Determining the Health of Prestressed Concrete Railroad Ties

by

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Abstract

Concrete railroad ties have been a critical component in railway infrastructure for over a century, providing rail car stability and longevity as compared to traditional wooden ties [1]. To ensure the safety of trains traveling upon track structure consisting of prestressed concrete ties, the American Railway Engineering and Maintenance-of-Way Association (AREMA) established standards and guidelines for the design, construction, and maintenance of railway infrastructure, which includes ties as a part of the track structure.

To confirm the continued safety of track structures consisting of concrete ties nearing the end of their service life, a comprehensive study was conducted using five different types of tie designs to evaluate the remaining health. This study aimed to provide an understanding of concrete tie degradation and failure modes to determine if the investigated ties that have served the railroad for over 40years can safely remain in service without posing an undue risk to train operations and safety. The experimental methods used in this study included a systematic dissection of the ties, AREMA's center negative bending and rail seat positive moment tests, and environmental tests.

Significant findings indicated that all concrete ties performed adequately in AREMA specified tests, two concrete ties were found to be nearing the end of their service lives due to extensive pre-existing cracks prior to testing. The environmental tests also showed significant degradation to two more concrete ties when they were exposed to freezing and thawing cycles. The last concrete tie, although it was nearing the end of its anticipated service life, was found to maintain its specified strength and performance capability when compared to newer concrete ties. The results of this study provide evidence to support the possible failure modes of prestressed concrete railroad ties which can promote a more reliable railroad system that protects lives, prevent derailments, and ensures the resilience of railroad infrastructure.

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Chapter One - Introduction

Background

Railroad crossties are a critical component of the track structure providing stability and facilitating operational performance for various size, weight and speeds of railcars and locomotives. Crossties are also designed to effectively hold the rails securely to the prescribed gauge and vertical position, transmit loads to the ballast, and anchor the rail-tie structure against lateral and longitudinal loads [2]. While wooden ties are prevalent in both early and modern rail infrastructure, engineers have continually explored alternative designs and materials to improve their durability and longevity. The American Railway Engineering and Maintenance-of-Way Association (AREMA) [3] provides industry-standards and guidelines, ensuring the continued advancement of railroad ties design and use.

Despite numerous efforts to extend the lifespan of wooden ties (e.g., the use of creosote or other external hardware), these ties have exhibited some inherent disadvantages over time. Wood (in both rail and other applications) is susceptible to mechanical degradation mainly due to splitting, checking, plate cutting, spike killing, and tamp killing. Additionally, wood ties are occasionally subjected to harsh environmental conditions which can cause rot and decay. It has been found that freshly cut ties start splitting during the first six months of air-drying, which is a significant cause of tie replacement. Furthermore, induced stresses due to drying can also result in cracks or checks that can extend the entire length of the tie [4]. The noted challenges to maintain the life of wood ties have forced the exploration of alternative materials such as concrete, which offers potential advantages in terms of durability and resistance to environmental degradation.

Concrete ties first appeared in the United States in 1893 when the Philadelphia and Reading Railroad installed 200 ties in Germantown, Pennsylvania. Since the first installation, numerous tie designs have emerged and installed into railroad networks including prestressed monoblocks, prestressed two-block, reinforced two-block, and longitudinal concrete ties with prestressed monoblock ties becoming the most widely used in North America. Concrete ties have been found to offer significant advantages over wood ties by providing improved vertical and lateral stiffness. This allows the ties to settle more uniformly and provide a smoother and safer ride which equates to greater comfort for passengers. Most notably, concrete ties have an expected service life of nearly twice that of wood ties, offering long-term durability and reduced replacement costs for the railroads [1].

However, research and railroads have noted concerning trends of premature failures of concrete ties, well before their anticipated lifespan of 50 years. This has prompted a comprehensive research study to evaluate the health of concrete ties and identify likely failure modes for various designs and use cases. This research study is designed to add to an extensive body of knowledge of concrete ties to increase the understanding of the degradation and failure modes.

Objective

The railroad industry relies on its infrastructure to safely move people, goods, and services between short and long distances. The maintenance of track infrastructure is a critical component to the overall success and in many cases a serious capital investment. However, determining the remaining service life of concrete ties is currently challenging due to the uncertainty in the relevant failure modes and their progression. The primary objective of this research was to investigate the likely failure modes of prestressed concrete railroad ties and estimate the remaining service life. A secondary objective was to evaluate the performance of newly manufactured ties to the same hypothesized failure modes as an older concrete tie, and to identify signs of early deterioration or long-term durability trends.

Organization of Thesis

Chapter Two covers the background on prestressed ties and summarizes previous research relating to the testing conducted. In addition, this chapter reviews experimental and analytical approaches for determining the health of aged concrete ties and how they relate to new ties.

Chapter Three outlines the initial condition of the ties along with a systematic dissection to reveal internal components and drill cores to determine the measured compressive strength and Young’s modulus.

Chapter Four details the flexural testing of the concrete ties to establish baseline values for the AREMA center negative bending and rail seat positive moment tests.

Chapter Five evaluates the potential environmental impacts on each of the ties. This includes exposure to rapid freezing and thawing cycles, the susceptibility to corrosion, and the permeability of the concrete ties.

Chapter Six summarizes the results of the testing and analysis, providing a discussion on the health of prestressed concrete railroad ties.

Chapter Seven encapsulates key findings and conclusions drawn from the research conducted in this study and recommends future work to enhance the railroad infrastructure.

Chapter Two - Literature Review and Theory

With the expected lifespan of the concrete ties being approximately 50 years, degradation is inevitable over time due to normal train operations. Degradation of concrete ties can result from environmental impacts or mechanical forces. These forces gradually weaken the ties and reduce their ability to transmit forces to the ballast, creating a weaker track structure that may affect a train's operation. To ensure concrete ties achieve their intended service life, considerable research has been conducted to identify and mitigate the deterioration and ultimate failure of concrete ties. The following sections summarize targeted research studies and research findings related to identified common failure modes of concrete railroad ties.

While in service, concrete ties are subjected to a variety of conditions, both mechanical and environmental, as noted previously. To mitigate the deterioration of the concrete ties, many variables are considered in the durability optimization including the tie's concrete compressive strength, volume, amount of prestressing steel, and the prestress eccentricity. Al-Qadi [5] concluded that to increase the tie's capacity, an increase in the concrete design strength was required. However, as the concrete strength increased, the governing limits on tie capacity transitioned from concrete stress to the quantity of prestressing that could be placed on the tie while maintaining adequate spacing and cover. Additionally, the center of gravity of the prestress tendons were found to be below the center of gravity of the concrete at the rail seat which acted in opposition of the forces the rail would place on the tie. However, the resistive forces at the center of the tie were to be opposite of those at the rail seat [6].

Considering the optimization of concrete ties, the materials used play a significant role in the longevity and durability. Research has noted that many factors affect concrete ties and how cracks form, such as the aggregate shape and size, water-to-cementitious ration, material proportioning, admixture types and quantities to name a few. The angularity and type of aggregate has been shown to increase fracture toughness by up to 25% when tested with the same compressive strength [7]. Additionally, there are multiple different types of cement that differ by their composition and are manufactured for different uses. Increasing or decreasing the amount of cement in a concrete mixture has been shown to affect the durability. When analyzing water and chloride penetration into concrete, Yigiter [8] found that an increase in the water/cement ratio also increased the chloride penetration depths significantly. Cement dosage also affected the chloride penetration depth and increases in cement dosage from 250 to 350 kg/m3 were found to decreased the chloride ion ingress considerably.

Concrete is an inherently durable material; however, one of its greatest weaknesses lies in its interaction with water. This concern is particularly severe in cold climates, where repeated freezing and thawing cycles can lead to an acceleration in damage. The American Society for Testing and Materials (ASTM) has established a standardized procedure for evaluating the freeze-thaw durability of concrete. However, ASTM C666 was designed for specimens smaller than 5 inches by 11 inches by 16 inches. To understand the freeze-thaw durability of concrete ties, Albahttiti [9] defined a methodology which subjected whole pre-tensioned concrete railroad ties to 300 freeze-thaw cycles. He found that the concrete ties did not experience significant deterioration because of freezing and thawing cycles. Additionally, saw-cut samples showed to have a minimal effect on freeze-thaw durability. It was ultimately determined that although testing large-scale samples for freeze-thaw durability was not feasible, cast prisms made with the same concrete as the ties could be tested and subjected to the same levels of handling and vibration.

Also, previous research has shown that post-tensioning concrete can further enhance its freeze-thaw durability. Musleh [10] found that post-tensioning concrete improved its durability against freeze-thaw conditions. Additionally, continuously post-tensioned concrete specimens were more durable than intermittently-stressed concrete specimens, but both were more resilient against freeze-thaw than unstressed concrete samples.

Despite the necessity to remain consistent with handling and vibration, Riding [11] found that the air void systems of the air-entrained mixtures were robust, as their spacing factors were generally unchanged by long exposure to vibration. The results suggested that freeze-thaw durability of the considered concrete ties would be insensitive to changes in vibration duration. While vibration was found to have minimal impact on freeze-thaw durability, concrete mixture properties were found to have a significant role. In particular, very high strength concrete, with a compressive strength of 29 ksi and flexural strength of 6 ksi, have good freeze-thaw resistance (durability factor >85%) and were found to avoid freeze-thaw damage [12]. Similarly, ultra-high performance concrete (UHPC) which demonstrates compressive strengths of 17 to 22 ksi (Tadros et al., 2020) exhibited minimal damage after being subjected to two times the normal number of ASTM C666 freeze-thaw cycles [13]. These results were found to be attributed to the tightly packed microstructure of higher strength concrete which reduced permeability.

While previous research studies have been performed to compare concrete with its freeze-thaw susceptibility, studies specifically investigating how different types of prestressing reinforcement (such as the use of 7-wire strands and indented wires) affect freeze-thaw performance are relatively limited. Newer prestressed concrete ties have transitioned from using 7-wire strands to indented wire strands which offer distinct advantages. Bogner [14] concluded that the benefits included the ability to specify prestressing wires that were uniquely suited for the indented application with tailored diameters and indent characteristics. Additionally, indented prestressing wires allowed for shorter development lengths as their bearing surfaces facilitated more efficient load transfer. While the prestressing tendons vary, the objective was to create a solid bond between the concrete and the tendons. While reviewing the possibility of strand pullout and bond quality, Arnold [15] determined that the pre-existing surface condition of prestressing wires was not the dominant bond characteristic. Rather, the indent geometry played a significant role. Since the area of the strand indents was smaller relative to the overall cross-sectional area of the 5/16 in.-diameter and 3/8 in.-diameter strands (than the ratio for 5.32-mm-diameter wires), the indent geometry showed to have a smaller role in the overall bond performance of the strands and the surface condition contributed a much more meaningful portion to the overall bond performance of the strands.

While water facilitates freeze-thaw damage, it also accelerates the possible corrosion of the prestressing steel reinforcement within concrete. In terms of the degradation for prestressed strands, pitting corrosion due to chlorides is critical and can lead to failure of the strands [16]. The high level of prestressing force in these strands accelerates corrosion: the cross-section reduces, leading to higher stresses and higher corrosion rates. This can lead to brittle rupture of the strands [17]. In the case of post-tensioning, grout is often used to protect the prestressed tendon from environment attack and improve the compatible strain between strand and concrete. Without the grout, the strands are more susceptible to the ingress of water and chlorides. Strand corrosion in an ungrouted duct has negligible effect on the initial stiffness of a beam but it reduces the ultimate strength of the beam and changes the failure modes from concrete crushing to wire rupture with the increase of corrosion [18].

One main cause of corrosion is due to the concrete cracking which creates a pathway for water and chlorides to penetrate. Abbas [19] found a direct relationship between transverse cracking due to loading and corrosion damage. As cracking increased, reinforcement corrosion increased. Larger crack width and crack density were found to be the cause of severe localized and uniform reinforcement-corrosion activity. Longitudinal or splitting cracks always indicated severe corrosion within a member. With concrete ties that are nearing the end of their estimated service life, cracking is common. Scott [20] investigated 12 different existing concrete tie designs that had performed well for over 25 years, approximately half of their estimated service life. After testing, the research team determined that only eight of the designs would meet the current requirements of the AREMA center negative bending moment test.

While cracking in concrete ties can lead to increased corrosion and susceptibility to environmental factors, certain design adjustments can mitigate long-term deterioration. Studying the effects of impact loading, Wang [21] determined that stirrups effectively retarded the deterioration of concrete ties. Reducing the concrete compressive strength or prestressing level of the tie may result in a reduction of the dynamic flexural stiffness and hence the magnitude of impact loads. These measures were found to not influence the tie capacity to resist quasi-static loading and the current design bending moment capacity of the ties was three times as high as the required quasi-static moment due to a 200% impact factor applied. These impact loads contributed to the deterioration of the concrete ties rail seat. Past research studies and associated field experience with concrete ties identified five concrete deterioration mechanisms that may occur during rail seat deterioration: (1) abrasion, (2) crushing, (3)freeze-thaw cracking, (4) hydraulic pressure cracking, and (5) cavitation erosion [22].

Based on previous research, the criticality of each failure mode was found to be influenced by how likely it was to cause the failure effect, the severity of its possible effects, and how difficult it was to detect the mode before the failure effect occurs. In a more formalized failure mode and effect analysis, these three factors were treated separately and were referred to as the occurrence, severity, and detection factors, respectively. To fill in the identified gap in research, the objective of this research study was to understand these factors and to assist with guiding future research and testing efforts aimed at evaluating and mitigating the risks associated with possible future concrete tie failures [23].

Chapter Three - Systematic Dissection and Material Properties

This research study examined five distinct types of concrete railroad ties, each reflecting different manufacturing methods and service histories. The selection of ties investigated included pre-tensioned and post-tensioned concrete ties, which also included variations in reinforcement and material compositions. The RCCC tie, first introduced in the early 1970s, and the SV tie, produced in the mid- to late 1970s represented some of the earliest pre-tensioned designs. Also pre-tensioned, the Pre-2003 tie was a design used prior to 2003 before switching to the modern Post-2003 design. The Pre-2003 ties obtained and tested were manufactured in 1999, while the Post-2003 tie was considered a brand-new specimen reflecting modern design improvements which included the switch from 7-wire strand to indented wires. Unlike the other concrete ties, the PT tie was a newly manufactured tie featuring a post-tensioned design. With concrete ties spanning over five decades of mass-production, this research study enabled a unique insight and comparative analysis of aging effects, reinforcement behavior, and long-term durability.

Initial Condition of Ties

Upon arrival to Kansas State University, each tie was inspected, photographed, and inventoried to assess its initial condition state. Since the Post-2003 and PT ties were new, only minor scratches and chipping from transport were observed. While significantly older, the SV ties were found to have remained resilient, with occasional small concrete sections missing but did not appear to compromise their overall performance. However, the RCCC ties raised some initial concerns. Of the 14 RCCC ties provided, approximately 85.7% exhibited existing cracking under the rail seat, starting at the bottom and extending to the lowest reinforcement layer, creating a T-shaped crack as shown in Figure 1. The cracking was found to range from minor to significant, often affecting either one or both rail seats, with some concrete loss like the SV ties.

Figure 1: Pre-existing Damage of RCCC Tie

The Pre-2003 ties were found to exhibit the worst deterioration of the five tie designs with approximately 87.5% showing predominant damage consisting of major cracking of a horizontal orientation intersecting with the top row of reinforcing strands as shown in Figure 2.

Figure 2: Pre-existing Damage of Pre-2003 Tie

These cracks, which were generally found near the ends of the ties, are often not visible in the railway track due to being covered with ballast, similar to the cracking formed on the RCCC ties. Past research found that this cracking was possibly attributed to a high concentration of tensile stress in the ties at the level of the prestressing steel due to forces associated with the transfer of load from the steel to the concrete during the strand detensioning process. These stresses were greatest at the top row of tendons, which were the bottom row during the casting process. While alkali-silica reaction (ASR) was viewed to be an additional cause of deterioration in previous research, no signs of ASR damage was observed on the investigated concrete ties. While past research found likely deterioration causes, it was also determined that the distress was not caused by freezing and thawing cycles, delayed ettringite formation (DEF), or other stresses from mechanical effects, such as from fastener inserts or unusual tie vibrations [16].

Systematic Dissection

Understanding the performance and durability of concrete ties begins with a comprehensive systematic dissection. While external observational methods described previously did not evaluate internal stresses, material inconsistencies, and subtle degradation; cutting open a concrete tie revealed many of these hidden factors. Using a 36" diameter diamond tip concrete saw as shown in Figure 3, each tie was carefully cut allowing for detailed measurements of the reinforcement and possible stirrups locations while revealing any inconsistencies in the concrete mixture itself.

Figure 3: Dissecting Ties With the Diamond Tip Saw

To fabricate pretensioned concrete ties, the prestressing tendons, typically indented wire or strands are tensioned. The ties are then cast around the already-tensioned tendons and once the concrete has cured, the tension is released [14]. This process transfers the prestress force through the mechanical bond, reinforcing the concrete. In contrast, to produce post-tensioned concrete ties, high-strength steel tendons are placed within sleeves before pouring the concrete. The concrete then cures around the sleeved tendons before tension is applied to the tendons which are anchored within the tie. Finally, the end is grouted to avoid water ingress within the tie. While both methods enhance the strength and durability of the tie, each construction method offers distinct benefits and limitations that impact the potential performance and lifespan of the prestressed concrete ties.

A limitation of the post-tensioned ties was observed while dissecting the tie. Due to the high internal stress on the tendons, cutting through the tie caused a sudden release of energy, resulting in a rapid fracturing of the exterior concrete and a forceful ejection of the tendons.

Table 1: Steel Reinforcement Specifications.

Tie Design	Tendon Type	Tendon Diameter	Tendon Quantity	Strand Preload (kips)	Total Prestress Load (kips)
SV	7-Wire Strand	0.375”	8	16.68	133.40
Pre-2003	7-Wire Strand	0.375”	8	17.21	137.70
Post-2003	Indented Single Wire	0.200”	24	6.55	157.20
RCCC	7-Wire Strand	0.375”	4	UNK	UNK
PT	Non-Indented Single Tendon	0.315”	6	15.50	93.00

As shown in Table 1, although the Post-2003 ties had the lowest strand preload, they exhibited the highest total prestress load of 157.20 kips. This was attributed to the substantial quantity of reinforcing steel. In contrast, the prestress force of the RCCC tie design remained unknown. However, based on design codes from the time the tie was created, it was likely to be less than 70 kips.

While the steel reinforcement in prestressed concrete ties has a significant role in their strength and performance under load, the geometry of the ties is just as critical. Factors such as length, weight, and the height and width at both the rail seat and tie center influences load distribution and track stability. Variations in these dimensions can affect how the tie interacts with ballast, the ease of installation and replacement, and its ability to resist cracking or deterioration over time. The two main areas of interest in the construction of ties were the rail seat (where the rail is affixed) and the tie center. Figures 4 through 8 present standard drawings of each tie. Each drawing includes the end, rail seat, and center cross-sections. These figures have been redrawn from pre-existing plans, are not to scale, and all dimensions are shown in inches.

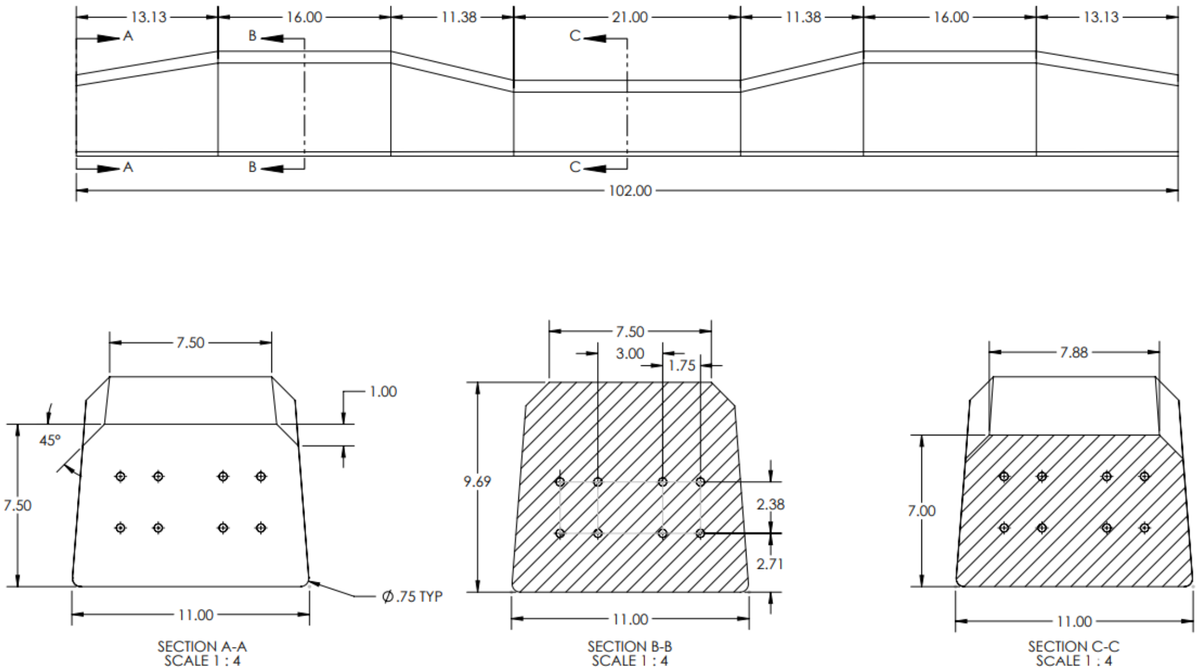

Figure 4: SV Geometry and Reinforcement Details

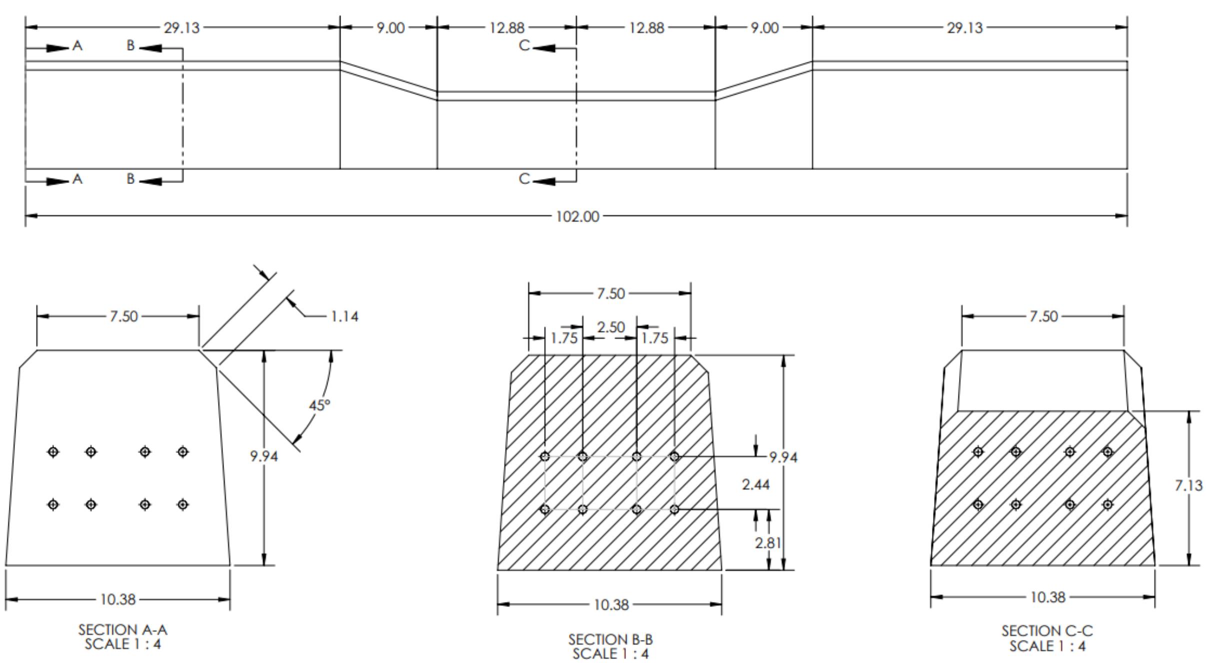

Figure 5: Pre-2003 Geometry and Reinforcement Details

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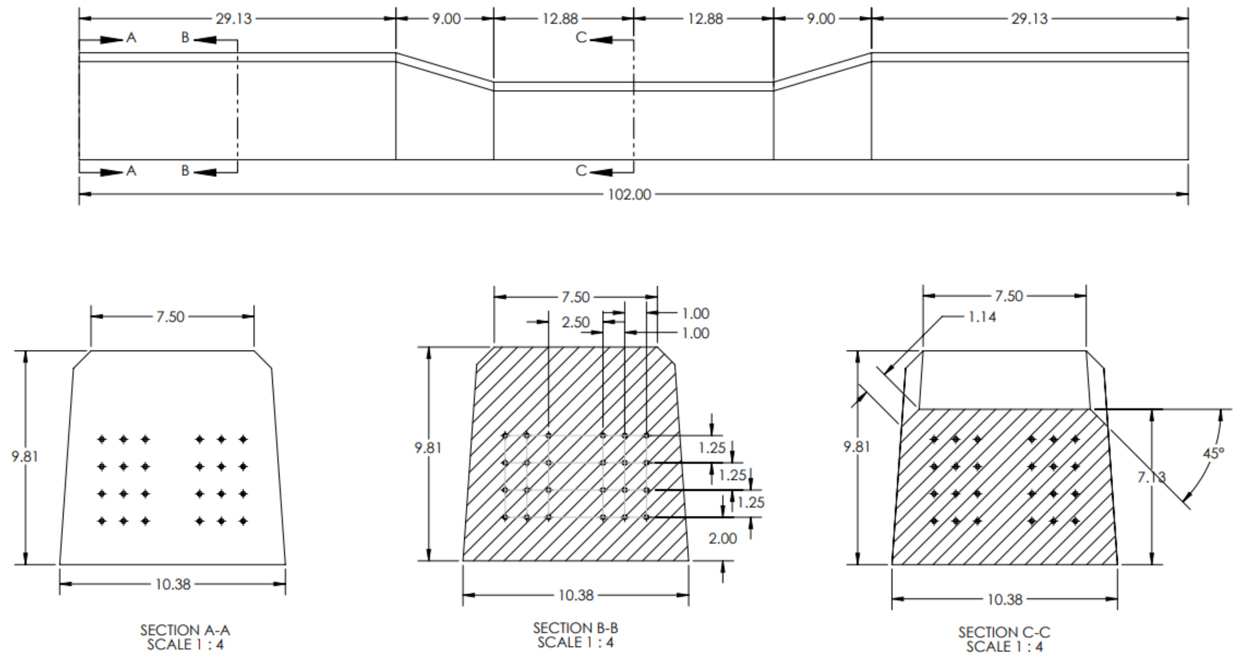

Figure 6: Post-2003 Geometry and Reinforcement Details

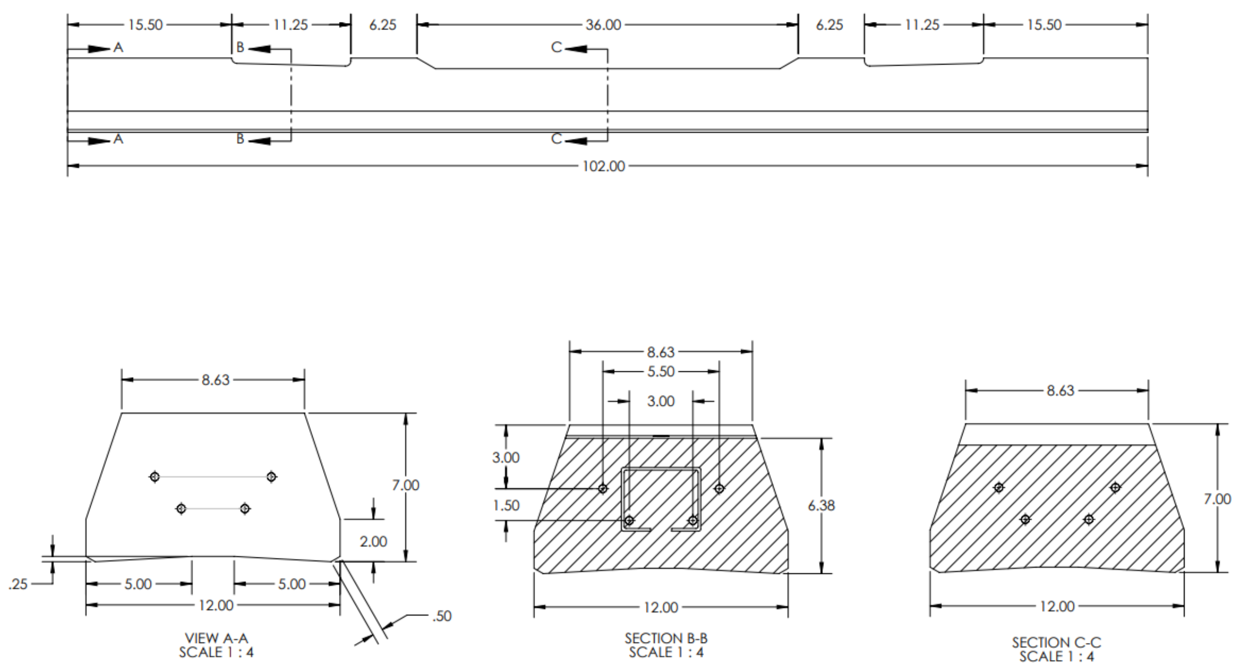

Figure 7: RCCC Geometry and Reinforcement Details

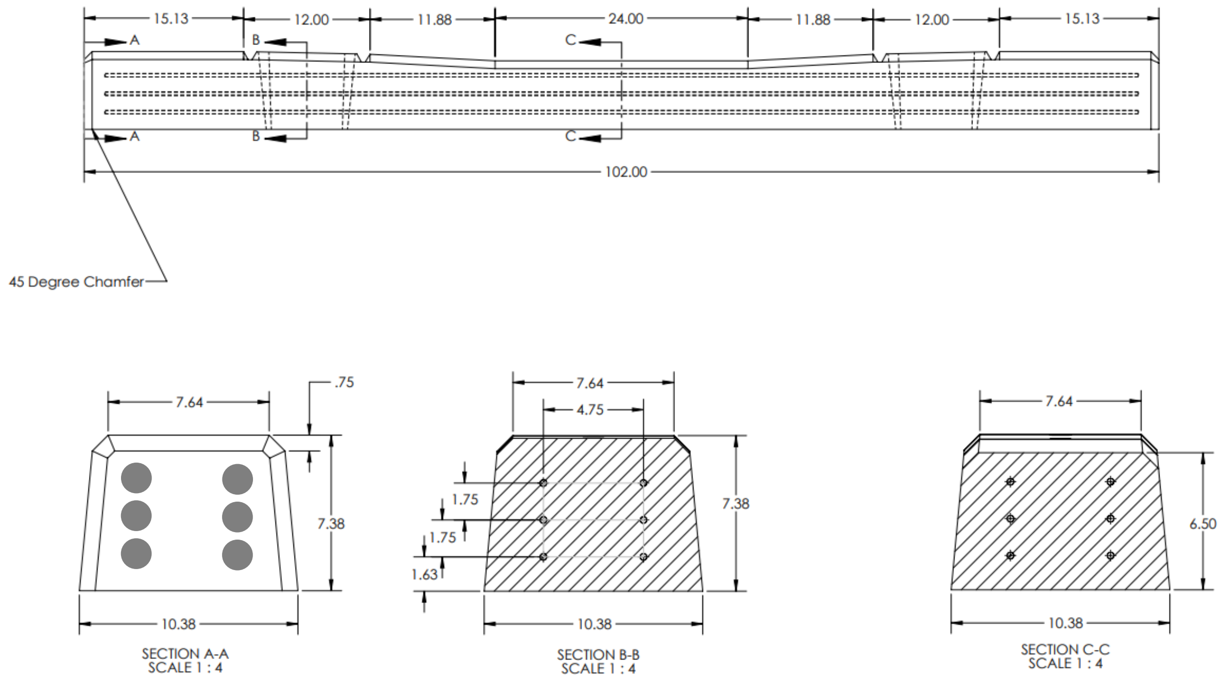

Figure 8: PT Geometry and Reinforcement Details

Table 2 summarizes each ties dimensions measured at the rail seat and center of each tie, including the height (h), width at the bottom of the tie (Wbot), and the width at the top of the tie (Wtop).

Table 2: Tie Geometry Summary

Type of Tie	Length (in.)	Weight (lbs.)	Rail Seat			Tie Center		
			h, (in.)	Wbot, (in.)	Wtop, (in.)	h, (in.)	Wbot, (in.)	Wtop, (in.)
SV	102	750	9.688	11.000	7.500	7.000	11.000	7.875
Pre-2003	102	765	9.938	10.375	7.500	7.125	10.375	7.500
Post-2003	102	845	9.813	10.375	7.500	7.125	10.375	7.500
RCCC	102	590	6.375	12.000	8.625	7.000	12.000	8.625
PT	102	630	7.380	10.375	7.640	6.500	10.375	7.640

While conducting the dissection of each concrete tie for the internal analysis, both the steel reinforcements and an approximately 12 inch long section of each tie were removed. The 12 inch sections were specifically saved to obtain cores for testing, allowing for the determination of the compressive strength and elastic modulus of the concrete, while the steel reinforcement from the ties were removed and set aside for accelerated corrosion testing.

Concrete Compressive Strength and Young's Modulus

Following the systematic dissection of each concrete tie, a compact diamond coring rig (as shown in Figure 9) was utilized to extract a minimum of three cores per tie. Each core was drilled parallel to the prestressing tendons, ensuring that both damaged regions and tendon interference were avoided.

Figure 9: Concrete Coring Rig

According to ASTM C42/C42M-20 [24], in order to tests cores for compressive strength, the cores shall have a minimum diameter of 3.7 inches or at least two times the nominal maximum size of the aggregate. Due to the reinforcement pattern of the ties, core diameters were limited to a diameter of 2 inches. After extraction, the cores were precision-cut to 2 inches by 4 inches specimens as shown in Figure 11. To ensure uniform load distribution during compressive testing (shown in Figure 10), the specimens were capped with sulfur mortar, creating flat surfaces perpendicular to the specimen axis.

Figure 10: Cored Samples

Figure 11: Broken Specimen

The measured compressive strength (f_c) of each concrete core was determined by testing according to ASTM C39/C39M–24 [25]. Prior to testing, each specimen underwent a thorough inspection to ensure conformance with testing requirements. The specimens were then subjected to continuous uniaxial loading at a rate of 35 psi per second, until failure occurred. Upon failure, the measured compressive strength was calculated based on the maximum load attained utilizing Equation 1. The average measured compressive strength for each tie type are shown in Figure 12.

Equation 1: $$f_c = \frac{4P_{max}}{\pi D^2}$$

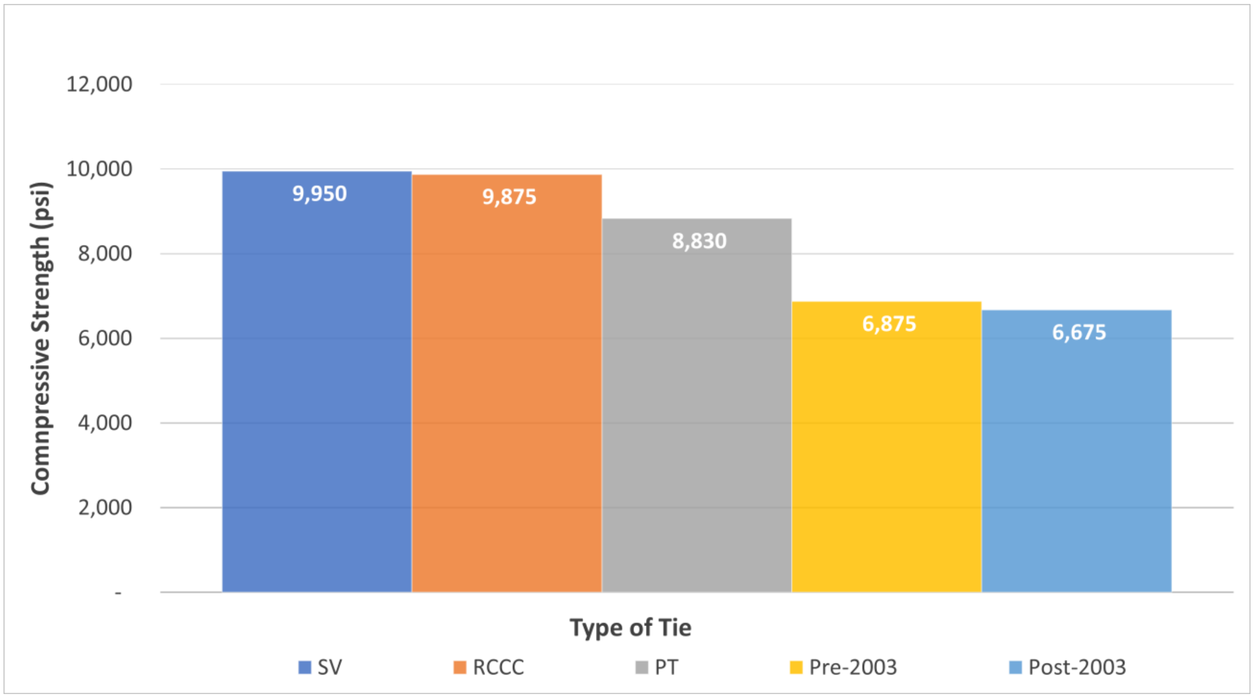

Figure 10: Compressive Strengths by Tie Type

Building upon the determined compressive strengths shown in Figure 12 for each concrete tie type, the Young's modulus of elasticity (E) was calculated to analyze the deformation behavior under load and the results are shown in Figure 13. Following the same trend as the compressive strength (Figure 12), the SV tie had the highest Young's Modulus at 5,685 ksi, followed by the RCCC, PT, Pre-2003 and lastly the Post-2003 had the lowest at 4,850 ksi, despite being one of the newest ties.

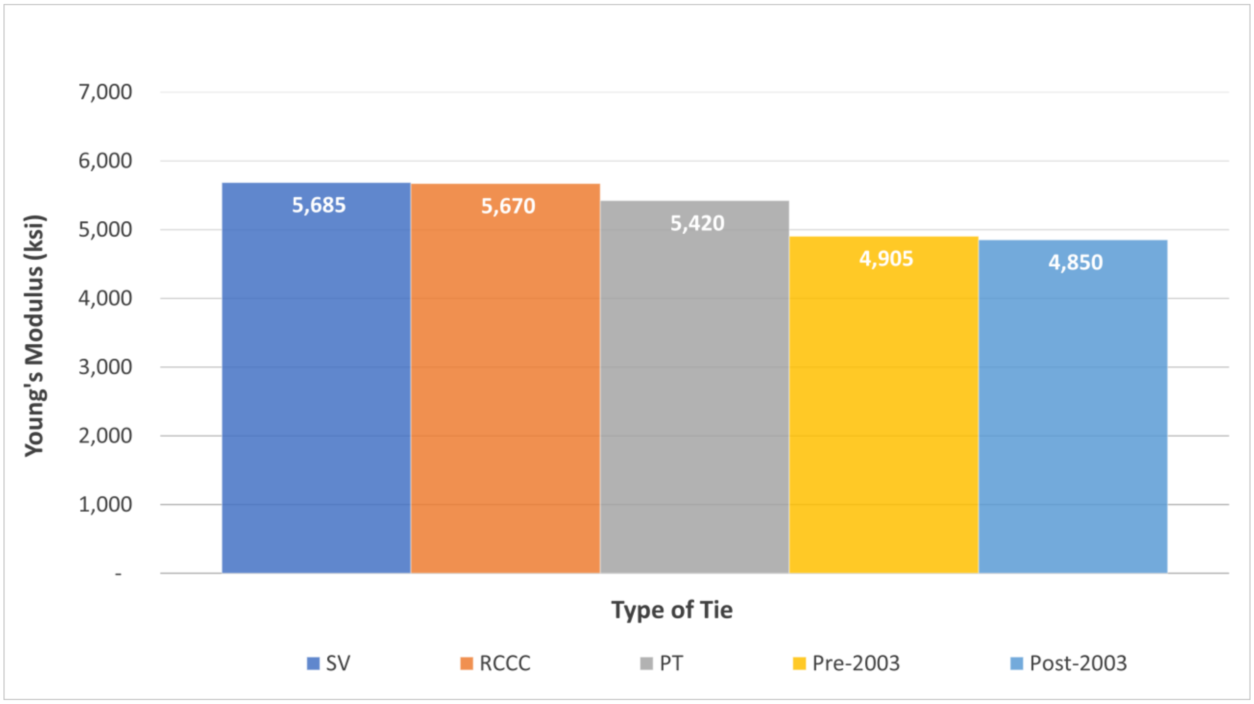

Figure 11: Young's Modulus of Elasticity Results

Due to the measured compressive strengths of some ties exceeding 8,000 psi as noted in Figure 12, which was considered high strength concrete according to ACI 363R-10 [19], differing equations were used to determine the elastic modulus. A total of ten different equations to find Young's Modulus were analyzed for the concrete ties, including formulas from both the American Concrete Institute (ACI) and Precast/Prestressed Concrete Institute (PCI) codebooks. The average of these equations were taken to account for variations in concrete properties and reduce potential bias from any single method. By incorporating multiple approaches, a more reliable estimation could be used to assess the stiffness and load distribution of the ties. The equations outlined in Table 3 provided a detailed formulation of Young's modulus.

Table 3: Equations for Young's Modulus of Elasticity

Equation Number:	Equations for Young's Modulus:	Units:	Citation:
2	$E_c = 57{,}000\sqrt{f'_c}$	Psi	[26]
3	$E_c = \rho^{1.5} * 33\sqrt{f'_c}$	Psi	[26]
4	$E_c = \rho^{2.5}(f'_c)^{0.325}$	Psi	[27]
5	$E_c = \rho^{2.55}(f'_c)^{0.315}$	Psi	[28]
6	$E_c = \left(40{,}000\sqrt{f'_c} + 1{,}000{,}000\right)$	Psi	[29]
7	$E_c = \left(40{,}000\sqrt{f'_c} + 1{,}000{,}000\right) * \left(\frac{\rho}{145}\right)^{1.5}$	Psi	[30]
8	$E_{cm} = 4{,}734\sqrt{f_{cm}}$	Mpa	[31]
9	$E_{cm} = 9{,}980\sqrt[3]{f_{cm}}$	Mpa	[32]
10	$E_{cm} = 22{,}000(0.1f_{cm})^{0.3}$	Mpa	[33]
11	$E_{cm} = 3{,}500 + 4{,}300(\sqrt{f_{cm}})^{0.325}$	Mpa	[34]

Chapter Four - Baseline Static Testing of Concrete Ties

Baseline testing for the concrete ties provided the fundamental performance data necessary for evaluation of their remaining service life. In accordance with AREMA Chapter 30 standards [3], two critical load tests, (1) center negative bending moment and (2) rail seat positive moment test were performed to assess the tie's ability to withstand service conditions. The center negative bending moment test evaluated stresses that develop due to the deterioration of the railways ballast, where the rail seat positive moment test simulated the loading applied at the rail seat under operational demands. Establishing baseline results for these tests ensured that the concrete ties met performance expectations and were able to remain in track.

Center Negative Bending Moment Test

The center negative bending moment test was used to evaluate new railroad ties resistance to cracking and ultimate failure when subjected to negative bending moments at the center. Adhering to the guidelines specified by AREMA Section 4.9.1.6 [3] for the center negative bending moment test, a four-point bending testing setup was conducted. Each tie was inverted for the correct testing configuration, where it was simply supported at the rail seats. A 6 inch spreader beam was placed at the center of the tie to distribute the applied load as shown in Figure 14.

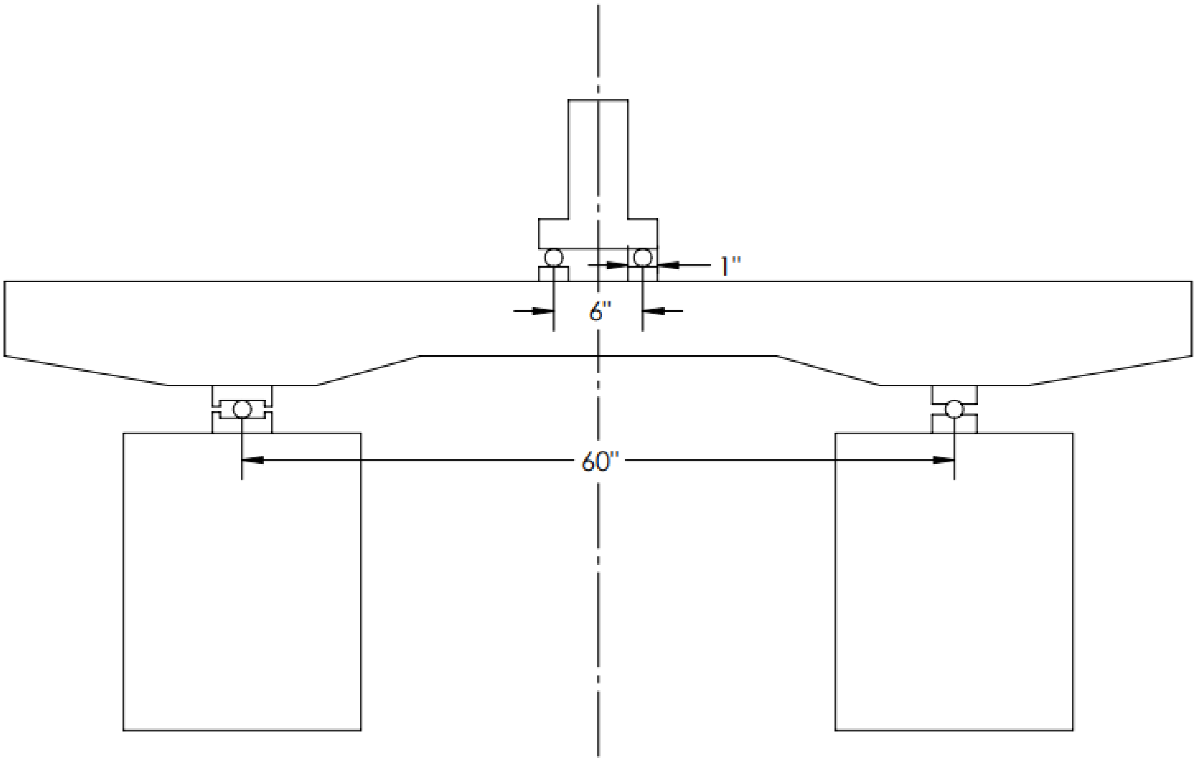

Figure 12: Center Negative Bending Moment Test Setup

A hydraulic actuator with a 55-kip capacity was employed to continuously increase the load at a rate of 1,200 pounds per minute until the first crack was observed. Following crack initiation, the loading transitioned to a displacement-controlled rate of 0.02 inches per minute.

To assist in the analyzation of the older railroad ties, a modification to the AREMA loading protocol was performed. By deviating from the specified center negative design moment by applying load until failure, a comprehensive assessment of each concrete tie's ultimate strength, ultimate deflection, and failure mode was achieved. Midspan deflection was measured using two linear variable differential transformers (LVDT), having a stroke of 10 inches, that were positioned on opposite sides of a flat bar spanning across the uppermost surface at the center of the tie shown in Figure 15.

Figure 13: Tie in Center Negative Orientation

A Keithley Series 2700 data acquisition system was utilized to measure both the applied load and midspan deflections. The Keithley was able to convert and record the voltage from the LVDTs into precise displacement measurements.

Rail Seat Positive Moment Test

The rail seat positive moment test also outlined in AREMA, provides a counterpart to the center negative bending test. Each test evaluates different flexural behaviors of prestressed concrete railroad ties. In the positive moment test, the tie was supported at points located 14 inches from the center of the applied load. The load was then applied directly to the rail seat using a spreader beam, which distributes it 2.25 inches on either side of the rail seat's midpoint as shown in Figure 16.

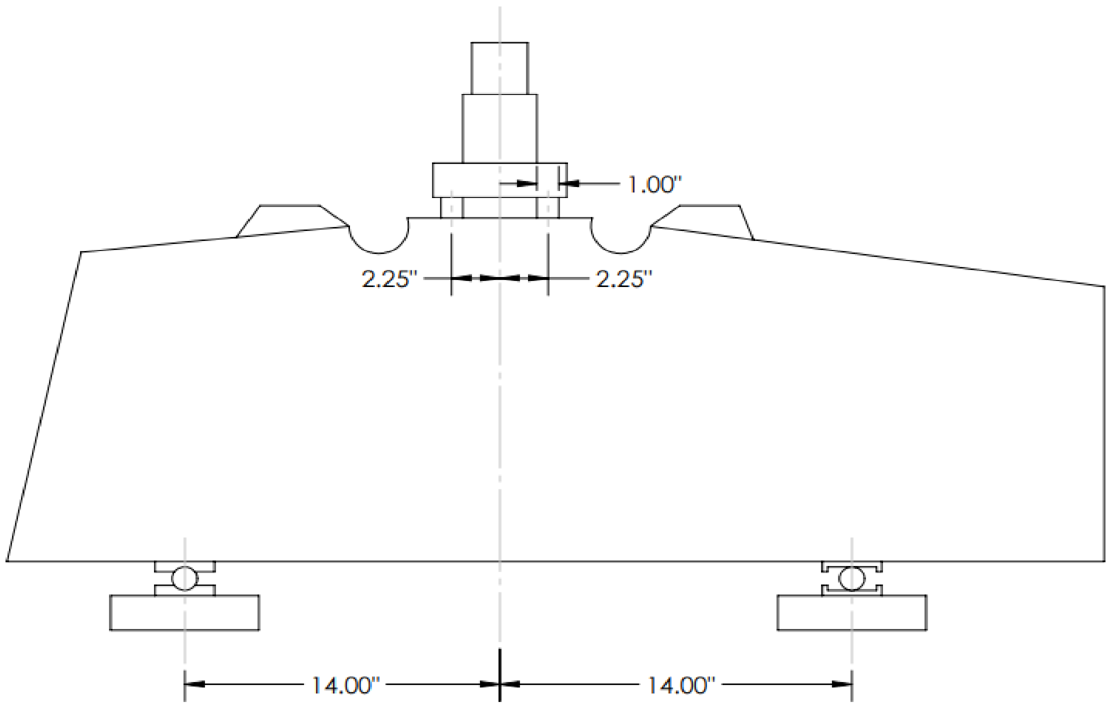

Figure 14: Rail Seat Positive Moment Test Setup

Due to the reduced span length and the larger cross-sectional area at the rail seat, each tie achieved a significantly greater load as compared to the center negative test. To accommodate the increased load demand, a 360-kip hydraulic actuator was used to apply the load at a rate of 5,000 lbs. per minute until the first crack was observed. The loading protocol was then shifted to a displacement-controlled rate of 0.02 inches per minute until failure. Each concrete tie was tested on one rail seat, then flipped to test the other side with side A always being tested first.

Similar to the center negative bending test, the deflection at the midpoint of the loading was measured through the use of two LVDTs located on a flat bar spanning the rail seat. Due to the shortened span, LVDTs with a stroke of 0.5 inches were utilized to accurately collect the displacement. Due to compressive failure cracking the concrete under the flat bar prior to the ultimate failure of the tie, the flat bar was attached to the tie with silicone to avoid improper readings. This allowed the LVDTs to accurately record data until the ultimate failure of the tie.

Figure 15: Tie in Rail Seat Positive Orientation

Chapter Five - Environmental Testing

While the mechanical loads imposed by trains, coupled with the cyclic stresses and fatigue from repeated loads have been found to contribute significantly to the deterioration and ultimate failure of prestressed concrete railroad ties. However, it's also important to recognize the influence of environmental conditions and their possible effects on concrete ties durability and strength. Environmental factors such as the number of freezing and thawing cycles in colder climates and the corrosive effects of saltwater exposure in warmer coastal climates warrants equal consideration. These environmental impacts, along with the mechanical forces, can accelerate the degradation of concrete leading to the onset of cracking, corrosion, and other structural failures that may affect railroad safety.

Rapid Freezing and Thawing Durability

With the lifespan of prestressed concrete ties expected to be approximately 35-50 years [35], ties can be subjected to harsh environmental conditions that may contribute to their ultimate failure. In colder regions, the action of freeze-thaw cycles are regarded as the main cause of concrete deterioration [36]. This type of deterioration is primarily driven by the expansion of water within the concrete's pore structure as it freezes. The crystal structure of solid water contains vacant "shafts" that cause a decrease in density and an increase in volume (9%) compared to the liquid [37]. By increasing the volume within the concrete, internal pressure is created leading to cracking, spalling, and scaling, ultimately leading to the failure of the concrete.

The permeability of concrete is an important variable in durability because it controls the rate of entry of moisture that may contain aggressive chemicals and the movement of water during heating and freezing [36]. Given that a water molecule is approximately 0.275 nanometers in size, achieving impermeability in concrete is both challenging and costly. Air entrainers are used to mitigate the damage by purposely introducing microscopic air bubbles into the concrete mixture and allowing water room to expand as it freezes. Despite these mitigation efforts, freezing and thawing still leads to the deterioration of concrete over time. To evaluate a concrete tie’s ability to withstand these conditions, various testing methods are employed.

The American Society for Testing and Materials (ASTM) C666/C666M-15 [38] establishes the standard test method for evaluating the resistance of concrete to rapid freezing and thawing. According to ASTM C666, each test specimen must be either a core or a prism, with dimensions ranging between 3 inches and 5 inches in width, depth, or diameter, and between 11 inches and 16 inches in length. The test involves subjecting the specimens to repeated freezing and thawing cycles and measurements are taken every 36 cycles to assess fundamental transverse frequency and length change. This process continues until each specimen has undergone 300 cycles or until its relative modulus of elasticity declines to 60% of its initial value.

However, as ASTM is an international standards organization, its requirements may not always align with region-specific durability needs. For instance, the Kansas Department of Transportation (KDOT) has established its own performance criteria tailored to the state's environmental conditions. Given that Kansas experiences approximately 33 annual “hard” freeze-thaw cycles, KDOT mandates a minimum relative dynamic modulus of elasticity of 95 and a maximum expansion of 0.025% at 660 freezing and thawing cycles for concrete [39]. Similarly, in the case of prestressed concrete ties, the dimensional constraints of ASTM C666 render it unsuitable for testing large specimens. Similar to how KDOT has developed specific criteria to address the unique freeze-thaw conditions in Kansas, the concrete ties also require a distinct testing methodology.

Each concrete tie was initially loaded in the rail seat positive configuration, including midspan LVDTs, until a visible crack reached the bottommost layer of reinforcement. The tie was then flipped, and the process was repeated on the opposite rail seat. Following cracking, the tie was placed in a Scientemp freeze-thaw machine capable of simulating three freeze-thaw cycles per day while accommodating up to three ties simultaneously as shown in Figure 18.

Figure 16: Railroad Ties in Freeze-Thaw Machine

After 30 cycles, the concrete tie was removed from the chamber, allowed to thaw completely for 48 hours, and then reloaded to the same force at which it was originally cracked. This procedure was repeated in increments of 30 cycles, up to a total of 90 cycles for each tie.

Accelerated Corrosion Testing of Prestressing Steel

Although freeze-thaw damage isn't always a concern for railroad track located in consistently mild temperatures, the continual exposure to corrosive elements along coastal regions pose a significant risk of degradation to concrete ties. Typically, concrete reinforcing steel is protected from corrosion by the high alkalinity of the concrete as it cures, which forms a passive iron oxide layer on the steel surface [40]. Unlike conventional reinforced concrete, post-tensioning tendons are cast in sleeves, preventing the formation of a passivation layer that results from direct contact with the high pH concrete during hydration. Given the periodic rise of the storm surges, which results in an abnormally high-water level that often floods roads and railroad track structures, a synthetic saltwater solution replicating the chemical composition of Atlantic Ocean water was prepared, as shown in Table 4 based on Habtemichael and Fuentes [41].

Table 4: Chemical Composition of Synthetic Saltwater

Reagent	Chemical Formula	Amount (g)
Sodium Chloride	$NaCl$	23.862
Sodium Sulfate	Na_2SO_4	3.361
Magnesium Chloride	$MgCl_2$	5.287
Calcium Chloride	$CaCl_2$	1.135
Potassium Bicarbonate	$KHCO_3$	0.110
Potassium Sulfate	K_2SO_4	0.775

To simulate real-world field conditions, scavenged tendons and other metallic components of the prestressing system were subjected to repeated submersion, followed by periods of exposure of air to allow for oxidation.

Figure 17: Post-Tension Components

The tendons were periodically inspected for signs of corrosion, with post-tensioned components assessed through both weight loss measurements and visual examination. In contrast, tendons from conventional pre-tensioned ties were evaluated solely through visual inspection.

Submersion for Water Ingress Testing

Given the inevitability of corrosion in steel reinforcement, the primary limiting factor is the potential for water ingress into the concrete ties. Due to the lack of a protective iron oxide layer, the high-strength steel tendons and accompanying components of post-tensioned ties are highly susceptible to corrosion if moisture penetrated the concrete. Since there exists no standardized testing method for evaluating the water-tightness of concrete ties, an experimental methodology was developed involving the submersion of a post-tensioned tie followed by a dry-cut dissection.

Prior to submersion, the concrete tie was cracked at both rail seats and the center negative region, with each crack extending to the first layer of reinforcement. These cracks were introduced to facilitate water ingress., Although present, each crack reduced in size to the extent that they were not visible to the naked eye. The tie was then fully submerged in water with its weight-in-water being recorded daily throughout the week-long test using a 500 kg. load cell as shown in Figure 20.

Figure 18: Post-Tensioned Tie Submerged in Water

After seven days, the tie was removed from the water and surface-dried by towels to ensure that there was no surface water that could potentially interfere with observations and the potential for internal moisture. To observe water ingress at the tendons and accompanying components, the ties were dry-cut using the 36-inch diameter diamond saw as described previously. Due to post-tensioning tendons housing a high concentration of stress, cutting through the tie releases a force capable of shattering concrete and poses a serious risk of injury. Therefore, a rigorous safety protocol was followed throughout the methodology to ensure safety as the concrete tie was cut in a restrained manner.

Following the submersion test, it was determined by the weight in water that the post-tensioned concrete tie was susceptible to water ingress. Due to the inherent porosity of concrete, the submersion test cannot accurately determine the amount of water entering the post-tensioning sleeves of the tie as water can be absorbed into the concrete rather than infiltrating the sleeves. To properly assess the potential for water ingress, a separate test evaluating the absorption characteristics of the concrete itself was conducted. Using cross-sections created in the systematic dissection, the absorption was calculated using Equation 12 by submerging the sections in water to determine the saturated surface dry (SSD) weight before being heated to establish an oven dry (OD) weight.

Equation 12: $$Absorption\ (\%) = \frac{SSD - OD}{OD} * 100$$

Based on the absorption of the cross-sections, the theoretical water absorption of the railroad tie could be determined by calculating the concrete's flux using Equation 13. The flux describes the rate at which the concrete absorbed water through each square inch of exposed concrete per hour. The flux of the concrete tie allowed the distinction to be made between the water that was absorbed by the concrete and direct water entry into the post-tensioning system, provided a clearer understanding of any potential water ingress concerns.

Equation 13: $$Flux = \frac{\Delta Mass}{Area * \Delta Time}$$

Chapter Six - Results and Discussion

Center Negative Bending Moment Test

An ideal pre-stressed concrete railroad tie is designed to withstand repeated loading while maintaining a high rotational capacity, ensuring its ability to accommodate track deformations and dynamic forces over time. In areas of poor ballast maintenance, ties are forced to bend under train loadings to conform to the ballast geometry. When this occurs, the prestressing tendons in these ties experience high stress levels at cracking locations which, in-turn, could reduce the service life and can result in premature failures [42].

The results from center negative bending moment test were important for assessing each concrete ties flexural capacity, cracking behavior, and overall durability. For this analysis, each tie's load was plotted against the average LVDT displacement, as shown in Figure 21.

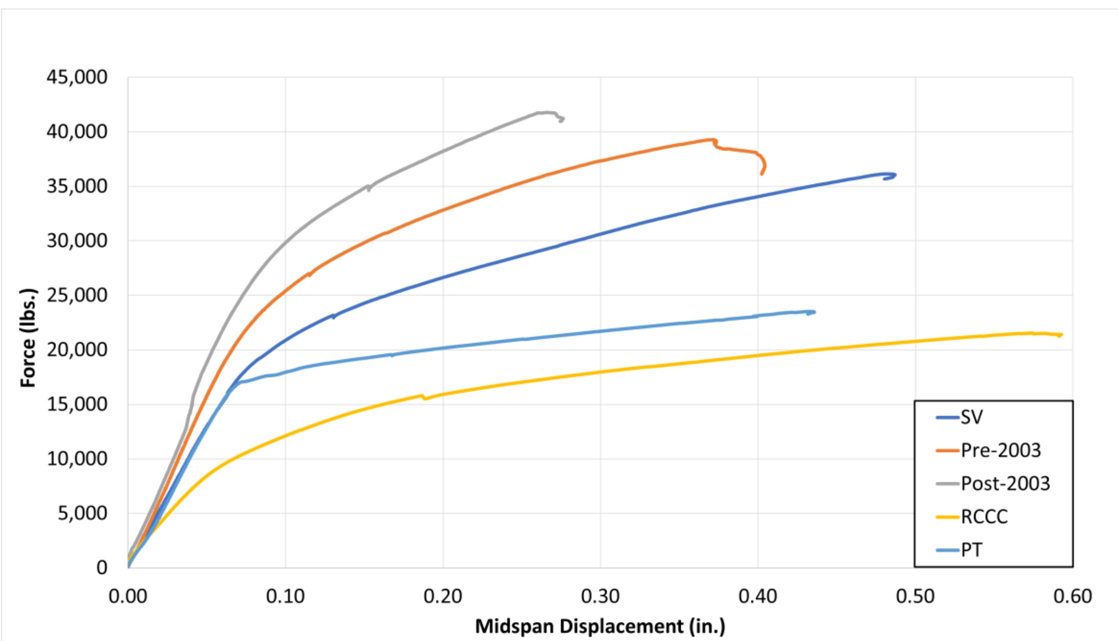

Figure 19: Center Negative Bending Moment Test Results

As shown in Figure 21, the results highlight variations in force-displacement behavior between the different concrete tie designs along with how pre-tensioned ties performed in comparison to post-tensioned.

The SV, Pre-2003, and Post-2003 concrete ties all withstood higher loads than the RCCC and PT ties, despite similar midspan dimensions. This can be attributed to the larger prestressing forces. Both the SV and RCCC ties which are over 45 years old, were found to have the largest deflections. In each case (except for the RCCC tie), the force-displacement relationship initially followed a linear trend before deviating prior to the initial crack, indicating potential internal damage. In contrast, the post-tensioned tie's force-displacement response increased similarly before reaching a critical point and while barely taking load, deflected greatly, prior to the initial crack. Notches were noted on the graph due to the brief pause from switching from force loading to displacement loading. This occurred following the sight of the initial crack key results are shown in Table 5.

Table 5: Center Negative Bending Moment Test Results Values

Type of Tie	Ultimate Load (lbs.)	Maximum Displacement (in.)	Load at Visible Crack (lbs.)	Displacement at Visible Crack (in.)
SV	36,143	0.487	23,100	0.130
Pre-2003	39,294	0.404	27,100	0.116
Post-2003	41,774	0.276	35,000	0.152
RCCC	21,554	0.593	15,800	0.187
PT	23,535	0.436	19,500	0.167

Rail Seat Positive Moment Test

The rail seat positive moment test was significant for evaluating the ability of a concrete tie to withstand the bending forces applied at the rail seat, where the rail is supported by the tie. Due to this, each tie was capable of being tested twice, once per rail seat. However, if significant bond failure or extensive damage had occurred during the testing of the first rail seat, labeled Side A, it could have negative effects on the performance of the other rail seat, labeled Side B. Figure 22 shows the results of the rail seat positive moment test for each type of concrete tie tested.

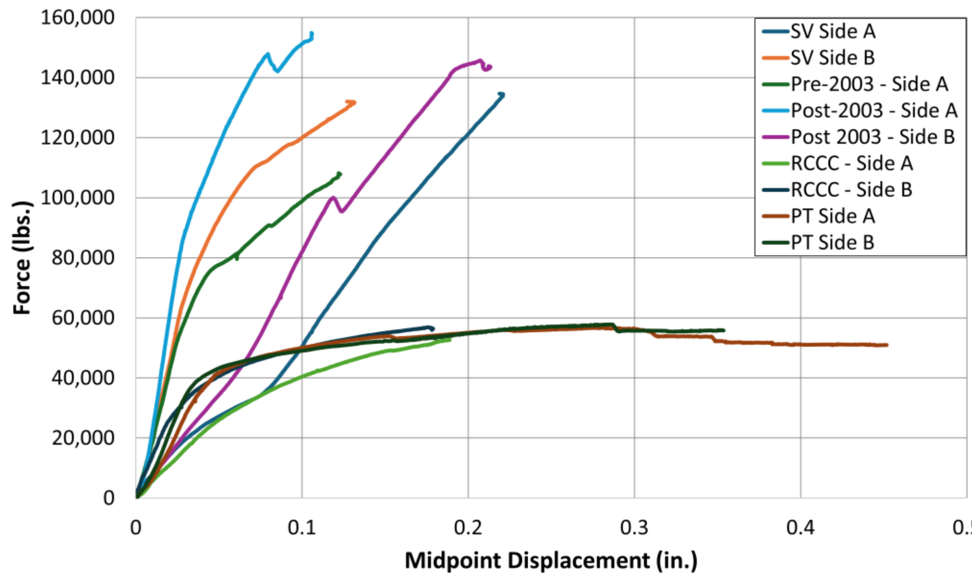

Figure 20: Rail Seat Positive Moment Testing Results

Similar to the center negative bending moment test, the SV, Pre-2003, and Post-2003 concrete ties all were able to withstand far higher loads than the RCCC and PT ties for the rail seat positive moment test as shown in Figure 22. While the RCCC tie counteracted its low strength with high deflection in the center negative bending, it exhibited the lowest force and one of the lowest displacements in rail seat positive bending. As shown in Table 6, Side A of the RCCC tie had pre-existing T cracking under the rail seat extending up to the first layer of reinforcement as shown in Figure 1.

Table 6: Rail Seat Positive Moment Test Results

Type of Tie	Ultimate Load (lbs.)	Average Maximum Displacement (in.)	Load at Visible Crack (lbs.)	Displacement at Visible Crack (in.)
SV Side A	134,650	0.228	56,669	0.106
SV Side A	133,082		81,297	0.035
Pre-2003 Side A	108,385	0.123	81,275	0.060
Post-2003 Side A	163,692	0.160	98,682	0.033
Post-2003 Side B	145,733		72,180	0.081
RCCC Side A	54,405	0.189	Pre-existing Crack	
RCCC Side B	56,879		30,893	0.027
PT Side A	56,704	0.403	33,127	0.036
PT Side B	57,888		41,793	0.044

In terms of steel reinforcement, no notable difference was determined on whether the Post-2003 concrete tie's indented wire outperforms the SV, Pre-2003, and RCCC's 7-wire strand for either the center negative bending or rail seat positive moment tests. Due to the Post-2003 tie being a new tie with significant cross-sectional area, it was expected to outperform its predecessors.

However, there was found to be a determinable difference in the results of the post-tensioned PT tie compared to the pre-tensioned tie. The PT tie was found to exhibit the greatest deflection at the midpoint of the rail seat, more than twice that of any other concrete tie. Additionally, upon removal of the load from the PT tie, even after failure, the cracks that appeared during the center negative bending and rail seat positive moment tests, closed to the point of near invisibility with the naked eye, showcasing the abilities of post-tensioned ties.

Rapid Freezing and Thawing Durability

The results of the freeze-thaw evaluation of concrete ties, recorded every 30 cycles, showed minimal variation between cycles, even with visible damage. This was accredited to the small deflections of just cracking the tie and the inherent difficulty of achieving a perfectly identical setup for each test. Because the deflections were minor, collected quantitative data alone could not provide significant insights into concrete tie degradation. However, the most meaningful results came from visual inspection of each tie’s condition over time. Noted characteristics such as surface cracking, corrosion, and other signs of deterioration became the primary indicators of freeze-thaw damage. This highlighted the importance of physical inspection when evaluating long-term performance of concrete ties within the track structure.

After 60 freeze-thaw cycles, the SV concrete tie showed slight corrosion and minimal strand end slippage, which is where the concrete typically loses bond with the prestressing tendon causing the tendon to slip and move relative to the concrete. It was noted at 120 cycles that a crack start forming at the upper strand of reinforcement traveling along the top face of the tie towards the rail seat. Due to the pre-existing damage of the Pre-2003 concrete ties, observational differences were limited. It was found that at 30 cycles, corrosion began, followed by end slip before a crack at midspan on the top face of the tie formed around at approximately 90 cycles. Pre-existing cracking continued to expand as the freeze-thaw cycles continued.

Figure 21: Post-2003 Cracking at 90 Freeze-Thaw Cycles

While the Post-2003concrete ties were new upon arrival at Kansas State University, they were found to have most severe deterioration of the pre-tensioned ties. Similar to the other concrete ties, corrosion and end slip occurred first. At 30 cycles, the Post-2003 tie exhibited more visible corrosion when compared to the other concrete ties. However, this was primarily attributed to its higher quantity of reinforcing steel. By 90 cycles, most of the tendons had slipped into the concrete and major cracking had appeared starting at the tendons and traveling along the side of the tie reaching under the rail seat as shown in Figures 23 and 24.

Figure 22: Post-2003 End Slip

Despite having a service life of over 50 years, the RCCC concrete tie was found to not develop any external damage except minor corrosion and end slippage after 120 cycles. Finally, the PT concrete tie was the only tie investigated that was post-tensioned and was checked more periodically. Within 10 cycles, cracking had formed between the grouted ends of the tendons and starting to form along the top of the tie as shown in Figure 25. Two of the grout caps had also begun to extrude from the tie while they initially started flush. After 60 cycles, no extended damage was observed but the grout caps had appeared to suck back into the concrete tie, once again becoming flush.

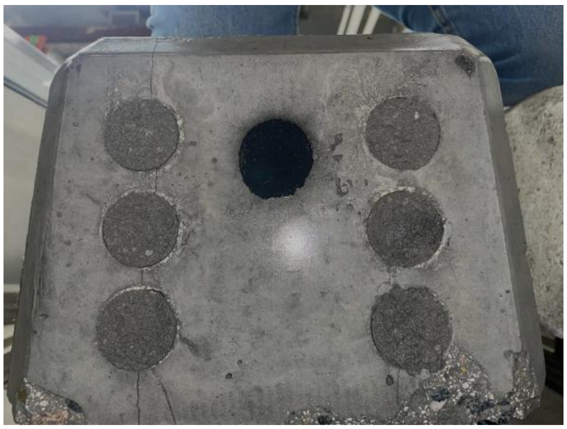

Figure 23: PT Cracking at 10 Cycles

Accelerated Corrosion Testing of Prestressing Steel

The accelerated corrosion testing provided insights into the susceptibility of prestressing tendons to degradation in aggressive environments. Corrosion was evident in the post-tensioned tendon specimens, with a recorded percent gain of over 1% of its original mass for the threaded rod, and approximately 0.7% for the straight pieces following 25 cycles of exposure. Visual inspection confirmed oxidation and surface degradation to each piece. The accumulation of corrosion on the threaded rod prevented the nut from moving freely. The observed mass gain highlights the vulnerability of post-tensioning systems, as the protective high-pH environment of conventional concrete does not extend to tendons housed in sleeves. If water infiltrates the housing sleeves, these tendons could be exposed to corrosive elements, accelerating oxidation and potential long-term degradation.

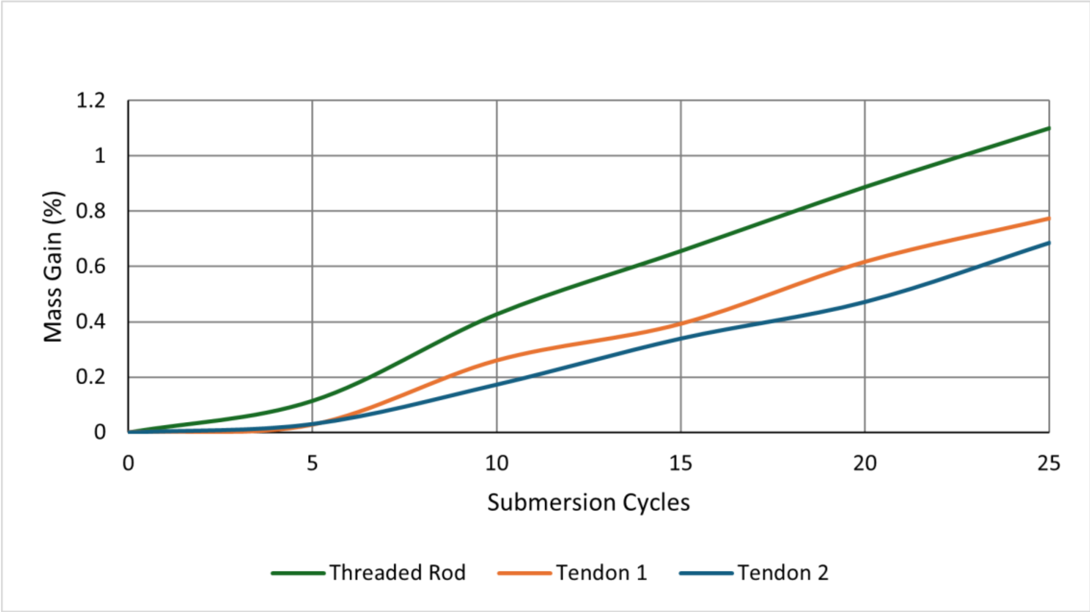

Figure 24: Corrosion of PT Tendon

For pre-tensioned tendons, visual inspections revealed surface oxidation and potential structural compromise almost immediately as shown in Figures 27 and 28. The larger pre-tensioned tendons were found to have significantly more oxidation than the smaller pieces of the post-tensioned tendons. Therefore, the it is speculated that if water were to enter the ties, the corrosion of unbonded tendons that could occur would eventually lead to the deterioration of the concrete ties.

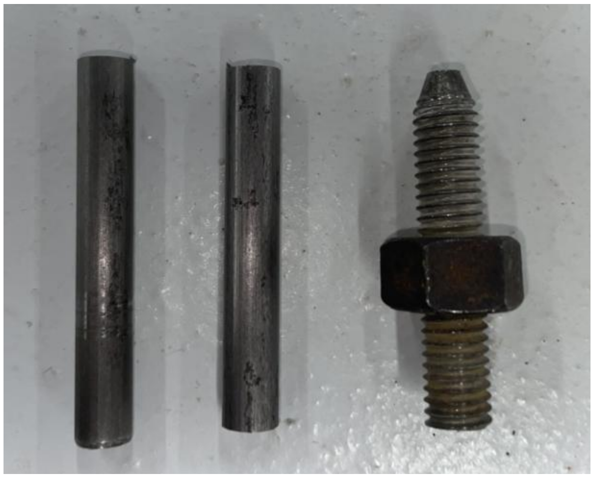

Figure 26: Corrosion at 0 Cycles

Figure 25: Corrosion at 25 Cycles

Submersion for Water Ingress Testing

The results from the 7-day submersion test indicated potential water ingress into the post-tensioned concrete tie. As shown in Figure 29, the recorded weight gain in water increased daily to a total of approximately 10 pounds. However, this measurement alone could not distinguish between infiltration into the post-tensioning components and common absorption of concrete.

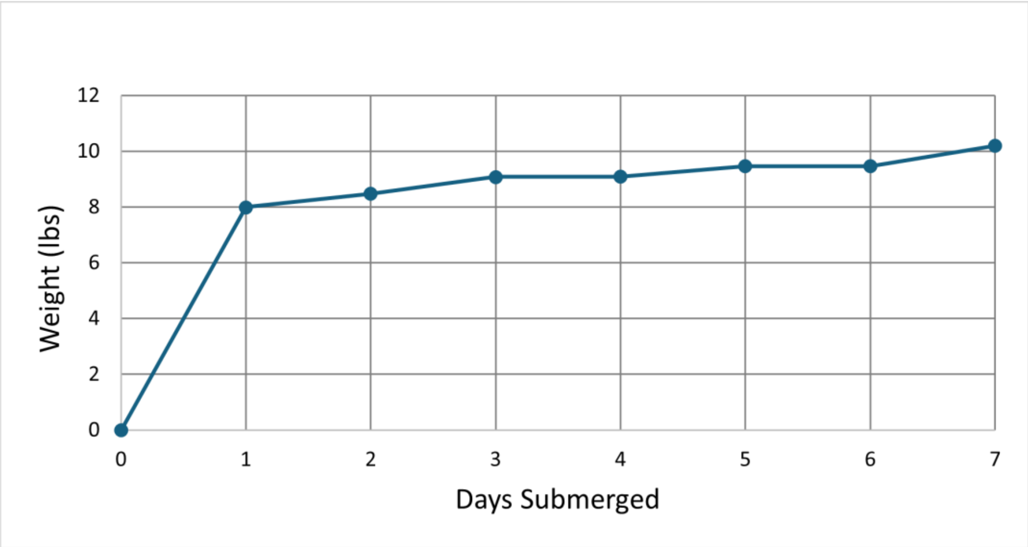

Figure 27: PT Weight Gained in Water

To address this identified limitation, the absorption for each of the concrete ties was calculated and the results are shown in Table 7. While the ties which featured a larger cross-sectional area were found to have absorptions absorb greater than 4.5%, both the RCCC and PT ties were found to slightly exceeded 2% absorption. The theoretical absorption of a full concrete tie was then determined and compared to the experimental as shown in Figure 30.

Table 7: Absorption Percentage by Tie

Name	SSD (lbs.)	Oven Dry (lbs.)	Absorption (%)
SV	7.23	6.90	4.83
Pre	7.12	6.82	4.52
Post	5.37	5.13	4.84
RCCC	5.62	5.47	2.63
PT-1	8.49	8.33	1.90
PT-2	7.93	7.78	2.01
PT-3	3.40	3.31	2.66

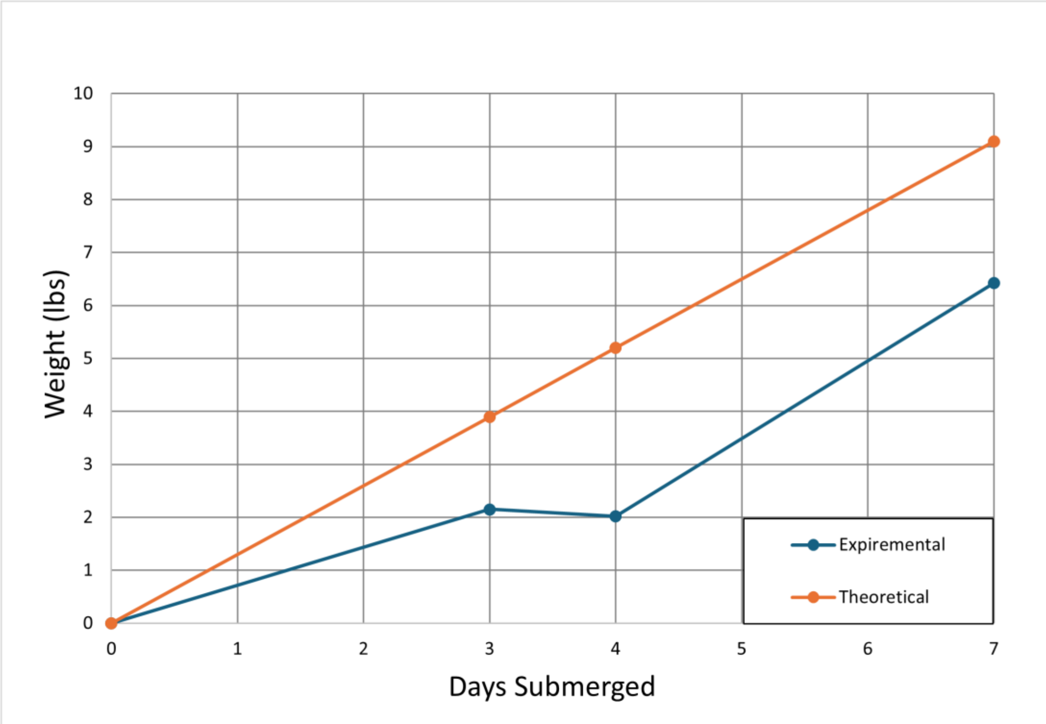

Figure 28: Absorption of PT Tie

As shown in Figure 30, the experimental absorption values were found to be consistently lower than the theoretical values. This finding suggested that although water entered the concrete, it was found to not significantly penetrate the post-tensioning components. After 7 days, the full concrete tie only gained approximately 6.5 pounds while the absorption predicted that it should have gained 9 pounds. This finding also indicated that the sleeves remained largely sealed during the test. While the weighing of the concrete tie during the submersion was only half of the evaluation, the dry cutting of the tie was found to be inconclusive. Due to the heat produced from cutting through concrete without a form of lubricant, any water that may have existed within the strands was found to not be visible. Nonetheless, the cutting process did present visual evidence of water seeping from the grouted end of the concrete tie as shown in Figure 31.

Figure 29: Water Seepage of PT Tie

This suggests the possibility of localized infiltration, despite the overall water tightness of the post-tensioning components. The infiltration of water into the grout aligned with the localized cracking observed from the freezing and thawing cycles which showcased cracking connecting the grout and the grout caps extruding from the tie.

Following the conclusion of tests on the post-tensioned concrete tie, extensive visible damage at the midspan led to a dry dissection of the affected area to inspect the health of the post-tension tendons. Removal of the protective sleeves revealed a noticeable layer of corrosion on every tendon as shown in Figures 32 and 33, despite the tie being less than a year old.

Figure 30: Live Threaded Ends **Figure 31: Corrosion at Midspan**

During the systematic dissection of the concrete tie, any slight corrosion was marked up to the use of a wet-saw for cutting. Further inspection of the dry-dissected tie found evidence that corrosion extended throughout the entire midspan of the concrete tie, but was reduced near the grouted end. A thin layer of grease was present on the non-corroded section of the tendon. It was unknown whether the tie's tendons succumbed to corrosion in such a short period or if the tendons were already corroded prior to the creation of the tie.

Chapter Seven - Conclusions and Future Research

Summary

The ensure the safe and efficient of people, goods, and services using trains, railroad companies must maintain an extensive network of track structure consisting of a system of rails, ties, ballast, and sub-ballast. The track structure is critical in transferring heavy loads, and compromised components can lead to serious derailments. The tie (concrete, wood, composite, steel) is part of the system and subjected to a lot of force. Specifically considering concrete ties which are common and have been installed for many years have an unknown service life, and varying types of mix design, reinforcement, and shape.

This research study focused primarily on the experimental evaluation of five different types of concrete crossties. The ties evaluated included three older, in-service ties and two recently manufactured concrete ties. Each tie was evaluated using a variety of hypothesized failure modes. This included AREMA's center negative bending and rail seat positive moment tests, freeze-thaw cycling, susceptibility to corrosion, and potential for water ingress to establish a baseline for mechanical performance. The results found in this study provided insights into a wide breadth and depth of research relating to tie durability and the likely failure mechanisms of aging concrete ties, providing possible insights into their remaining service life. At the same time, the performance of the newer concrete ties were assessed to validate current manufacturing standards and identify how modern concrete tie manufacturing compared to older concrete ties.

Conclusions

While the five different concrete ties were manufactured with the shared goal of supporting the track structure by load transmission, these concrete ties will inevitably need to be taken out of service as a part of routine track maintenance. The research provided findings that offer a clearer understanding into which mechanisms were most critical and how the current condition of each tie affected its remaining service life.

Despite nearing the end of its expected service life, the SV concrete ties maintained a strength and performance capability which was comparable to newer concrete ties. It was found that the SV tie offered the highest measured compressive strength of the ties at 9,950 psi and were found to withstand forces approximately 86% of the new Post-2003 concrete ties in both the center negative and rail seat positive moment testing. The SV ties also demonstrated a notable retention of its structural capacity. The SV tie also exhibited one of the largest rotational capacities recorded in this research study, further supporting its resilience over 40 years of service. Finally, when faced with freezing and thawing cycles, the SV tie showed minimal signs of deterioration with only minor surface cracking after 120 cycles. Based on these results, the SV concrete tie did not appear to be nearing the end of its possible service life.

The Pre-2003 concrete tie, while being newer than the SV concrete tie, arrived with significant horizontal cracking along the top layer of reinforcement on many of the ties provided. Despite the pre-existing damage, the Pre-2003 tie performed averagely having a measurement compressive strength of 6,875 psi and also having an ultimate load of only 2,000 lbs. less than the new Post-2003 concrete tie while offering a greater deflection in the center negative bending moment test. However, for the rail seat positive moment test, the Pre-2003 tie performed slightly poorer, failing at 108,000 lbs. while the SV and Post-2003 ties withstood approximately 133,900 lbs. and 154,700 lbs., respectively. While additionally not experiencing extensive damage due to the freezing and thawing process, it was found that the Pre-2003 concrete ties may be approaching the end of their service life due to the existing cracking.

Representing the newest design of prestressed concrete railroad ties, the Post-2003 concrete ties exhibited greater ultimate loads than the other ties in both center negative bending and rail seat positive moment tests, while having one of the lowest recorded displacements. Despite this, the Post-2003 ties have the lowest measured compressive strength of 6,675 psi and performed poorly in freeze-thaw cycling. The tie displayed rapid cracking growth stemming from the ends of the tie and progressing inwards with the majority of the prestressing tendons presenting slippage after only 90 cycles. Based on the testing, it is uncertain if the Post-2003 concrete ties will meet their expected service life.

The RCCC concrete ties were the oldest ties evaluated, manufactured approximately 50 years ago. Similar to the Pre-2003 concrete ties, the majority of the RCCC ties arrived with pre-existing cracking. However, the RCCC ties cracking exhibited a T shape located under the rail seat area. While being cracked, the RCCC ties were found to have a measured compressive strength similar to the SV concrete ties at 9,875 psi. Despite having a high measured compressive strength, the RCCC ties were found to have the lowest ultimate loads of the ties evaluated for both center negative bending and rail seat positive moment tests. In terms of deflection, the RCCC ties were found to have the highest center deflection, but an average rail seat deflection. Despite experiencing 50 years' worth of freeze-thaw cycles and railroad traffic, the RCCC tie experienced little to no damage caused by the freezing and thawing process after 120 cycles. Due to the pre-existing cracking, the RCCC concrete ties may be approaching the end of their service life.

Lastly, the PT concrete ties were a new design of prestressed concrete railroad ties featuring post-tensioned tendons. The PT ties exhibited an average measured psi of 8,830 psi and performed similarly to the RCCC concrete ties in baseline testing. While having the medium deflection of the ties in the center negative bending moment, they exhibited the greatest deflection at the rail seat positive moment test, over twice as much as any of the other ties. Similar to the Post-2003 concrete ties, the PT ties were new, but quickly began deteriorating due to the freezing and thawing test. Within 10 cycles, the grouted end of the tie exhibited cracking. Corrosion testing also revealed no significant difference between the post-tensioned and pre-tensioned tendons. All specimens exhibited comparable levels of corrosion when exposed to salt water. Finally, the submersion test indicated that water was not infiltrating the post-tensioning components, but that it was penetrating the grout. Due to the early freeze-thaw damage, it is uncertain if the PT concrete ties will meet their expected service life.

Investigating the likely failure modes of prestressed concrete ties offered valuable insights. This research study identified the deterioration caused by failure modes such as the freeze-thaw cracking, thus railroad maintenance-of-way personnel could make informed decisions on when a concrete tie should be removed or monitored more closely. By linking observable damage to specific failure mechanisms, this study contributed to a more predictive and proactive approach to tie replacement.

Study Limitations

While this research study provided invaluable insights into the performance and condition of aging concrete railroad ties, several limitations were found. One notable limitation was that not all potential failure modes could be investigated, which may leave certain degradation mechanisms unaccounted for in overall assessment of concrete tie service life. Additionally, the number of ties investigated was relatively limited, both in terms of the number of ties and the variety of concrete tie types evaluated. The concrete ties selected for testing were all removed from active railroads, which introduces a degree of survivorship bias. Concrete ties that had already succumbed to a failure mode were removed from service prior to the study, skewing the data towards those that have performed relatively well over time.

Additional limitations were related to sample preparation, time, and resources. Due to the limited spacing, 2-inch diameter cores were taken, which reduced the accuracy of the measured compressive strength. Additionally, only three concrete ties could be placed in the freeze-thaw machine at one time which slowed the testing schedule. Testing was additionally delayed due to the late arrival of the ties themselves. Due to the extensive use of the machinery, proper mechanical maintenance and operator training to maintain the systems throughout testing was required.

Future Research

Based on the conclusions found in this research study, it is recommended that future research should include investigating how variations in prestressing tendons influence the freeze-thaw durability of concrete railroad ties. It is also hypothesized that differences in surface geometry or transfer length may play a role in how these tendons affect long-term performance. The use of indented wires compared to 7-wire strand may have contributed to the early deterioration of the Post-2003 concrete ties despite it having similar geometry to the Pre-2003 concrete ties.

Another potential research area based on this study's findings is the use of epoxy-coated prestressing tendons in concrete railroad ties. Similar to how epoxy-coated rebar is used in conventional reinforced concrete to reduce corrosion risk, applying this protective layer to prestressing steel could significantly limit moisture ingress and chloride penetration.

Finally, to gain a more accurate understanding of how concrete ties perform under real-world conditions, it is recommended that future research incorporate cyclic fatigue testing. This type of testing would provide insight into long-term deterioration patterns, help identify early signs of failure and improve predictive models for service life. As the continued safety of the rail infrastructure is prioritized, research is essential to create a more reliable system that protects lives and ensures the resilience of rail networks.

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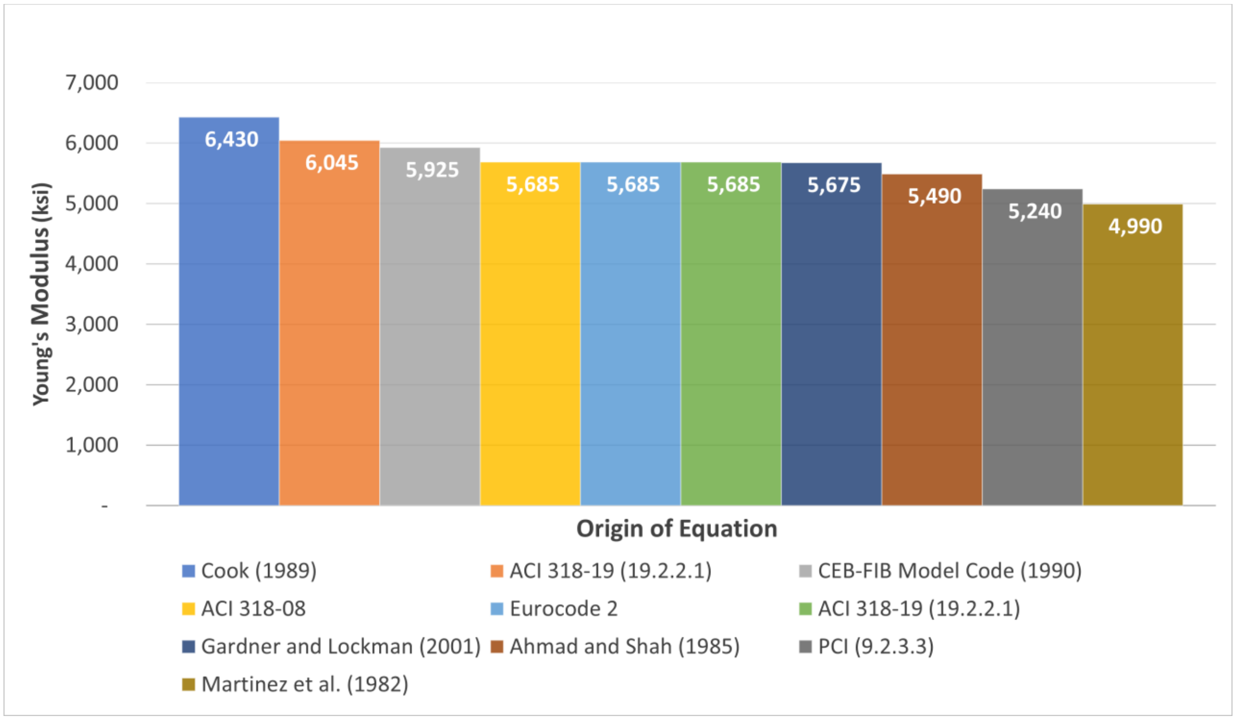
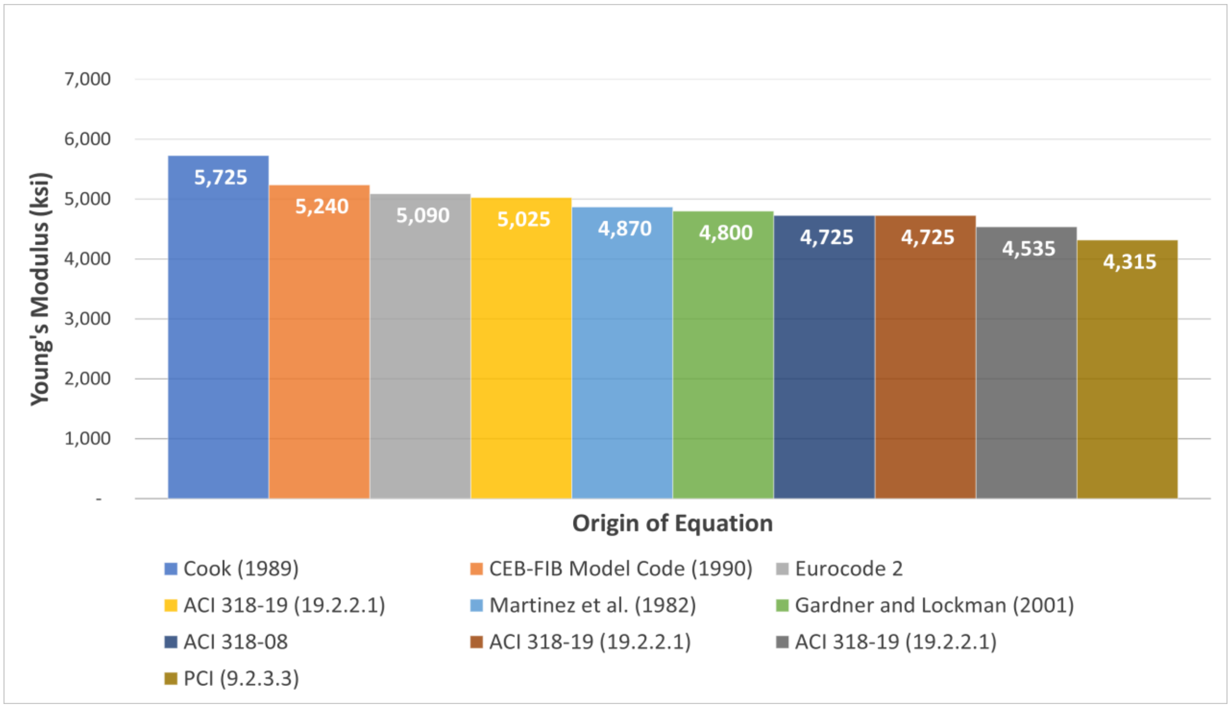
Appendix A - In-Depth Testing Results

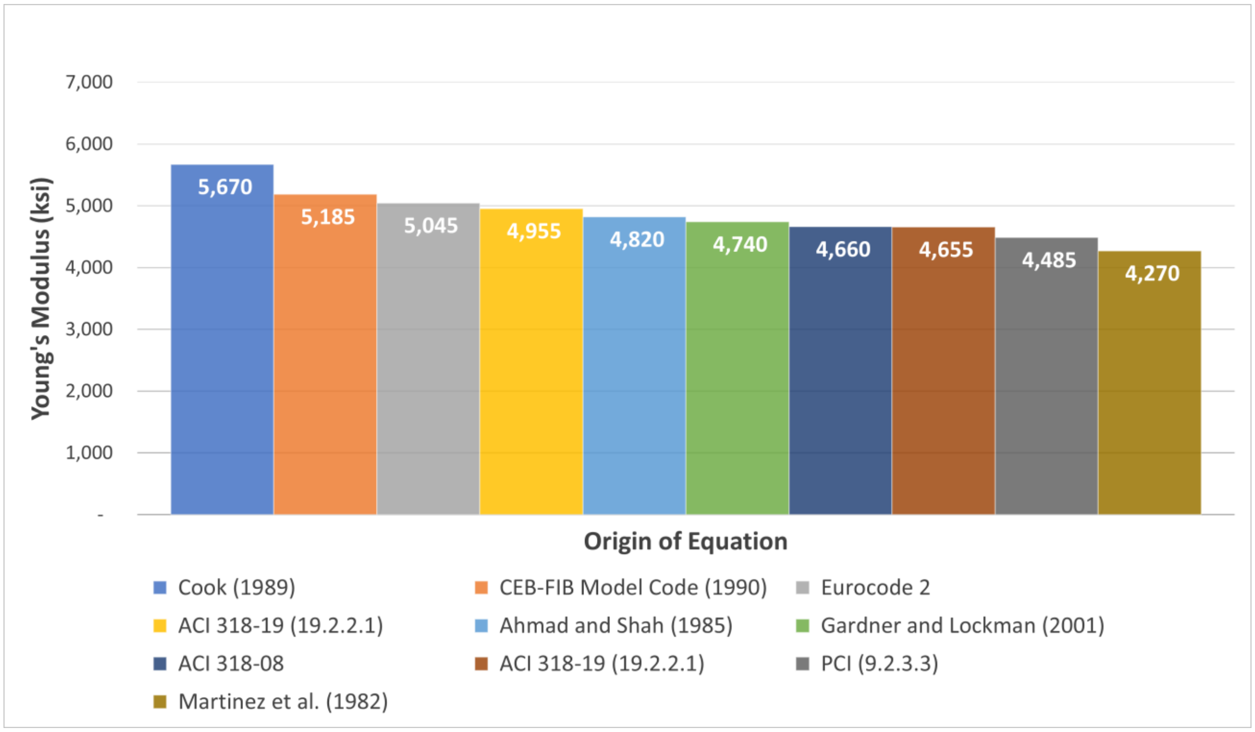
Young's Modulus of Elasticity Results



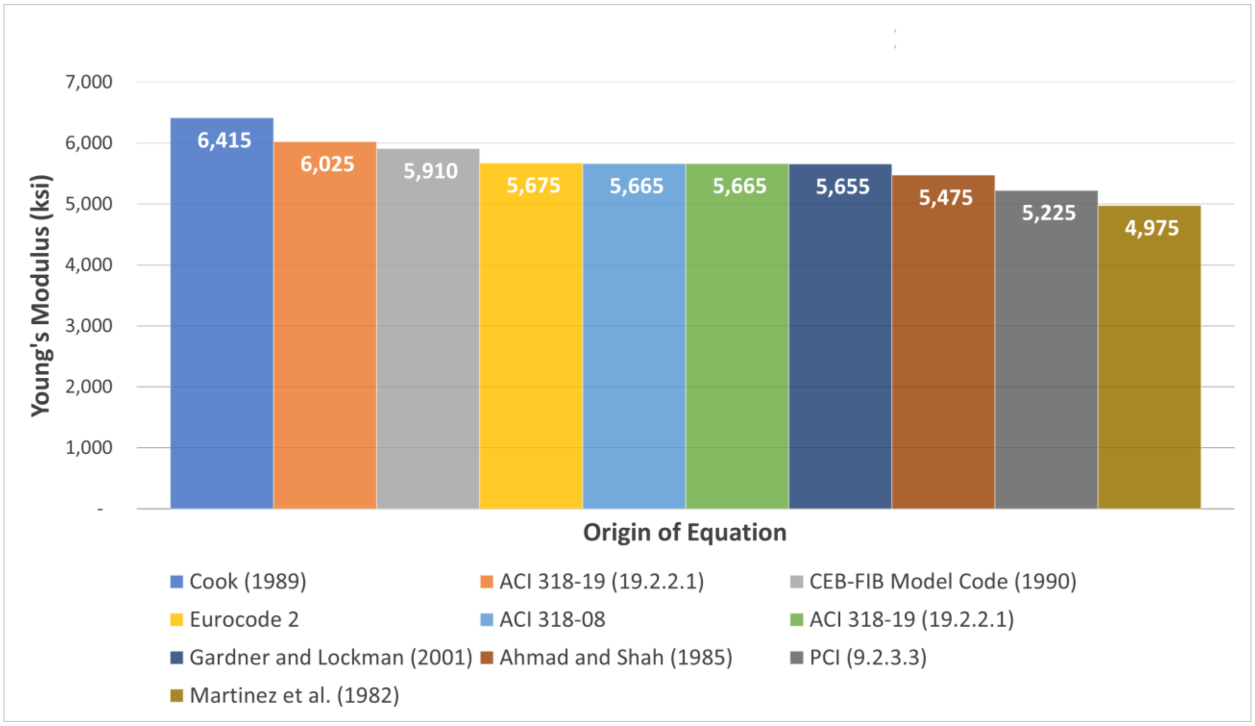
Appendix A Figure 1: Young's Modulus for SV



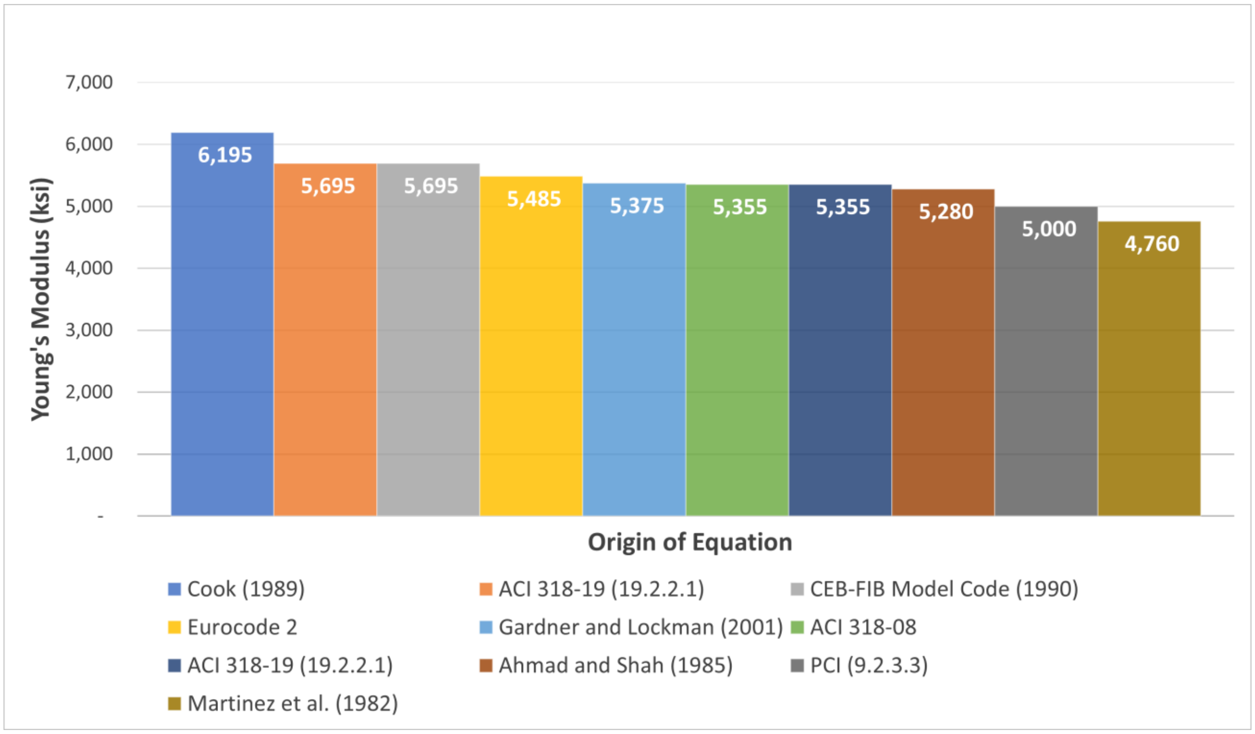
Appendix A Figure 2: Young's Modulus for Pre-2003



Appendix A Figure 3: Young's Modulus for Post-2003

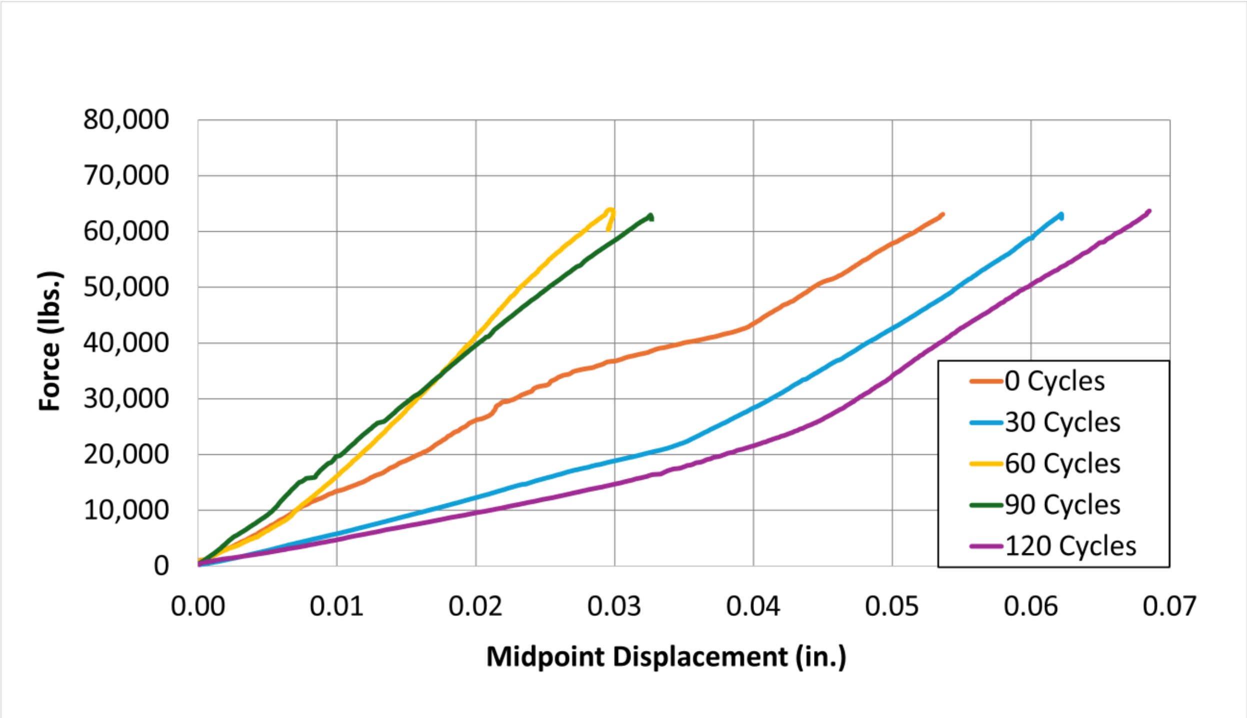


Appendix A Figure 4: Young's Modulus for RCCC

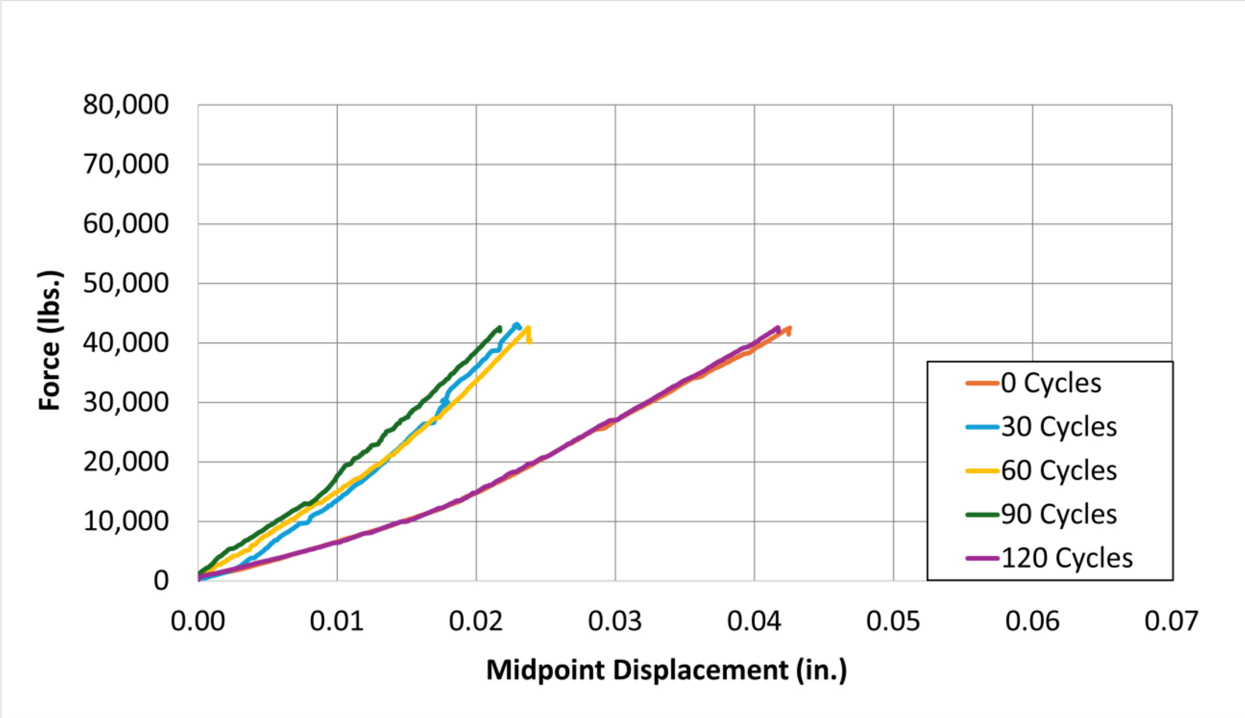


Appendix A Figure 5: Young's Modulus for PT

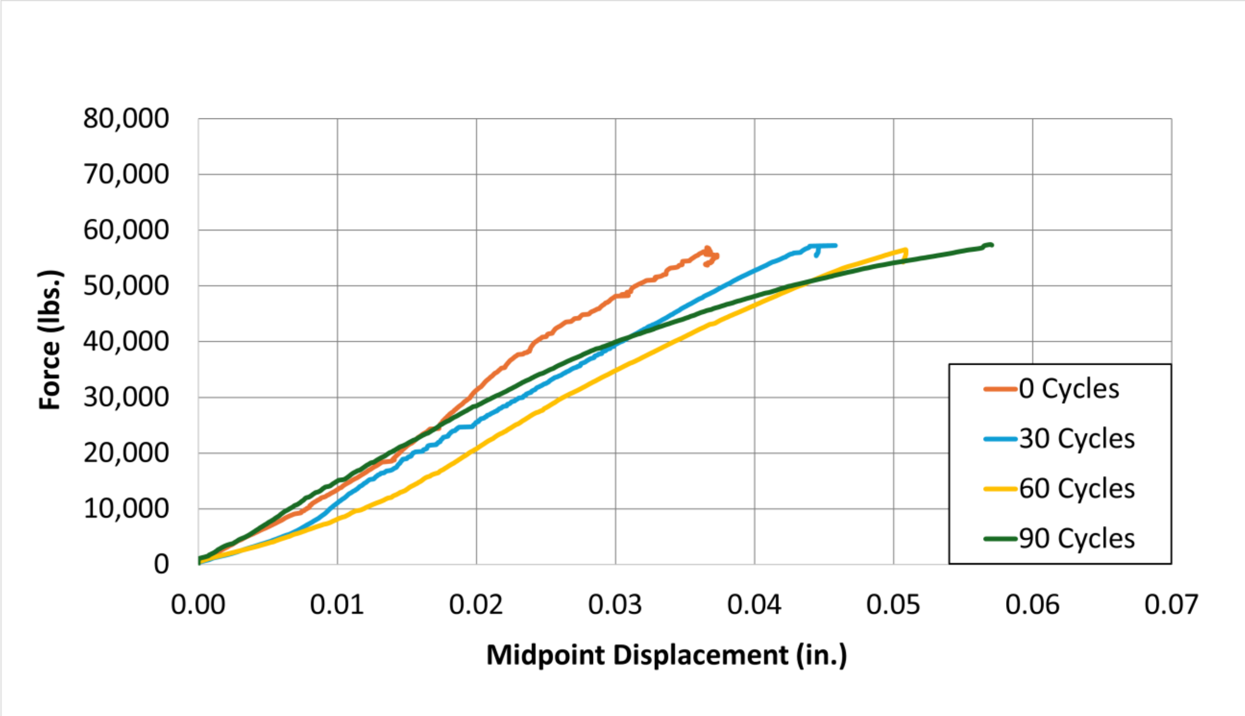
Freeze-Thaw Durability Test Results



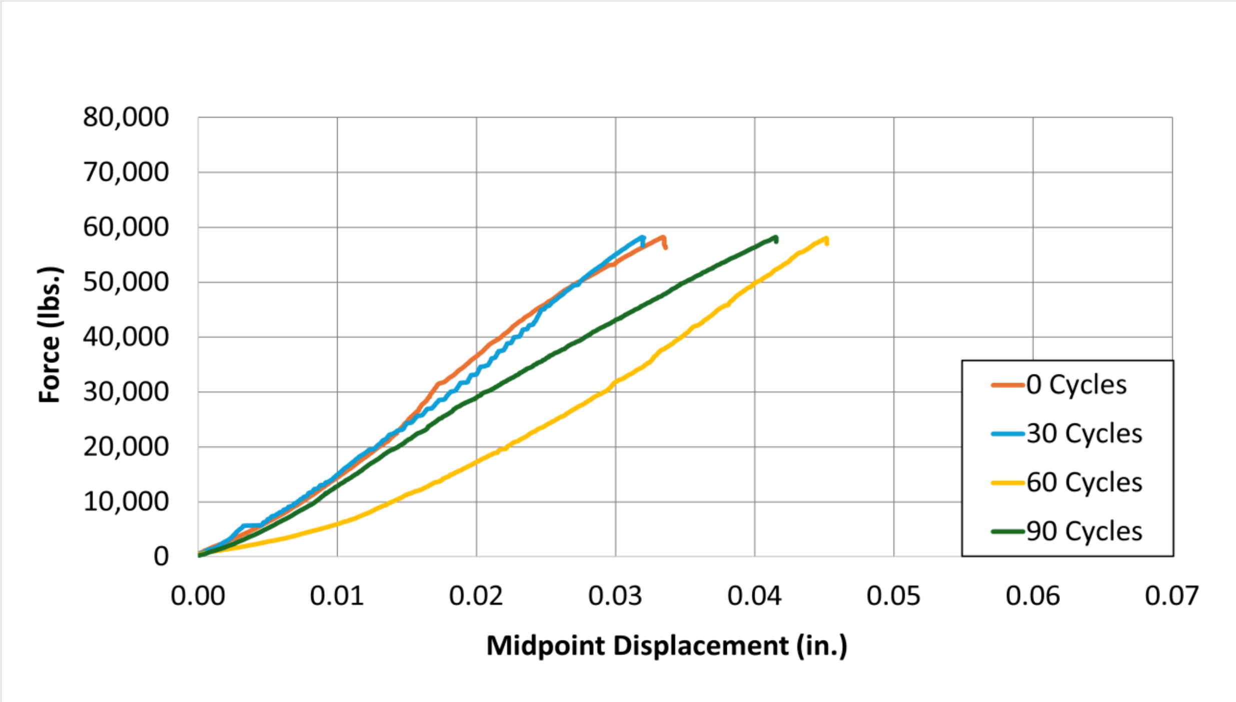
Appendix A Figure 6: Freeze-Thaw Overall Results for SV Side A



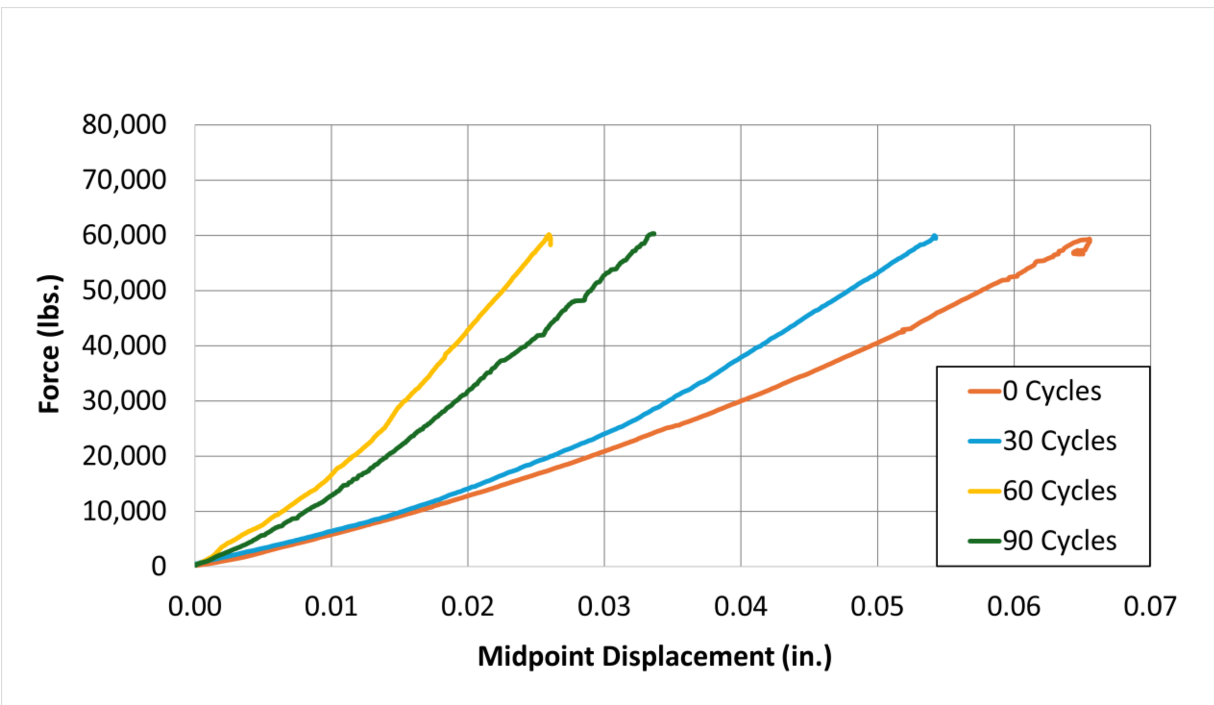
Appendix A Figure 7: Freeze-Thaw Overall Results for SV Side B



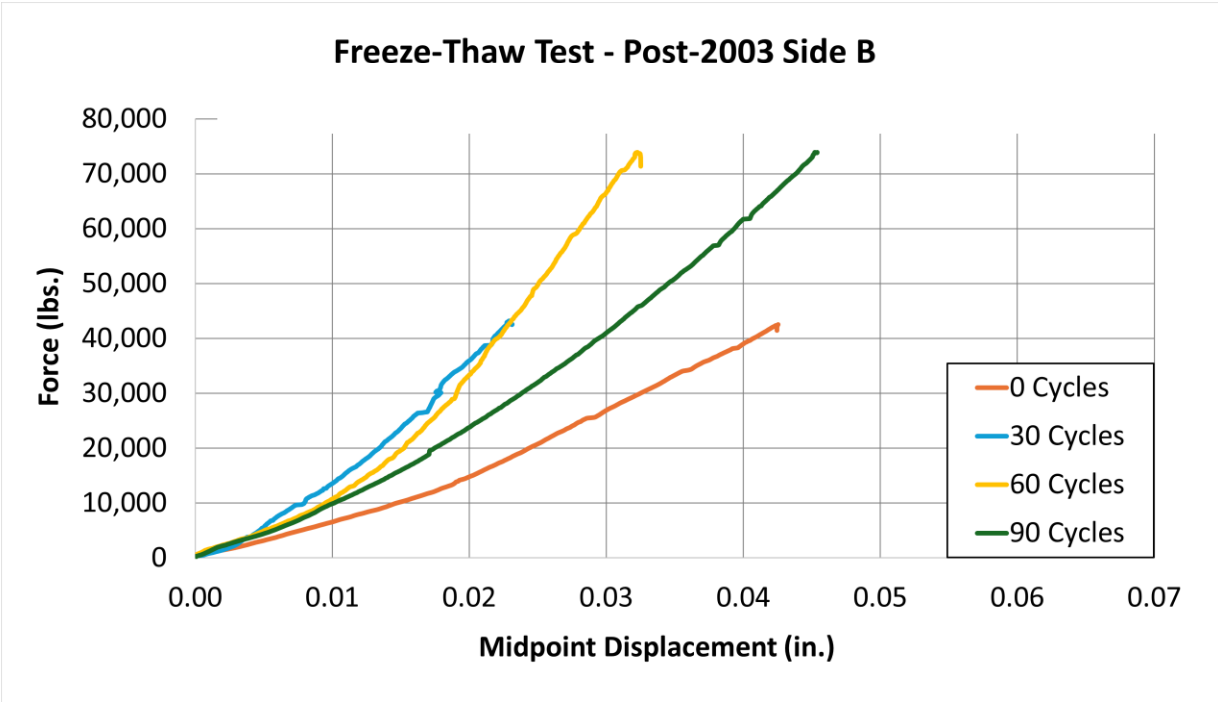
Appendix A Figure 8: Freeze-Thaw Overall Results for Pre-2003 Side A



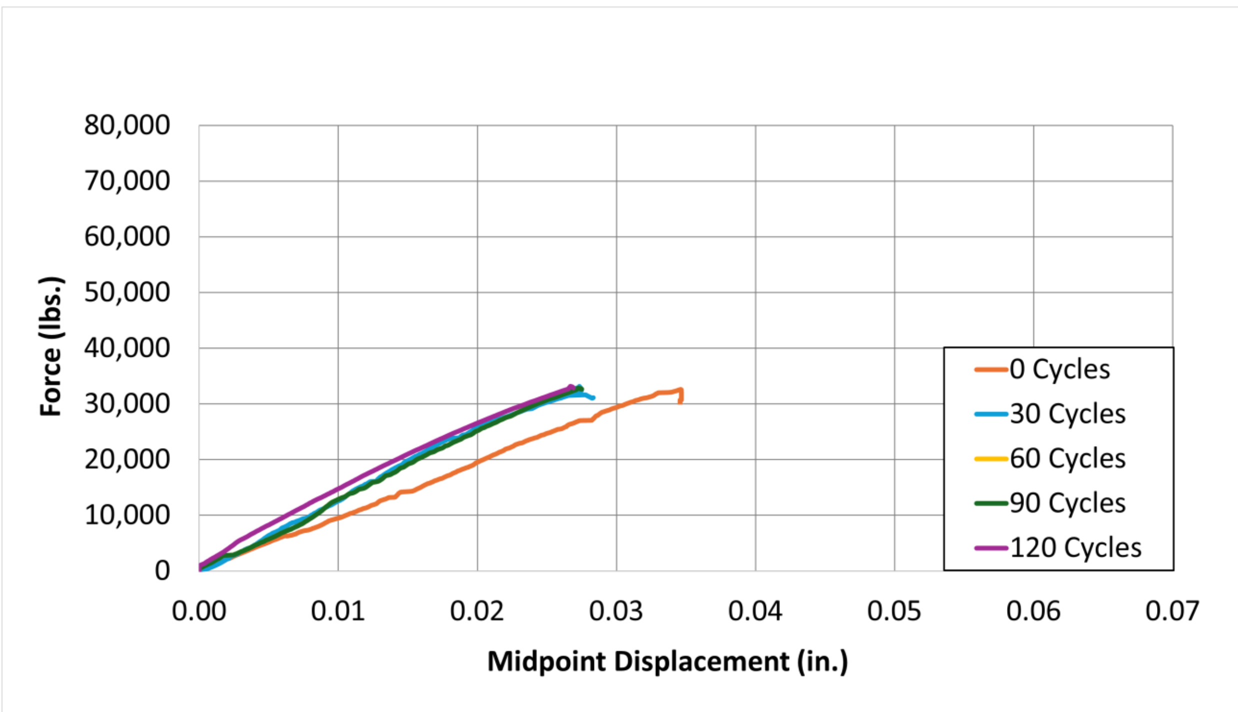
Appendix A Figure 9: Freeze-Thaw Overall Results for Pre-2003 Side B



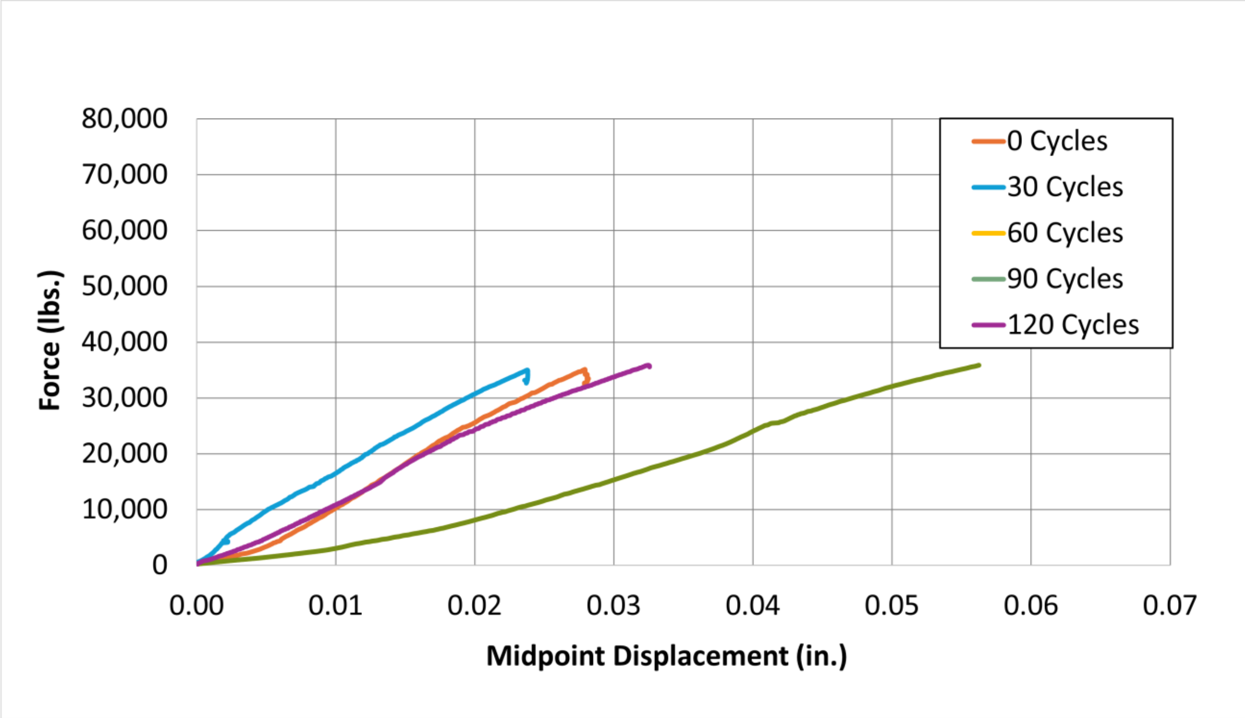
Appendix Figure 10: Freeze-Thaw Overall Results for Post-2003 Side A



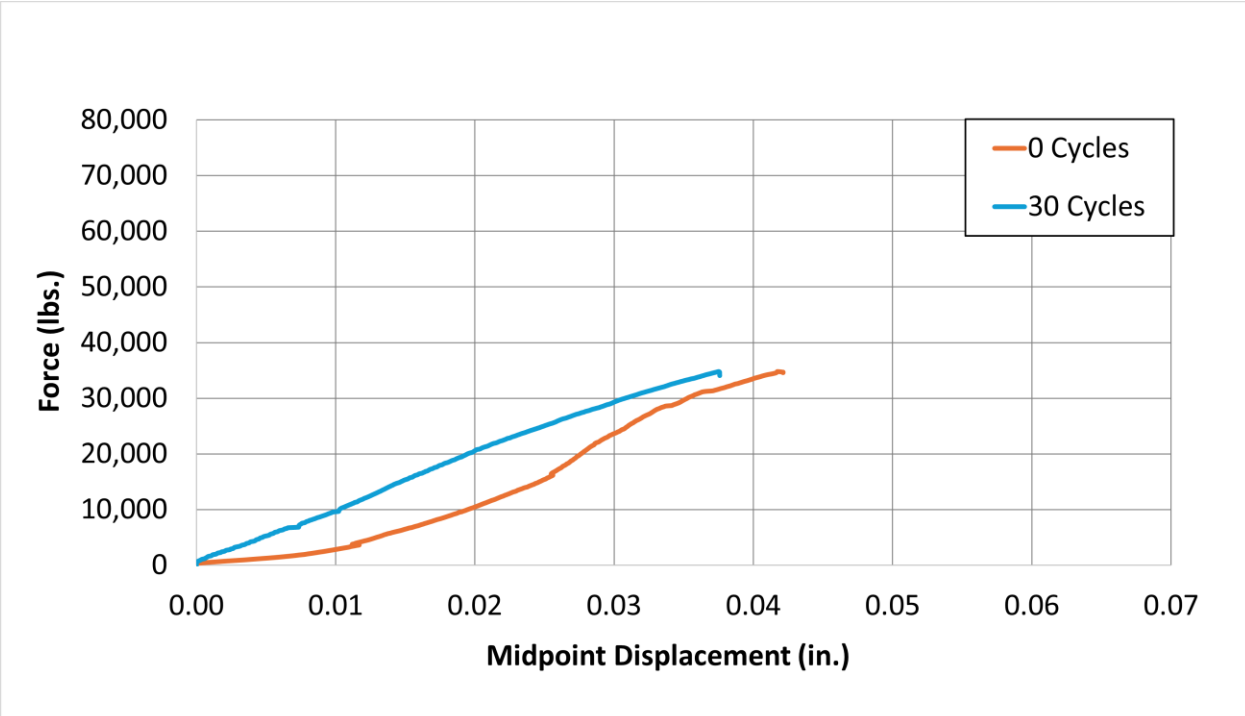
Appendix A Figure 10:Freeze-Thaw Overall Results for Post-2003 Side



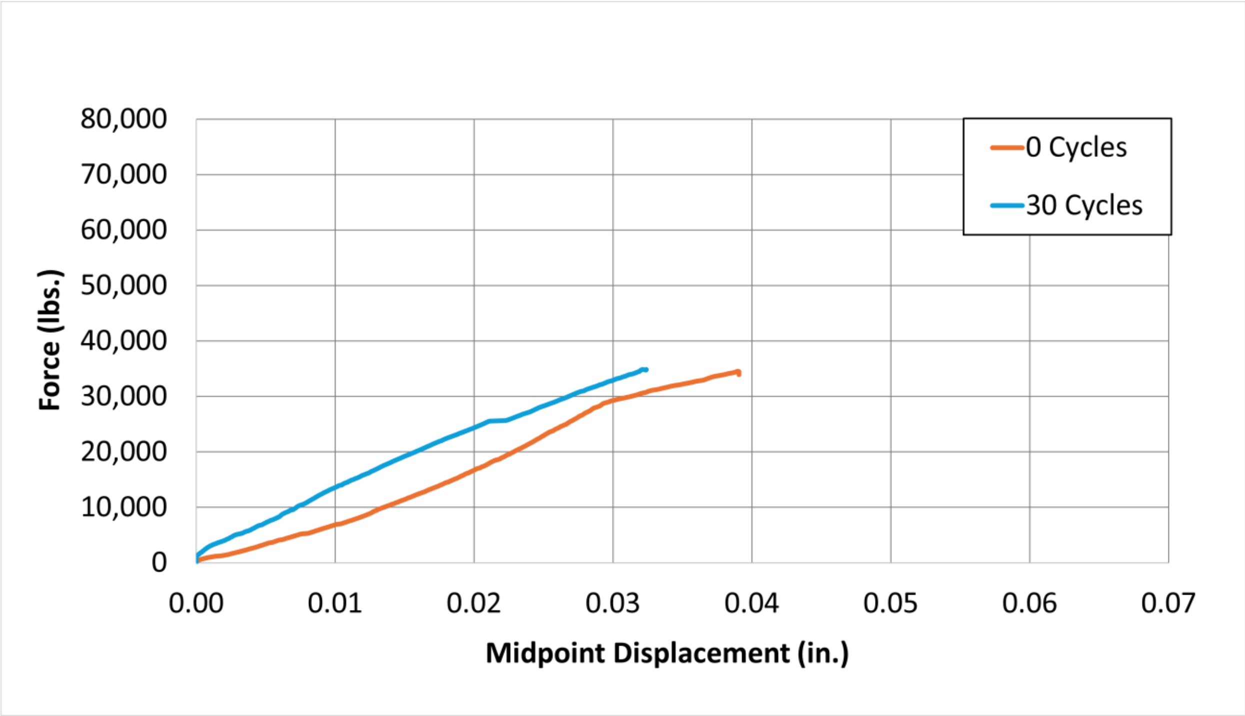
Appendix A Figure 11: Freeze-Thaw Overall Results for RCCC Side A



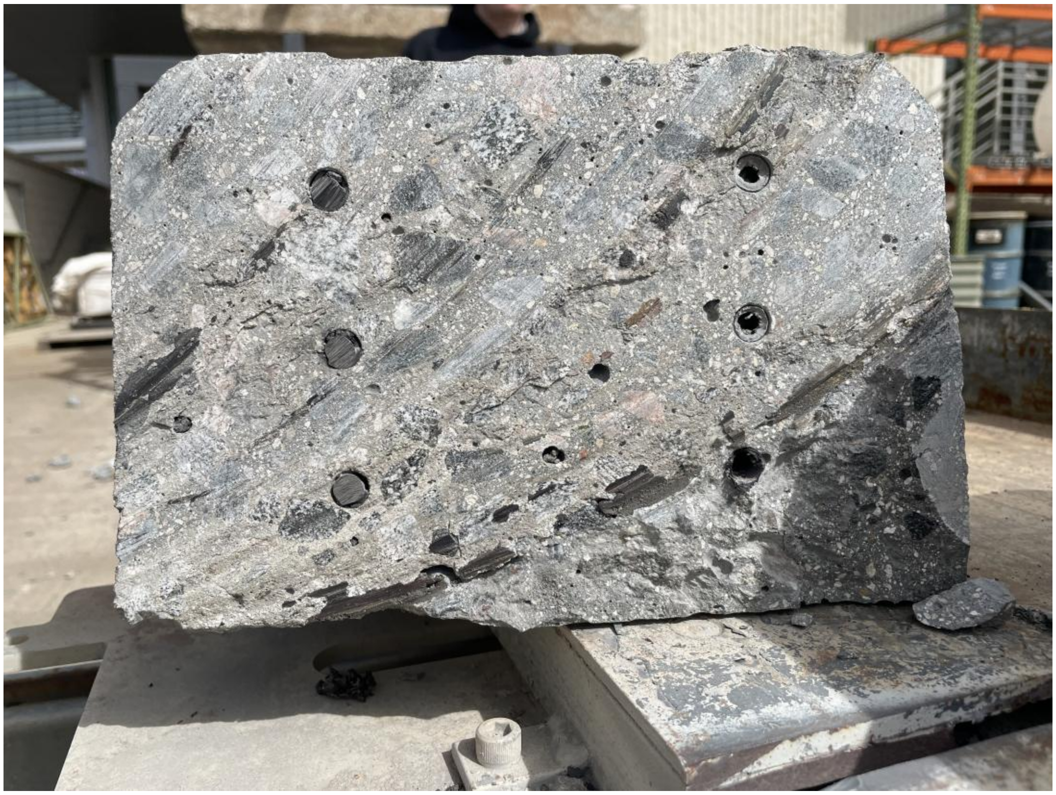
Appendix A Figure 12: Freeze-Thaw Overall Results for RCCC Side B



Appendix A Figure 13: Freeze-Thaw Overall Results for PT Side A



Appendix A Figure 14: Freeze-Thaw Overall Results for PT Side B



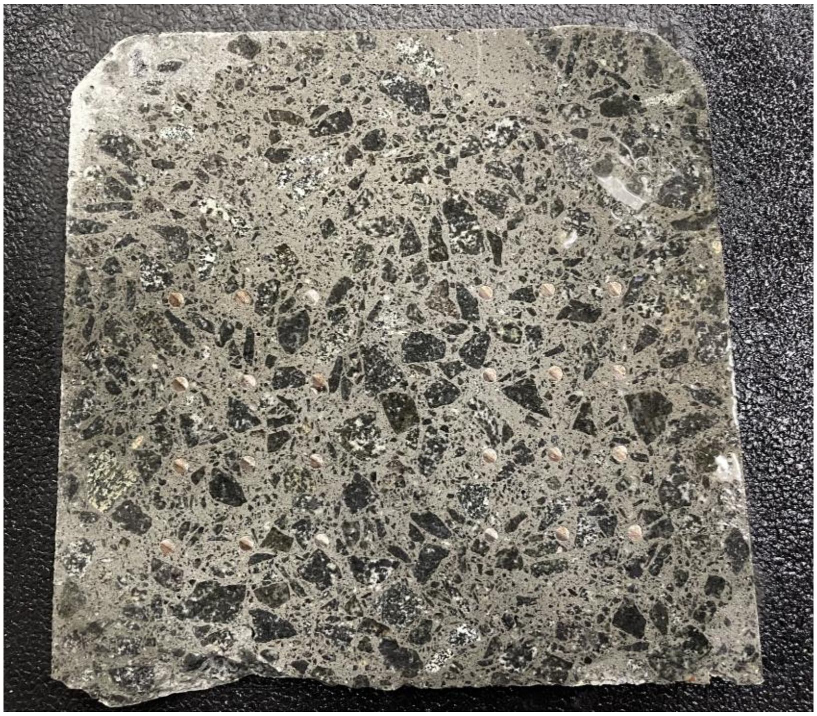
Appendix A Figure 15: Results from Dry Cutting PT Tie at Cut

Appendix A Figure 16: Results from Dry Cutting PT Tie at End

Appendix B - Pictures of Tie Cross-Sections

Appendix B Figure 1: SV Tie Cross-Section

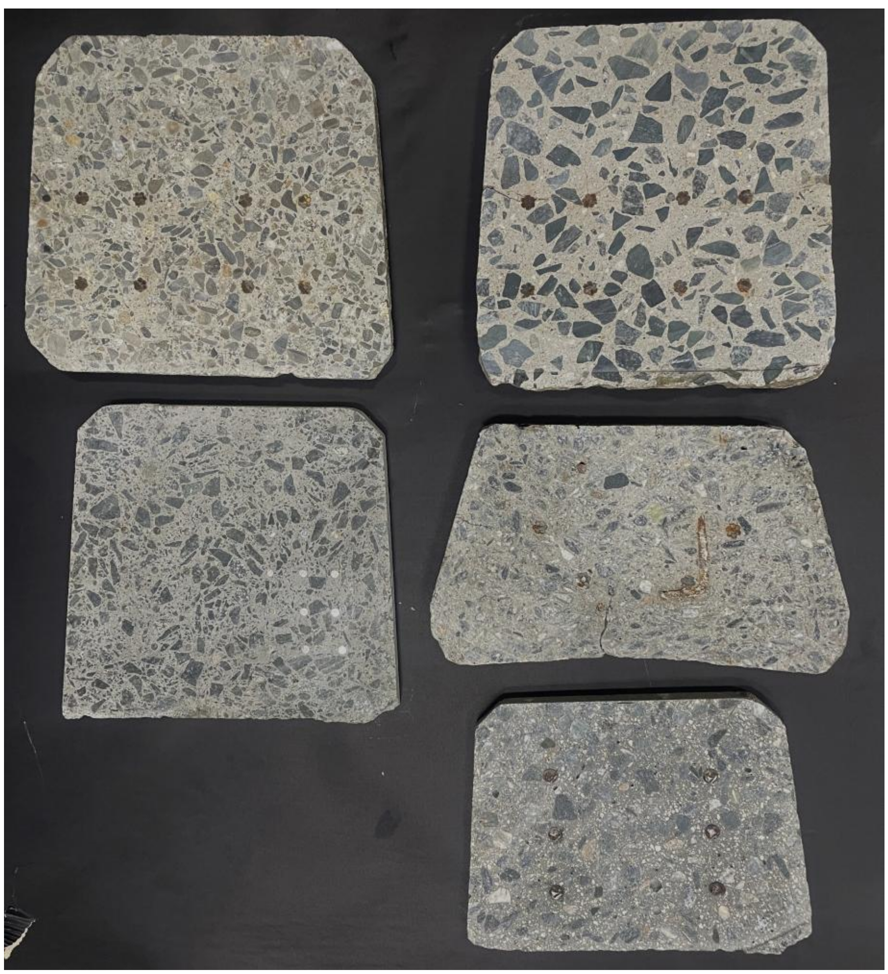
Appendix B Figure 2: Pre-2003 Tie Cross-Section



Appendix B Figure 3: Post-2003 Tie Cross-Section

Appendix B Figure 4: RCCC Tie Cross-Section

Appendix B Figure 5: PT Tie Cross-Section



Appendix B Figure 6: All Ties Cross-Sections