165	0.0008	0.829		9.637			
B-M-40%-2	0.161	0.0030	0.505	0.377	1.101	4.807		
B-M-40%-3	0.110	0.0020	0.658		3.684			
B-M-60%-1	0.453	N/A	N/A					
B-M-60%-2	0.488	N/A	N/A	0.377	FAILED DURING TESTING			
B-M-60%-3	0.211	N/A	N/A					
B-FT-40%-1	0.204	0.1260	0.05		0.427			
B-FT-40%-2	0.213	0.1280	0.031	0.505	0.395	0.365		
B-FT-40%-3	0.202	0.058	0.02		0.274			

Table 5.3 – Displacement projection summary for specimens with Type-C adhesive based on 42 days of displacement data

Specimen	$\Delta_{t=0}$ (mm)	By regression analysis a	b	Average $\bar{\Delta}_{limit}$ (mm)	10 years	10 years Average	50 years	50 years Average
C-R-40%-1	0.154	0.0000	0.888		0.680		2.352	
C-R-40%-2	0.162	0.0000	0.00E+00	0.616	0.162	0.332	0.162	0.889
C-R-40%-3	0.154	0.0000	0		0.154		0.154	
C-R-60%-1	0.216	N/A	N/A		0.216		0.216	
C-R-60%-2	0.217	0.0000	1.747	0.616	28.021	10.384	125.000	48.085
C-R-60%-3	0.217	0.0000	1.207		2.915		19.038	
C-M-40%-1	0.202	0.0050	0.325		0.404			
C-M-40%-2	0.200	0.0003	0.602	0.365	0.489	0.422		
C-M-40%-3	0.202	0.0050	0.31		0.372			
C-M-60%-1	0.168	0.0040	0.454		0.869			
C-M-60%-2	0.256	N/A	N/A	0.365	N/A	0.753		
C-M-60%-3	0.142	0.0200	0.282		0.637			
C-FT-40%-1	0.200	0.7950	0.012		0.212			
C-FT-40%-2	0.206	0.0340	0.210	0.439	0.577	0.340		
C-FT-40%-3	0.116	0.0560	0.064		0.231			

Table 5.4 – Displacement projection summary for specimens with Type-A adhesive based on 90 days of displacement data

<table>
<tr><td colspan="2"></td><td colspan="2">By regression analysis</td><td>Average</td><td colspan="4">Δ_t (mm)</td></tr>
<tr><td rowspan="2">Specimen</td><td rowspan="2">$\Delta_{t=0}$ (mm)</td><td rowspan="2">a</td><td rowspan="2">b</td><td rowspan="2">$\overline{\Delta}_{limit}$ (mm)</td><td colspan="2">10 years</td><td colspan="2">50 years</td></tr>
<tr><td></td><td>Average</td><td></td><td>Average</td></tr>
<tr><td>A-R-40%-1</td><td>0.161</td><td>0.016</td><td>0.246</td><td rowspan="3">0.552</td><td>0.424</td><td rowspan="3">0.413</td><td>0.552</td><td rowspan="3">0.521</td></tr>
<tr><td>A-R-40%-2</td><td>0.178</td><td>0.017</td><td>0.241</td><td>0.442</td><td>0.567</td></tr>
<tr><td>A-R-40%-3</td><td>0.186</td><td>0.019</td><td>0.201</td><td>0.373</td><td>0.445</td></tr>
<tr><td>A-R-60%-1</td><td>0.179</td><td>0.203</td><td>0.17</td><td rowspan="3">0.552</td><td>1.584</td><td rowspan="3">1.301</td><td>2.026</td><td rowspan="3">1.799</td></tr>
<tr><td>A-R-60%-2</td><td>0.185</td><td>0.028</td><td>0.291</td><td>0.953</td><td>1.412</td></tr>
<tr><td>A-R-60%-3</td><td>0.217</td><td>0.061</td><td>0.258</td><td>1.366</td><td>1.958</td></tr>
<tr><td>A-M-40%-1</td><td>0.349</td><td>0.025</td><td>0.227</td><td rowspan="3">0.556</td><td>0.680</td><td rowspan="3">0.697</td></tr>
<tr><td>A-M-40%-2</td><td>0.306</td><td>0.021</td><td>0.233</td><td>0.604</td></tr>
<tr><td>A-M-40%-3</td><td>0.385</td><td>0.035</td><td>0.219</td><td>0.808</td></tr>
<tr><td>A-M-60%-1</td><td>0.42</td><td>0.041</td><td>0.147</td><td rowspan="3">0.556</td><td>0.638</td><td>0.638</td></tr>
<tr><td>A-M-60%-2</td><td>0.412</td><td>N/A</td><td>N/A</td><td rowspan="2" colspan="2">FAILED DURING TESTING</td></tr>
<tr><td>A-M-60%-3</td><td>0.548</td><td>N/A</td><td>N/A</td></tr>
<tr><td>A-FT-40%-1</td><td>0.195</td><td>0.018</td><td>0.337</td><td rowspan="3">0.552</td><td>1.028</td><td rowspan="3">0.838</td></tr>
<tr><td>A-FT-40%-2</td><td>0.2</td><td>0.024</td><td>0.292</td><td>0.866</td></tr>
<tr><td>A-FT-40%-3</td><td>0.2</td><td>0.025</td><td>0.248</td><td>0.620</td></tr>
</table>

Table 5.5 – Displacement projection summary for specimens with Type-B adhesive based on 90 days of displacement data

<table>
<tr><td rowspan="3">Specimen</td><td rowspan="3">$\Delta_{t=0}$ (mm)</td><td colspan="2">By regression analysis</td><td>Average</td><td colspan="4">Δt (mm)</td></tr>
<tr><td rowspan="2">a</td><td rowspan="2">b</td><td rowspan="2">$\bar{\Delta}_{limit}$ (mm)</td><td colspan="2">10 years</td><td colspan="2">50 years</td></tr>
<tr><td></td><td>Average</td><td></td><td>Average</td></tr>
<tr><td>B-R-40%-1</td><td>0.160</td><td>0.008</td><td>0.200</td><td rowspan="3">0.586</td><td>0.238</td><td rowspan="3">0.531</td><td>0.267</td><td rowspan="3">0.829</td></tr>
<tr><td>B-R-40%-2</td><td>0.194</td><td>0.003</td><td>0.413</td><td>0.524</td><td>0.835</td></tr>
<tr><td>B-R-40%-3</td><td>0.097</td><td>0.014</td><td>0.348</td><td>0.832</td><td>1.383</td></tr>
<tr><td>B-R-60%-1</td><td>0.267</td><td>0.001</td><td>0.595</td><td rowspan="3">0.586</td><td>1.140</td><td rowspan="3">1.140</td><td>2.540</td><td rowspan="3">2.187</td></tr>
<tr><td>B-R-60%-2</td><td>0.262</td><td>0.005</td><td>0.483</td><td>1.482</td><td>2.915</td></tr>
<tr><td>B-R-60%-3</td><td>0.308</td><td>0.016</td><td>0.301</td><td>0.800</td><td>1.106</td></tr>
<tr><td>B-M-40%-1</td><td>0.165</td><td>0.001</td><td>0.728</td><td rowspan="3">0.377</td><td>4.129</td><td rowspan="3">2.531</td></tr>
<tr><td>B-M-40%-2</td><td>0.161</td><td>0.005</td><td>0.428</td><td>0.813</td></tr>
<tr><td>B-M-40%-3</td><td>0.110</td><td>0.002</td><td>0.628</td><td>2.651</td></tr>
<tr><td>B-M-60%-1</td><td>0.453</td><td>N/A</td><td>N/A</td><td rowspan="3">0.377</td><td colspan="2" rowspan="3">FAILED DURING TESTING</td></tr>
<tr><td>B-M-60%-2</td><td>0.488</td><td>N/A</td><td>N/A</td></tr>
<tr><td>B-M-60%-3</td><td>0.211</td><td>N/A</td><td>N/A</td></tr>
<tr><td>B-FT-40%-1</td><td>0.204</td><td>0.071</td><td>0.173</td><td rowspan="3">0.505</td><td>0.713</td><td rowspan="3">0.505</td></tr>
<tr><td>B-FT-40%-2</td><td>0.213</td><td>0.117</td><td>0.042</td><td>0.402</td></tr>
<tr><td>B-FT-40%-3</td><td>0.202</td><td>0.128</td><td>0.039</td><td>0.402</td></tr>
</table>

Table 5.6 – Displacement projection summary for specimens with Type-C adhesive based on 90 days of displacement data

		By regression analysis		Average	Δ_t (mm)			
Specimen	$\Delta_{t=0}$ (mm)	a	b	$\bar{\Delta}_{limit}$ (mm)	10 years		50 years	
						Average		Average
C-R-40%-1	0.154	8.08E-04	0.312	0.616	0.182	0.166	0.201	0.172
C-R-40%-2	0.162	-1.6E-09	0.000		0.162		0.162	
C-R-40%-3	0.154	-1.5E-09	0.000		0.154		0.154	
C-R-60%-1	0.216	0.002	0.140	0.616	0.226	0.235	0.228	0.253
C-R-60%-2	0.217	N/A	N/A		0.217		0.217	
C-R-60%-3	0.217	1.8E-04	0.483		0.262		0.314	
C-M-40%-1	0.202	0.006	0.288	0.365	0.361	0.416		
C-M-40%-2	0.200	4.3E-04	0.587		0.545			
C-M-40%-3	0.202	0.004	0.312		0.341			
C-M-60%-1	0.168	0.006	0.393	0.365	0.693	0.589		
C-M-60%-2	0.256	N/A	N/A		N/A			
C-M-60%-3	0.142	0.031	0.211		0.484			
C-FT-40%-1	0.200	0.029	0.130	0.439	0.327	0.511		
C-FT-40%-2	0.206	0.028	0.245		0.661			
C-FT-40%-3	0.116	0.008	0.350		0.546			

Table 5.7 – Projected displacement status at a service life of 50 years in room temperature, based on 90 days of test data

Specimen	Status @ 50 years	Specimen	Status @ 50 years	Specimen	Status @ 50 years
A-R-40%-1	Below limit	B-R-40%-1	Below limit	C-R-40%-1	Below limit
A-R-40%-2	Failed	B-R-40%-2	Failed	C-R-40%-2	Below limit
A-R-40%-3	Below limit	B-R-40%-3	Failed	C-R-40%-3	Below limit
A-R-60%-1	Failed	B-R-60%-1	Failed	C-R-60%-1	Below limit
A-R-60%-2	Failed	B-R-60%-2	Failed	C-R-60%-2	Below limit
R-R-60%-3	Failed	B-R-60%-3	Failed	C-R-60%-3	Below limit

Table 5.8 – Projected displacement status at a service life of 10 years under the exposure of moisture and freeze/thaw cycles, based on 90 days of test data

Specimen	Status @ 10 years	Specimen	Status @ 10 years	Specimen	Status @ 10 years
A-M-40%-1	Failed	B-M-40%-1	Failed	C-M-40%-1	Below limit
A-M-40%-2	Failed	B-M-40%-2	Failed	C-M-40%-2	Failed
A-M-40%-3	Failed	B-M-40%-3	Failed	C-M-40%-3	Below limit
A-M-60%-1	Failed	B-M-60%-1	Failed during testing	C-M-60%-1	Failed
A-M-60%-2	Failed during testing	B-M-60%-2	Failed during testing	C-M-60%-2	Failed during testing
A-M-60%-3	Failed during testing	B-M-60%-3	Failed during testing	C-M-60%-3	Failed
A-FT-40%-1	Failed	B-FT-40%-1	Failed	C-FT-40%-1	Below limit
A-FT-40%-2	Failed	B-FT-40%-2	Below limit	C-FT-40%-2	Failed
A-FT-40%-3	Below limit	B-FT-40%-3	Below limit	C-FT-40%-3	Failed

The displacement projections were carried out twice based on the two ranges of test data. Displacement projections based on the two ranges were quite close to each other except for the displacement projections for specimens with Type-A, and Type C adhesives a under freeze/thaw exposure. When the displacements for specimens with Type-A and Type-C adhesives in freeze/exposure were projected using the first range (the last 20 days of 42 days test data), the projected displacement satisfied the displacement limit. On the other hand, when the displacement was projected based on the second range (day 22 to day 90 of the test data), the projected displacement failed to satisfy the displacement limit. Based on this it was deemed that 42 days of displacement data may produce an unconservative displacement projection.

When examining the time versus displacement curves for specimens with both Type-A (Figure 4.8 - Type-A adhesive under 40%fy in freeze/thaw cycles) and Type-C (Figure 4.20) exposed to freeze/thaw cycles, it is observed that for up to 50 days the increase in displacement had a decreasing rate, while from day 50 to day 90 the creep displacement rate increases. This can be interpreted as the initiation of a tertiary creep phase, which would explain the difference in the displacement projections outcomes based on the two ranges, since the first range (42 days) would not include the initiation of a tertiary creep phase and would thus produce an unconservative displacement projection.

5.2 Proposed test protocol

The testing protocol adopted in this study was mainly based on the requirements of ES-ICC AC308, however, some modifications were implemented based on the findings of this study. The recommended adjustments for prequalifying adhesive anchors under sustained loads are as follows;

1. The minimum testing duration shall be 90 days rather than 42 days, as discussed above the displacement projection based on a test duration of 42 days can produce unconservative results.

2. A displacement sampling rate at a maximum interval of 3 days shall be used after the first 10 days of testing to obtain 20 data points.
3. A displacement projection shall be based on the test data from day 20 to day 90 (a minimum of 20 data points at a sampling rate of every 3days).

The disadvantages of the qualification method adopted in ICC ES-AC308 are the uncertainty that accompanies a displacement projection by means of a Findley power law, as well as the limitation imposed on the adhesive manufacturers that they cannot qualify their products beyond a pass/fail criterion (Cook 2009). On the other hand, the stress versus time-to-failure method presented in Cook (2009) minimizes the uncertainty as it relies on the failure points to construct a creep-rupture curve, and gives the opportunity for individual products to stand out as the creep rupture curve would allow designers to know the predicted time-to-failure for each adhesive anchor at a certain stress level rather than labeling them all as passed or failed. However, this approach involves an extensive amount of testing to construct the envelope for different embedment depths.

An integration of the methods presented in Cook (2009), ICC ES-AC308 requirements and the recommended modifications above would result in a well rounded qualification method and a means to evaluate the mathematical displacement projection method. An overview of the integrated procedure is as follows:

- Five specimens shall be tested statically to failure to determine the mean tensile strength. The specimens surface in to be confined to avoid failure by concrete cone formation. The confinement requirements shall be in accordance to section 5.7.3.2 of ICC ES-AC308. Where a confinement plate to be placed on top of the concrete specimen with minimum thickness equal to the anchor diameter and center hole with 1.5 to 2 times the anchor's diameter.

- Based on the creep results of this study testing three specimens per adhesive would be impractical for determining a mean value, as specimens vary widely in creep response under sustained load. Therefore, five specimens shall be tested under sustained stress levels of 85% and 75% of the mean tensile strength determined from static testing. Failure will be defined by the initiation of the tertiary creep phase, and if catastrophic failure does not occur by 3000 hours at a 75% stress level testing would be stopped and the specimen assumed to have failed.
- A creep response envelope for adhesive anchors should be constructed using the stress versus time-to-failure method at stress levels of 100%, 85%, and 75%. A least square trendline should be constructed through the data and projected linearly.
- To obtain the time-to-failure at a stress level of 55% (the stress level specified in AC308 for sustained load testing) a horizontal line corresponding to a 55% stress level is extended to intersect the creep envelop, and the time corresponding to the intersection is taken to be the time-to-failure at a 55% sustained stress level
- To quantify the uncertainty arising from the mathematical displacement projection (the findley power law), an additional set of five specimens shall be tested under a sustained load level of 55% of the mean tensile capacity as per ICC ES-AC308. The testing duration shall be a minimum of 90 days, with a sampling rate of every 5 minutes for the first hour, hourly for the next 24 hours, daily for the next 10 days and every 3 days thereafter.
- Time versus displacement curves for all five specimens shall be plotted. Unlike the stress versus time-to-failure method, failure will be governed by a displacement limit as per AC308 (section 5.1). The mean time-ot-failure shall be determined as the intersection of the displacement limit and the time-versus-displacement curves. To quantify the difference in the projected displacement based on AC308 and the stress versus time-to-failure method, the mean

time to failure obtained based on AC308 is then compared to the time of failure obtained from the stress versus time-to failure method.

Creep performance of adhesives anchors should be evaluated under sustained load for a freeze/thaw exposure, in-service moisture exposure, and elevated temperature. Each exposure condition should follow the above described procedure.

Chapter 6

Conclusions

A research study was conducted to examine the effect of various environmental exposures on the creep performance of adhesive anchors in concrete. The study focused on three types of commonly available adhesives. The sustained load test results were analysed and projected to an estimated service life to evaluate the long-term behaviour of such anchors under the exposure of various environmental conditions.

6.1 Experimental findings

1. Static test results from specimens tested at room temperature showed that specimens with Type-B and Type-C adhesives failed by yielding of the anchor followed by steel rupture. Specimens with a Type-A adhesive failed by yielding of the anchor followed by bond failure.
2. Epoxy-based adhesives (Type-B, Type-C) exhibited higher ultimate capacities than Type-A.
3. In terms of residual capacity, test specimens retained a higher percentage of their capacity after exposure to ambient conditions than specimens exposed to moisture and freeze/thaw cycles.
4. In terms of long term creep behaviour, specimens with all three types of adhesives had fairly similar initial elastic displacements.
5. At room temperature, specimens with Type-C (standard set, epoxy based) adhesive exhibited a very stiff response with little creep displacement with time, while specimens with Type-B and Type-A adhesives exhibited a high creep displacement with time.
6. In creep tests with moisture exposure, both specimens with Type-A, and Type-B adhesives showed almost double the displacement as compared to specimens with a Type-C adhesive.

7. Freeze/thaw cycles had a minimal effect on specimens with a Type-B adhesive, but there was a significant increase in overall creep displacement for specimens with a Type-A adhesive.
8. Specimens with a Type-C adhesive exhibited higher displacement when exposed to freeze/thaw cycles than at room temperature, with a high variability in the creep displacement within the three specimens.

6.2 Data analysis findings

Data analysis was carried out to assess the effect of environmental conditions on the anchor systems within their intended service life. The data collected during the test duration was projected to a service life of 50 years under a room temperature conditions, and to a service life of 10 years for exposure to moisture or cyclic freeze/thaw. The displacement at the service life was compared to a failure criteria governed by the mean limit displacement corresponding to the anchors yield load during static pullout testing. Results of the analysis revealed the following:

1. Under a sustained load level of 40%f_y at a room temperature condition, specimens with Type-A adhesive satisfied the displacement limit for an estimated projection of 50 years; however, they failed to satisfy the displacement limit under an extrapolation for a sustained load of 60%f_y in a room temperature exposure. Under an exposure to moisture and freeze/thaw cycles, specimens with a Type-A adhesive were considered to have failed after an estimated service life of 10 years, at which time their projected displacement exceeded the displacement limit.
2. Specimens with a Type-B adhesive were considered to have failed under both load levels (40%f_y and 60%f_y) at room temperature after 50 years, and with moisture exposure after 10 years. However, displacement levels did not exceed the failure criteria when subjected to a freeze/thaw exposure.

3. The estimated data projection for 50 years indicates that specimens with a Type-C sustained both load levels (40%f_y and 60%f_y) at room temperature, and satisfied the displacement requirement. However, specimens with a Type-C adhesive failed under moisture and freeze/thaw exposure after an estimated projected service life of 10 years.
4. A comparison between projected displacements based on 42 days of the test data versus projection based on 90 days of test data revealed that the projection based on 42 days could produce unconservative results.
5. An integrated testing and evaluation procedure was proposed to eliminate and evaluate the uncertainty of a mathematical displacement projection.

6.3 Recommendations

In summary, the effects of various environmental exposures are evident in the experimental results obtained in this research study. The effect of moisture exposure and freeze/thaw cycles on the creep behaviour of all three commonly used adhesives is evident. Type-C (Standard set two part epoxy) adhesive appears to be superior in terms of creep behaviour to both the fast setting Type-B (epoxy based), and Type-A (acrylic base) adhesives.

However, a definite conclusion on the relative performance of these anchoring materials based on the limited number of experiments conducted is not feasible. Further experimental testing on each individual adhesive material is required to accurately assess their response under different environmental exposure. The incorporation of environmental effects on the long-term behaviour of adhesives anchor into available design models and evaluation criteria is important.

Appendix A

Displacement projection based on 90 days of test data

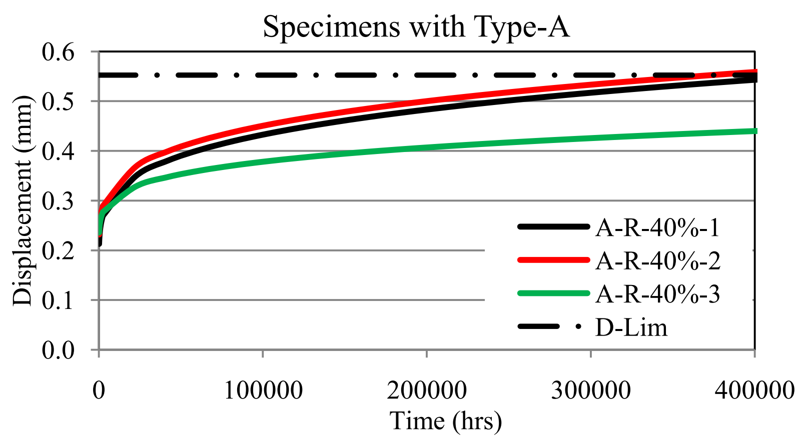


Figure A. 1 – Projected displacement for Specimens with Type-A adhesive under 40%fy in room temperature

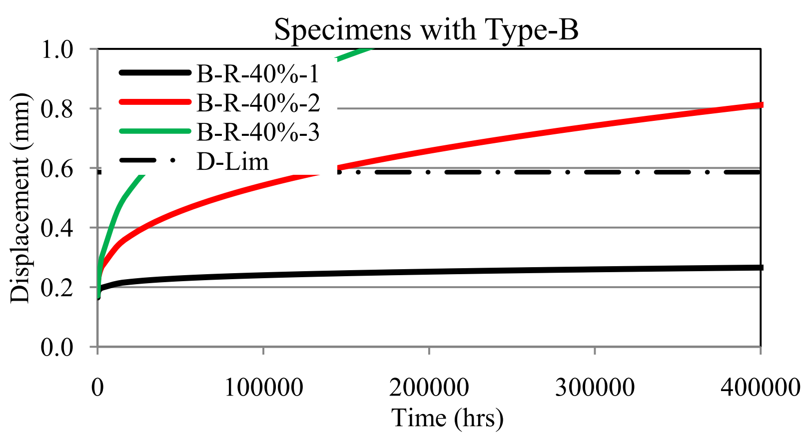


Figure A. 2 – Projected displacement for Specimen with Type-B adhesive under 40%fy in room temperature

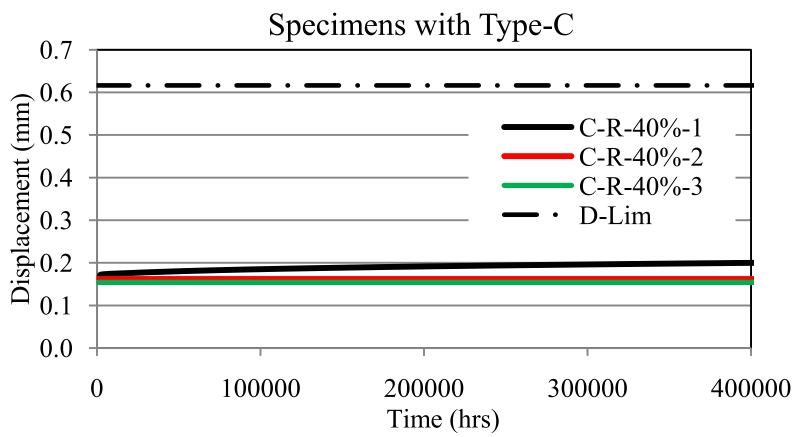


Figure A. 3 – Projected displacement for Specimens with Type-C adhesive under 40%fy in room temperature

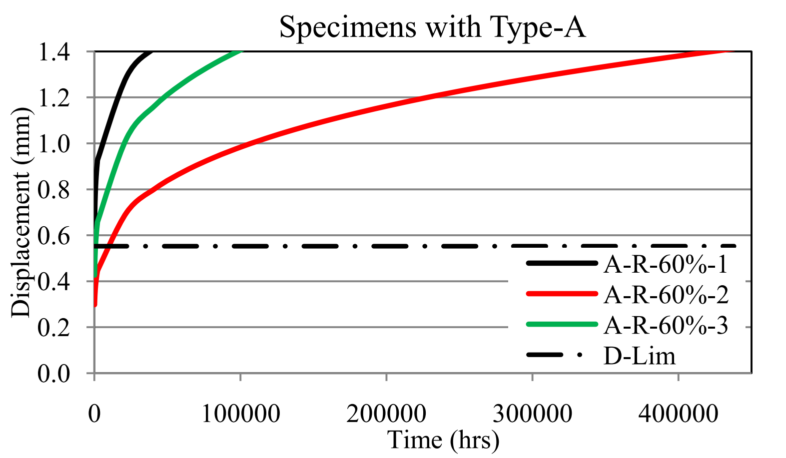


Figure A. 4 – Projected displacement for Specimens with Type-A adhesive under 60%fy in room temperature

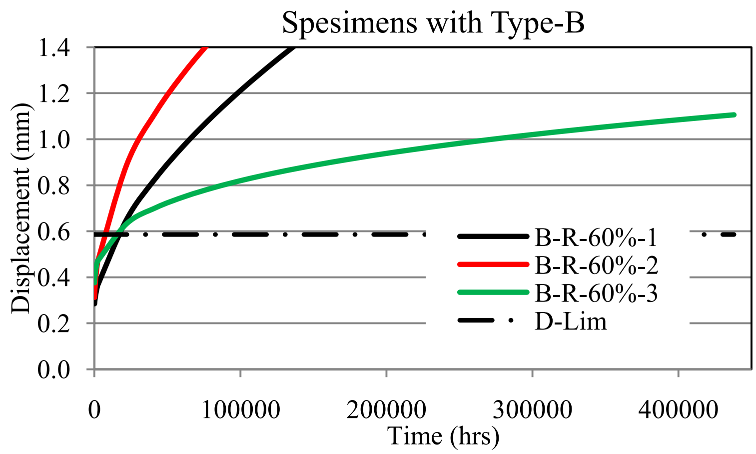


Figure A. 5 – Projected displacement for Specimen with Type-B adhesive under 60%fy in room temperature

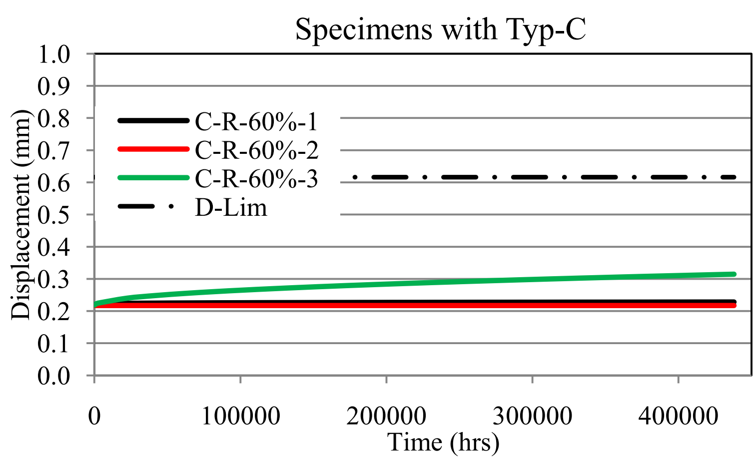


Figure A. 6 – Projected displacement for Specimens with Type-C adhesive under 60%fy in room temperature

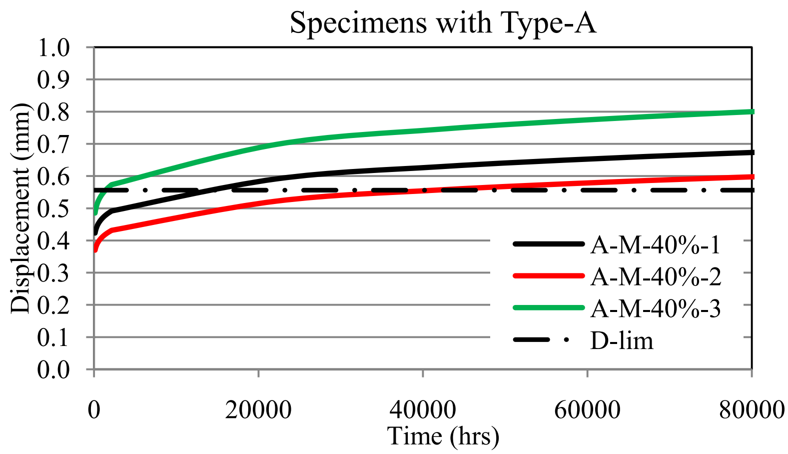


Figure A. 7 – Projected displacement for Specimens with Type-A adhesive under 40%fy and moisture exposure

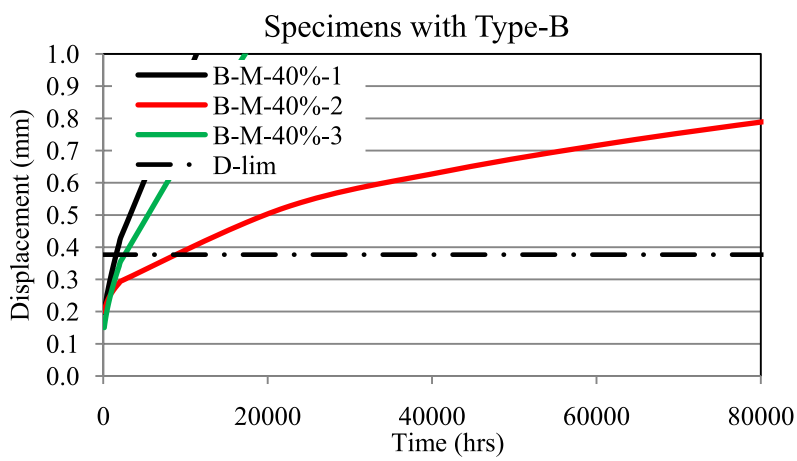


Figure A. 8 – Projected displacement for Specimen with Type-B adhesive under 40%fy and moisture exposure

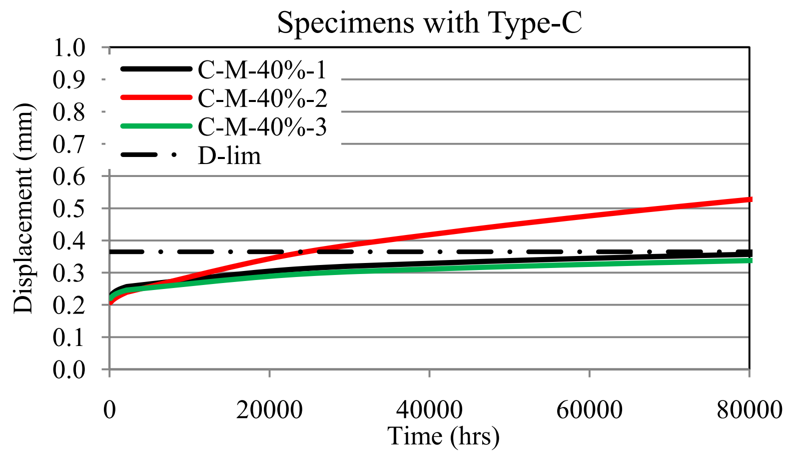


Figure A. 9 – Projected displacement for specimens with Type-C adhesive under 40%fy and moisture exposure

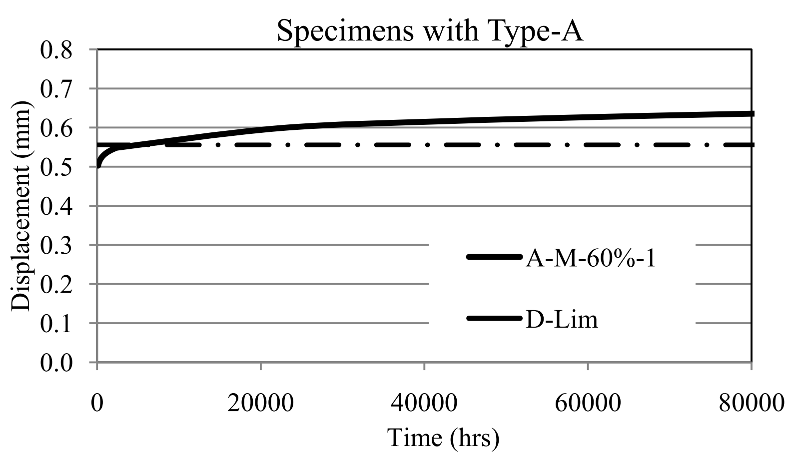


Figure A. 10 – Projected displacement for Specimens with Type-A adhesive under 60%fy and moisture exposure

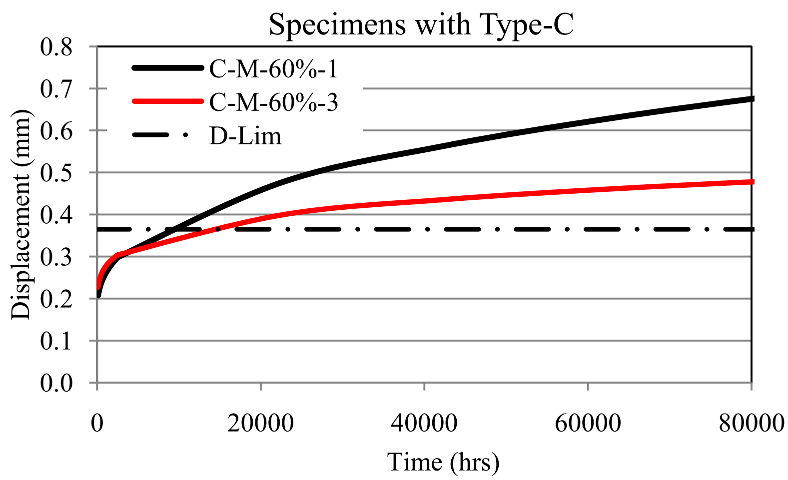


Figure A. 11 – Projected displacement for Specimens with Type-C adhesive under 60%fy and moisture exposure

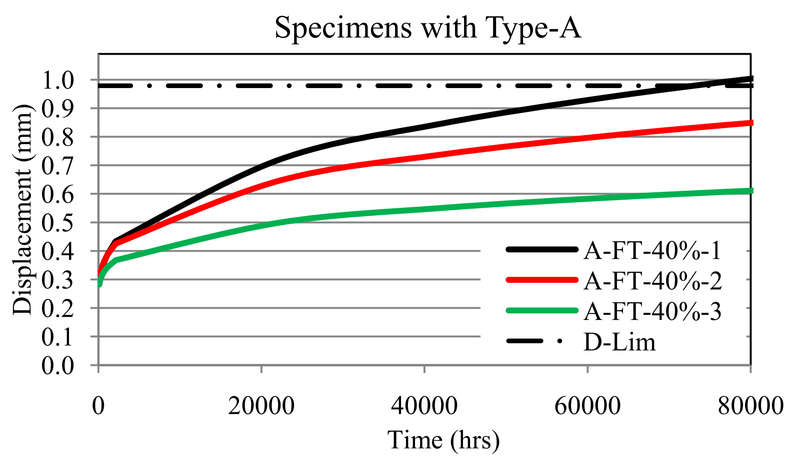


Figure A. 12 – Projected displacement for Specimens with Type-A adhesive under 40%fy and freeze/thaw cycles

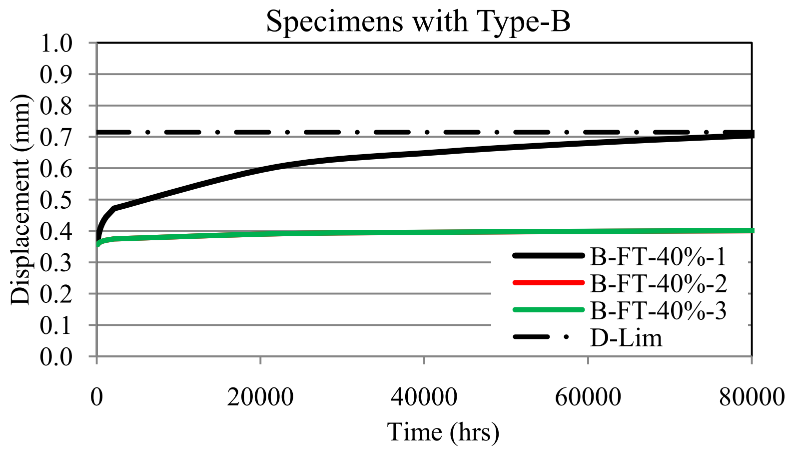


Figure A. 13 – Projected displacement for Specimen with Type-B adhesive under 40%fy and freeze/thaw cycles

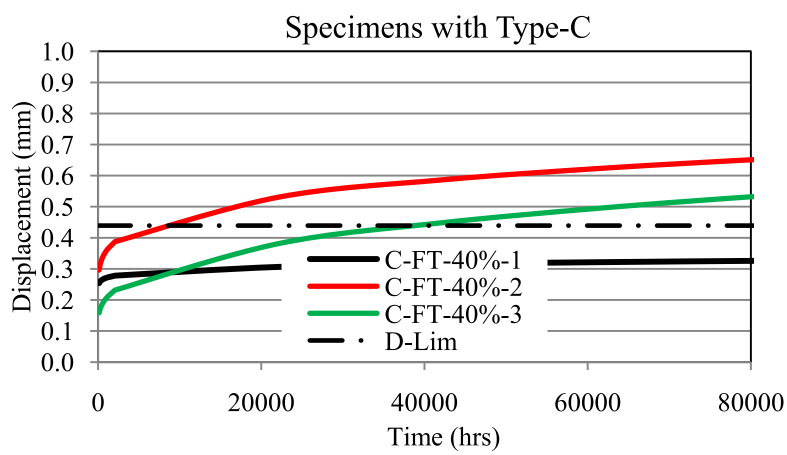


Figure A. 14 – Projected displacement for Specimens with Type-C adhesive under 40%fy and freeze/thaw cycles

Appendix B

Displacement projection based on 42 days of test data

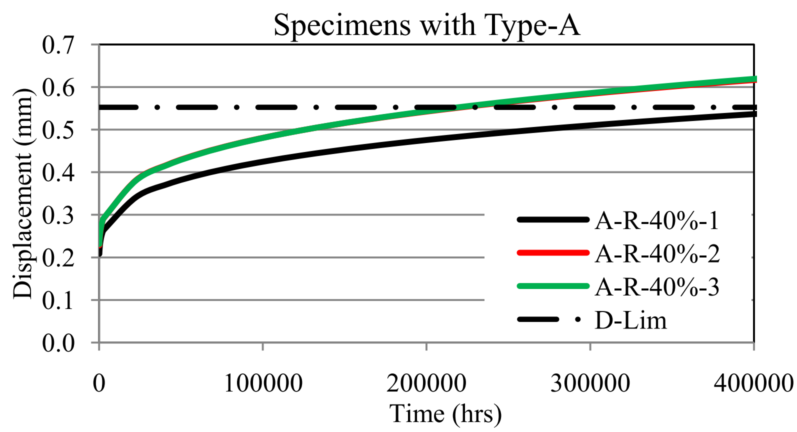


Figure B. 1 – Projected displacement for Specimens with Type-A adhesive under 40%fy in room temperature

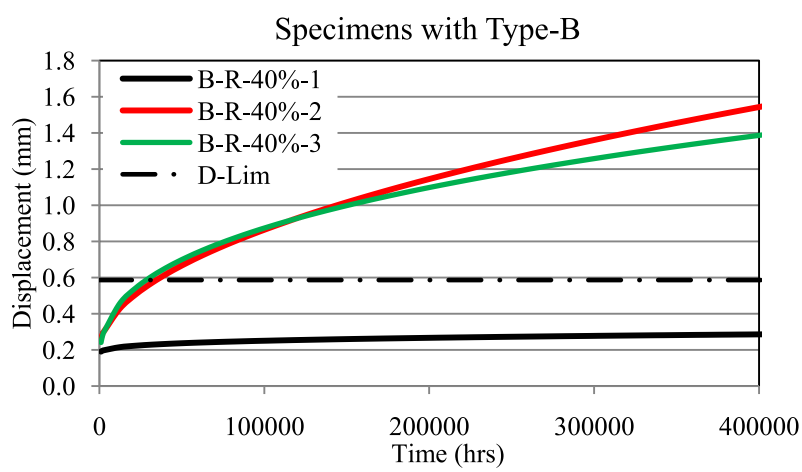


Figure B. 2 – Projected displacement for Specimens with Type-B adhesive under 40%fy in room temperature

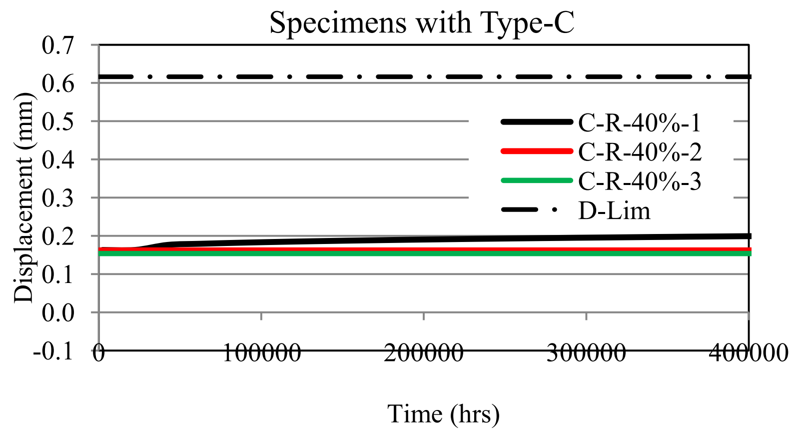


Figure B. 3 – Projected displacement for Specimens with Type-C adhesive under 40%fy in room temperature

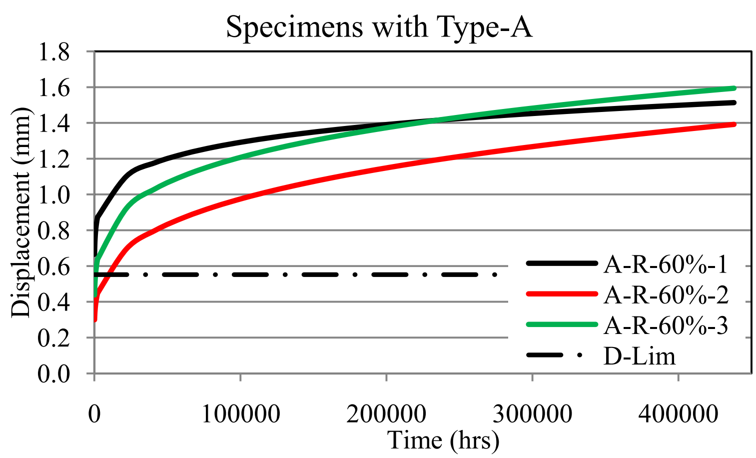


Figure B. 4 – Projected displacement for Specimens with Type-A adhesive under 60%fy in room temperature

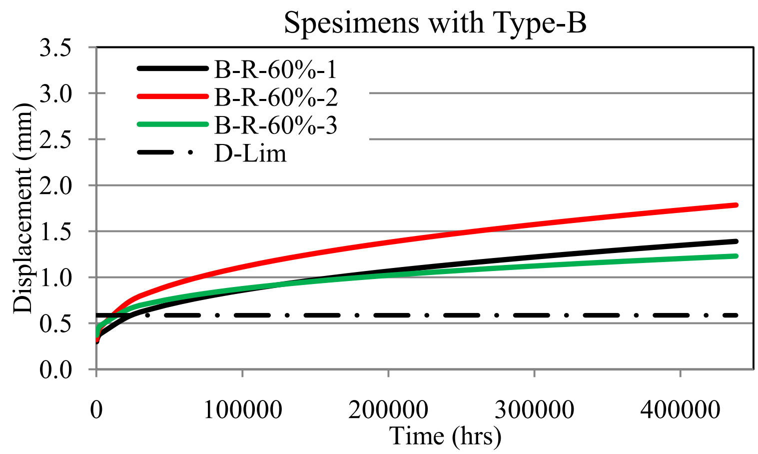


Figure B. 5 – Projected displacement for Specimens with Type-B adhesive under 60%fy in room temperature

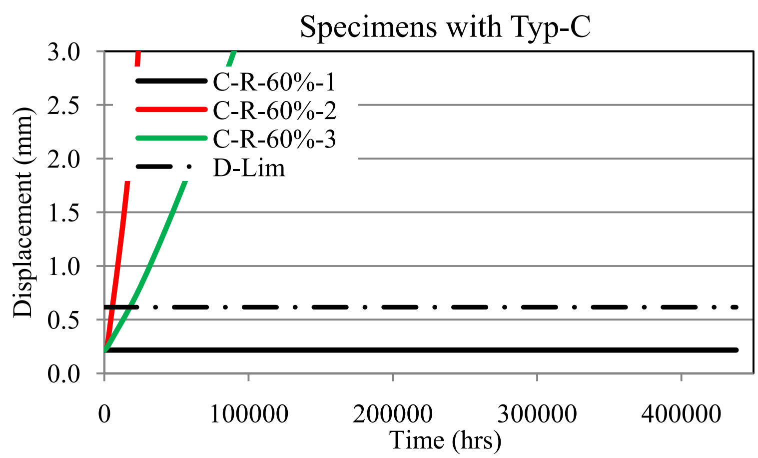


Figure B. 6 – Projected displacement for Specimens with Type-C adhesive under 60%fy in room temperature

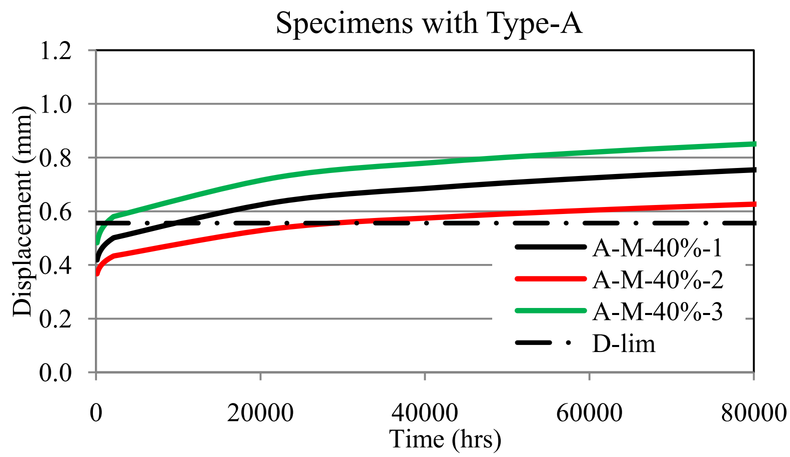


Figure B. 7 – Projected displacement for Specimens with Type-A adhesive under 40%fy and moisture exposure

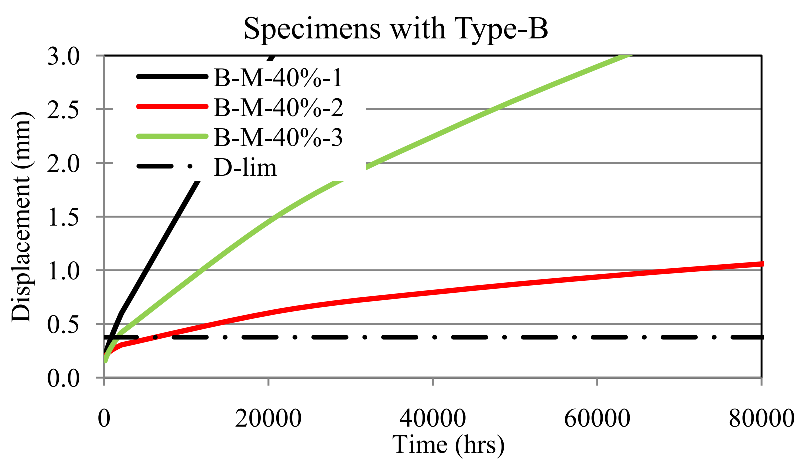


Figure B. 8 – Projected displacement for Specimens with Type-B adhesive under 40%fy and moisture exposure

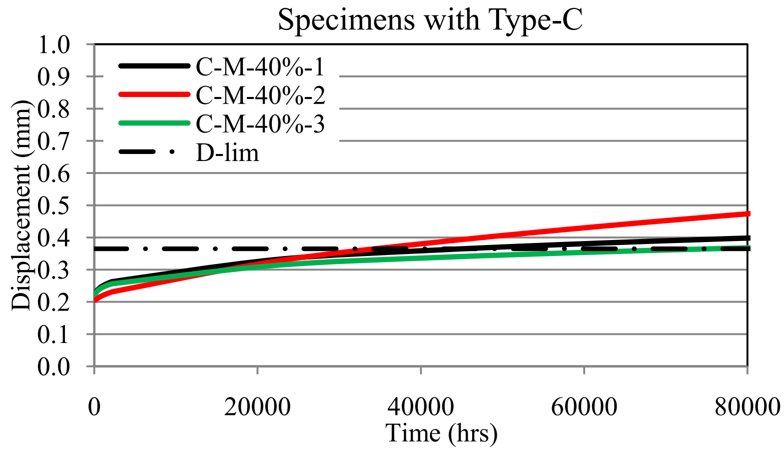


Figure B. 9 – Projected displacement for Specimens with Type-C adhesive under 40%fy and moisture exposure

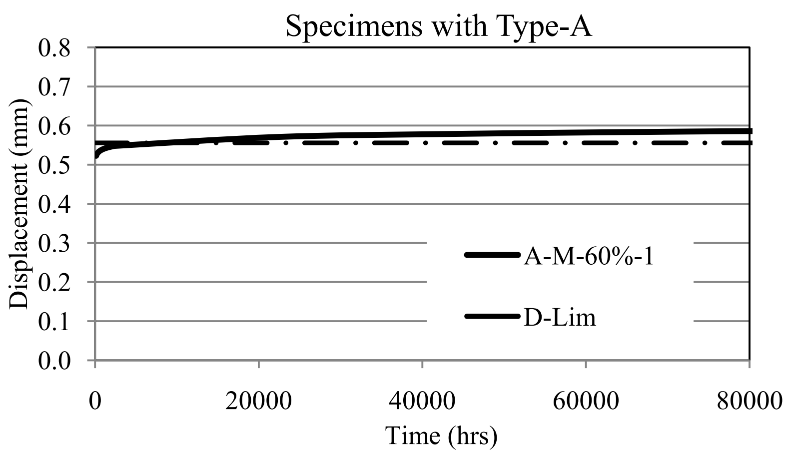


Figure B. 10 – Projected displacement for Specimens with Type-A adhesive under 60%fy and moisture exposure

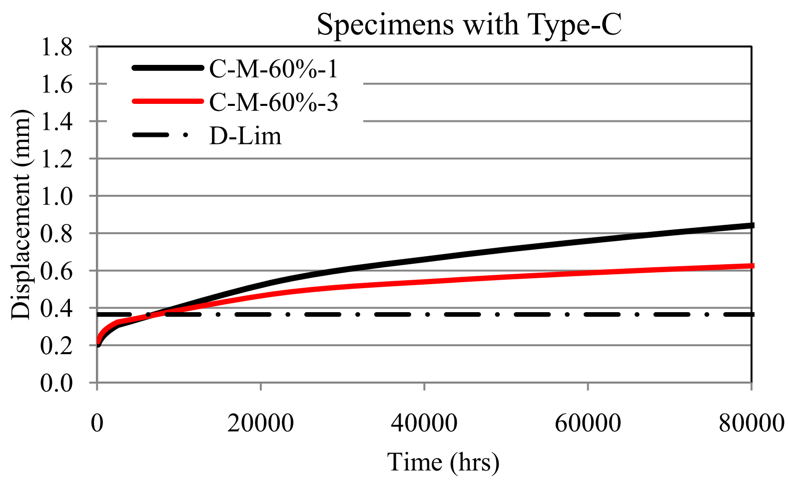


Figure B. 11 – Projected displacement for Specimens with Type-C adhesive under 60%fy and moisture exposure

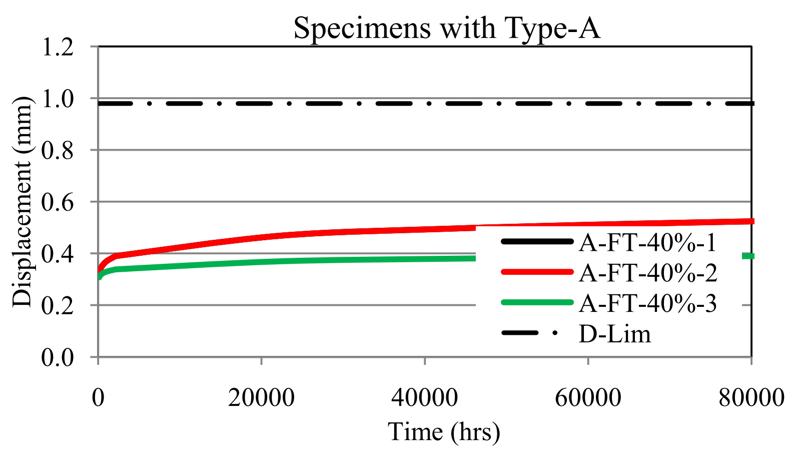


Figure B. 12 – Projected displacement for Specimens with Type-A adhesive under 40%fy and freeze/thaw cycles

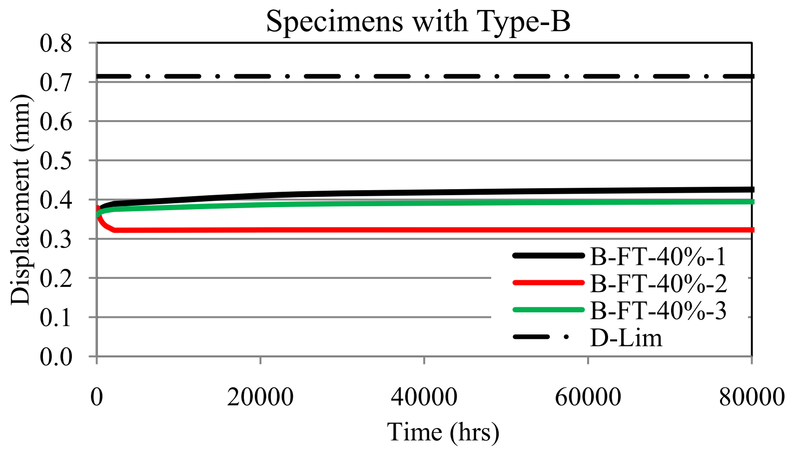


Figure B. 13 – Projected displacement for Specimens with Type-B adhesive under 40%fy and freeze/thaw cycles

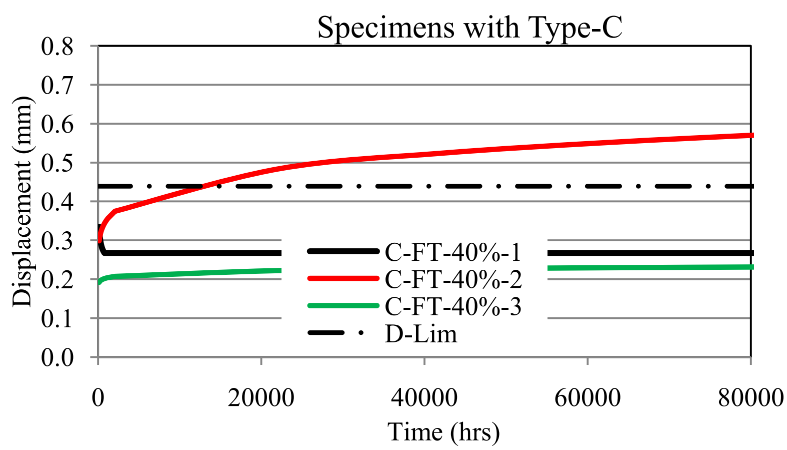


Figure B. 14 – Projected displacement for Specimens with Type-C adhesive under 40%fy and freeze/thaw cycles

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