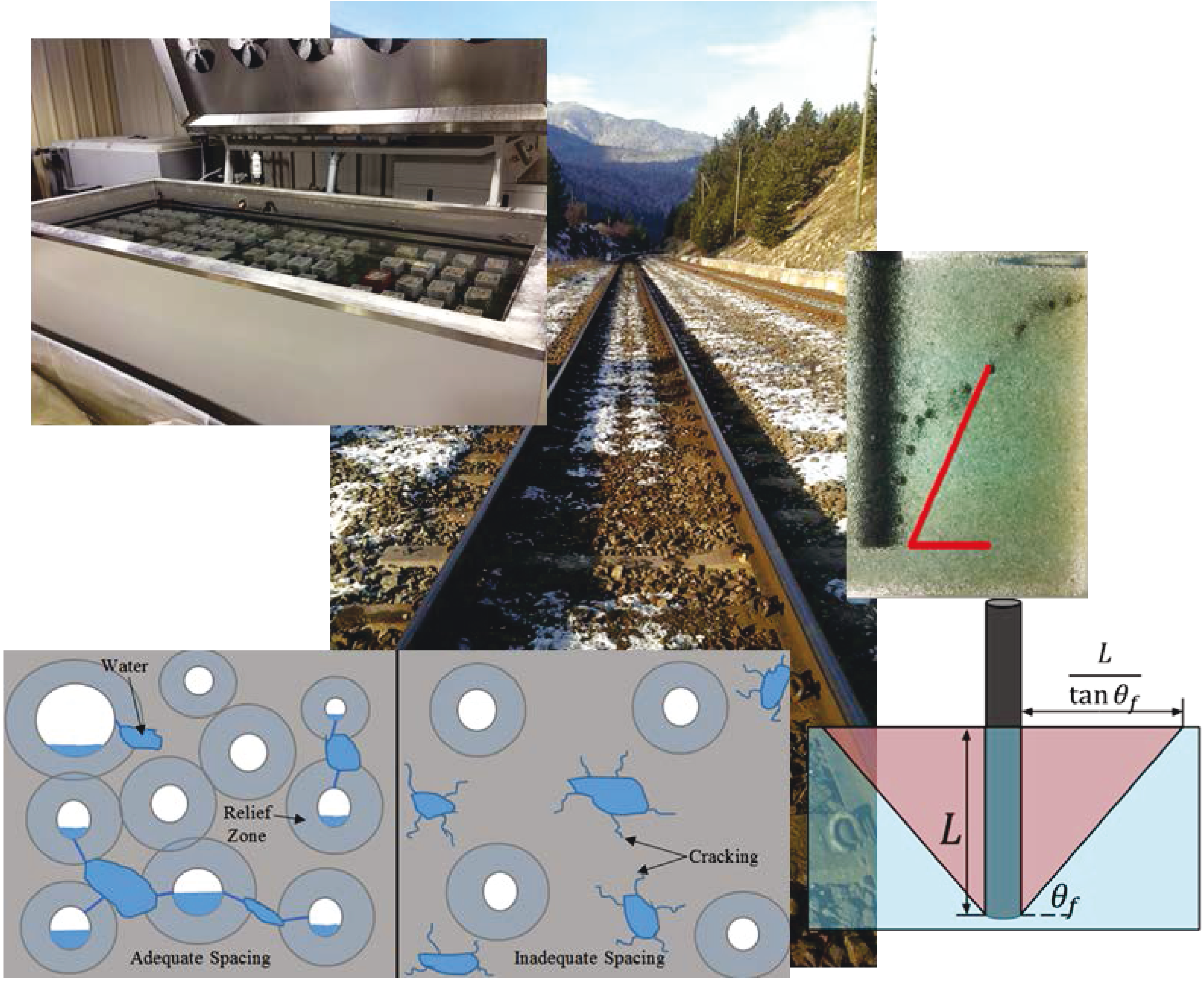
U.S. Department of
Transportation

**Federal Railroad
Administration**

Material and Manufacturing Requirements for Freeze-Thaw Durable Concrete Railroad Ties: Volume I

Office of Research,
Development
and Technology
Washington, DC 20590



DOT/FRA/ORD-18/31

Final Report
August 2018

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. Any opinions, findings and conclusions, or recommendations expressed in this material do not necessarily reflect the views or policies of the United States Government, nor does mention of trade names, commercial products, or organizations imply endorsement by the United States Government. The United States Government assumes no liability for the content or use of the material contained in this document.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE August 2018	3. REPORT TYPE AND DATES COVERED Technical Report

4. TITLE AND SUBTITLE

Material and Manufacturing Requirements for Freeze-Thaw Durable Concrete Railroad Ties: Volume I

5. FUNDING NUMBERS

DTFR53-12-C-00026

6. AUTHOR(S)

Kyle A. Riding, David A. Lange, Daniel Castaneda, Jeremy Koch, Mohammed Albahttiti, Ahmad Ghadban, Yu Song, and Ruofei Zou

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Kansas State University
2118 Fiedler Hall
Manhattan, KS 66506

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
Office of Research, Development and Technology
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

DOT/FRA/ORD-18/31

11. SUPPLEMENTARY NOTES

COR: Cameron D. Stuart

12a. DISTRIBUTION/AVAILABILITY STATEMENT

This document is available to the public through the FRA Web site at http://www.fra.dot.gov.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This research program was conducted as a partnership between the University of Illinois at Urbana-Champaign (UIUC), Kansas State University (KSU), and the Illinois Department of Transportation to study the freeze-thaw durability of concrete railroad ties as air is purposefully entrained in concrete railroad ties to impart freeze-thaw durability, and vibration used during manufacture to consolidate concrete can reduce entrained air needed for freeze-thaw protection. This report is divided into two volumes. Volume I is a summary report that emphasizes key project methodologies, results, and recommendations. Volume II contains detailed project results from field monitoring of concrete tie temperature and moisture, laboratory experiments, and modeling performed. The objective of this research was to gain insight into the environment conditions that concrete ties experience, and to better understand how the interaction of materials and processes used in tie construction affect freeze-thaw durability. Key research questions were answered by measuring concrete tie manufacturing conditions, as well as developing a robust laboratory-based experimental research program, computational modeling of systems, and measuring field conditions. The results of this research program is to facilitate improved concrete tie specifications and quality assurance testing.

14. SUBJECT TERMS

Concrete consolidation, air void system, freeze-thaw durability, concrete crosstie

15. NUMBER OF PAGES

26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

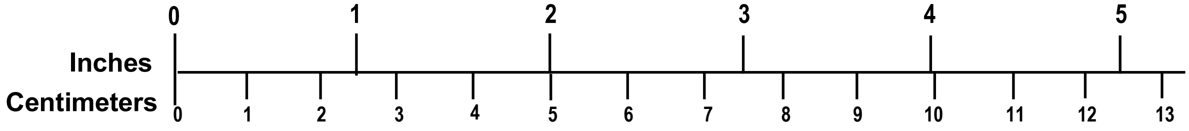
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

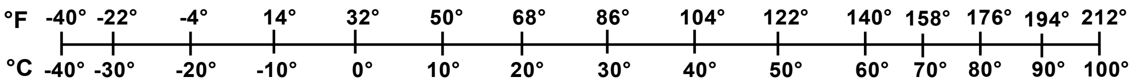
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgements

This project was performed with the cooperation of industry partners CXT Concrete Ties Inc., voestalpine Nortrak, and Canadian National Railway. The assistance of Jim Parsley, Steve Mattson, Tara Ross, and Nigel Peters is gratefully acknowledged. We also acknowledge assistance from researchers at the University of British Columbia who helped with data retrieval from sensors installed in the track at Lytton, BC. Professors Gord Lovegrove and Ahmad Rteil, and students Trevor Billows and Kyle Stratton assisted in that effort. We appreciate the assistance of Tim Crouch, a volunteer at the Monticello Railway Museum, who helped us install sensors in the track at their facility in Monticello, IL.

Contents

Illustrations

Executive Summary

This research program was conducted as a partnership between the University of Illinois at Urbana-Champaign (UIUC), Kansas State University (KSU), and the Illinois Department of Transportation to study the freeze-thaw durability of concrete railroad ties. The program was sponsored by the Federal Railroad Administration and executed between September 2012 and January 2016.

Concrete railroad ties must be resistant to freezing deterioration to withstand cold climates. Concrete can be durable in freeze/thaw environments if the concrete does not become critically saturated, or is made with a sufficient amount of well distributed, very small air voids in the cement paste (ASTM Standard C 666, 2008). Railroad track structures are designed to drain water freely during precipitation events, but the ballast can also retain moisture below the surface. Ballast covering the ties on the sides and bottom can insulate the concrete ties, reducing the number of freeze-thaw cycles the concrete railroad ties experience, but the ballast can retain moisture on the sides and bottom of the crossties. The objective of this research was to gain insight into the environment conditions that concrete ties experience, and to better understand how the interaction of materials and processes used in tie construction affect freeze-thaw durability.

Key research questions were answered by measuring concrete tie manufacturing conditions as well as developing a robust laboratory-based experimental research program, computational modeling of systems, and measuring field conditions. The results of this research program is intended to facilitate improved concrete tie specifications and quality assurance testing.

This research established a fundamental understanding of vibration transmission for immersion vibrators which lead to improvements in concrete rheology and vibration transmission models. Vibration intensity was shown to have a positive correlation with air loss and increased spacing factor. Total air content before and after vibration was not found to correlate with freeze-thaw durability of vibrated concrete. The spacing factor after vibration was found to be a good quality control parameter for concrete acceptance for freeze-thaw durability, but not rejection. It was found that excising samples from pre-stressed concrete by saw cutting may induce micro-cracking, and therefore, should be avoided in quality control protocols. Our research also found that the concrete tie surface could become critically saturated in the field and cause progressive damage and mass loss, especially on the tie sides and bottom.

This report is divided into two volumes. Volume I is a summary report that emphasizes key project methodologies, results, and recommendations. Volume II contains detailed project results from field monitoring of concrete tie temperature and moisture, laboratory experiments, and modeling performed

1. Introduction

This research program was conducted as a partnership among the University of Illinois at Urbana-Champaign (UIUC), Kansas State University (KSU), and the Illinois Department of Transportation to study the freeze-thaw durability of concrete railroad ties. Participating concrete railroad tie manufacturers and railroads included CXT Concrete Ties, voestalpine Nortrak, and Canadian National Railway (CN). The University of British Columbia also participated in this study by monitoring the field instrumentation.

Key research questions were answered by measuring concrete tie manufacturing conditions as well as developing a robust laboratory-based experimental research program, computational modeling of systems, and measuring field conditions. The results of this research program is intended to facilitate improved concrete tie specifications and quality assurance testing.

1.1 Background

Concrete railroad ties are commonly used in high-speed and heavy-haul railroad applications. Approximately 8 percent of all railroad ties in the U.S. are concrete (Borchardt, J. K., 2010). Most concrete railroad ties are made using pre-stressed concrete. Concrete railroad ties are the material of choice for heavy-haul applications because they are capable of a long service life in demanding environmental and loading conditions. They are used in high-speed rail applications due to their long service life and lower deflections under load.

Concrete railroad ties must be resistant to freezing deterioration to withstand cold climates. Concrete can be durable in freeze/thaw environments if the concrete does not become critically saturated, or is made with a sufficient amount of well distributed, very small air voids in the cement paste (ASTM Standard C 666, 2008). Railroad track structures are designed to drain water freely during precipitation events, but the ballast can also retain moisture below the surface. Ballast covering the ties on the sides and bottom can insulate the concrete ties, reducing the number of freeze-thaw cycles the concrete railroad ties experience, but the ballast can retain moisture on the sides and bottom of the crossties. The objective of this research was to gain insight into the environment conditions that concrete ties experience, and to better understand how the interaction of materials and processes used in tie construction affect freeze-thaw durability.

Fundamental knowledge of the response of air bubbles in concrete is needed to understand material and vibration requirements to produce freeze-thaw durable concrete. Pre-stressed concrete ties are typically vibrated during placement to consolidate the concrete. Vibration removes the large air voids from the concrete and improves strength. However, if concrete is excessively vibrated, the vibration can remove the smaller, entrained air bubbles (i.e., 10 µm to 1 mm diameter) that enhance freeze-thaw resistance (Hover, K., 2003). Concrete railroad tie producers use different methods of vibrating the concrete, including internal probes and form-mounted vibrators. These methods impart different amounts of vibrational energy to the concrete. Modern concrete is made with a wide variety of cementitious materials, including water reducing chemical admixtures and air entraining chemical admixtures. Different manufacturing plants and processes use concrete with a wide range of rheological properties. Entrained air voids could be lost at a faster rate in a flowable mixture compared to a stiff concrete mixture. This research explores basic fluid mechanics of granular materials and bubble behavior in concrete to provide material models that can be used to improve manufacturing processes.

Concrete railroad tie quality control procedures are not uniform across the industry and, in many cases, are determined by customer specifications. However, all procedures require control of the air content in concrete before it is vibrated, and all require periodic freeze-thaw testing prescribed by standard ASTM C 666. The procedures used to make samples for ASTM C 666 varies across the industry. Some of the specifications require the concrete used in the freeze-thaw test to be saw cut from production ties, whereas other specifications allow for test samples made from the fresh, un-vibrated concrete. Pre-stressing steel may be present in ASTM C 666 samples. The pre-stressing forces are released when the concrete has reached sufficient strength to bond to the concrete and withstand the compressive pre-stressing forces imposed on the ties. This transfer of forces between the steel and concrete occurs over some distance. When the concrete end is cut from the tie to make prisms for testing the freeze-thaw durability, the pre-stressing force at the newly cut end is transferred to the concrete, creating a new force transfer zone. There is concern in the industry that saw cutting samples for freeze-thaw testing from pre-stressed concrete can result in cracks. Small micro-cracks could create locations for ice-lens to form during testing, wedging open the concrete and causing cracks to grow. This research studies the effects of the saw cut process on the freeze-thaw test results.

1.2 Objectives

The research goals of this project were to determine the material, fabrication, and quality control testing requirements necessary to manufacture freeze-thaw durable concrete railroad ties. To create a more durable railroad tie, the following research objectives were developed:

1. Study how air bubbles in concrete of different rheological properties respond to vibration.
2. Quantify the freeze-thaw exposure conditions that concrete railroad ties experience in track.
3. Establish material and fabrication standards to produce ties with adequate freeze-thaw resistance.
4. Establish recommended material qualification and quality control test procedures to ensure freeze-thaw durability of pre-stressed concrete railroad ties.

1.3 Overall Approach

This project used an integrated approach of plant, field, laboratory experiments, as well as modeling to address critical knowledge gaps in concrete material technology that are needed to ensure durable production and quality control testing of concrete railroad ties.

New methods were developed to measure vibration energy used to consolidate concrete at several concrete railroad tie plants. Concrete properties were also measured, and the researchers studied the rheology of fresh concrete. The results of this study were used to guide the selection of vibration frequency, energy, and duration used in laboratory experiments.

Concrete field tests were performed to determine the temperature history and moisture levels of concrete railroad ties exposed to cold environments seen in North America. Concrete railroad tie measurements were used to gauge the severity of freezing rates in accelerated freezing and thawing tests. This data were also used to gauge the number of yearly freeze-thaw cycles ties may experience during their service life. Concrete railroad ties were fabricated with embedded temperature and relative humidity sensors. These ties were shipped to Lytton, British Columbia, and installed in track in a mountainous region known for cold and wet conditions. Additional ties were shipped to Rantoul, IL, and installed in a simulated track.

Tie producers seek vibration methods that will adequately compact concrete while still ensuring an air void system that provides frost-resistance. The concrete rheological properties, vibration frequency and vibration time are among the factors that govern air loss. At rest, air bubbles in concrete are held in place by the yield stress of concrete. When vibrated, the yield stress is overcome, and the buoyant forces cause air bubbles to rise in the viscous fluid. Given enough time, the bubbles will rise and escape at the surface. Per Stokes' law, the higher the viscosity of the fluid and the smaller the bubble, the longer it takes for the bubble to escape to the surface (Du, L., and Folliard, K. J., 2005). The laboratory investigation portion of this project included work with concrete, mortars, pastes and simple surrogate materials that idealize the physical action of bubbles in viscous fluids under vibration. Image analysis of clear viscous liquids under different frequencies and amplitudes of vibration were used in this study to establish the relationship among viscosity, vibration and air void response. The range of materials was used to develop relationships among viscosity, cement particle inclusion, and effect of aggregates in the mix.

The effects of saw cutting, specimen size and location, and air void system on the freeze-thaw durability of concrete railroad ties were measured through laboratory freeze-thaw testing. The study examined the effects of excising concrete prism from pre-stressed concrete ties on bursting strains and freeze-thaw durability. Concrete ties were made with pre-stressed steel wires, unstressed steel wires, and no steel wires to determine whether saw cutting pre-stressed ties or saw cutting reinforced concrete causes damage in concrete prisms that could cause failure in freeze-thaw testing. Freeze-thaw testing was compared on both specimens cut from ties using ASTM C 666 samples and from entire tie shoulders to show the effects of saw cutting and thermal gradients on the test results.

1.4 Scope

The scope of this report includes experimental results and analyses that will increase industry knowledge of concrete railroad tie manufacturing and testing requirements for freeze-thaw durability. Implementation of these methods and procedures can significantly reduce the uncertainty and risk for concrete tie manufacturers and concrete railroad tie customers. Specific outcomes include:

1. Improved understanding of bubble mechanics during vibration.
2. Improved understanding of concrete railroad tie exposure conditions, including the relationship between concrete freeze-thaw testing and expected service life.
3. Guidelines for concrete material qualification tests to ensure freeze-thaw durability in new concrete mixtures intended for use in concrete railroad ties. Guidelines include when qualification tests should be performed, test methods that should be used, and potential acceptance criteria.
4. Guidelines for concrete railroad tie quality control testing. Recommendations include concrete quality control tests and potential acceptance criteria.

1.5 Organization of the Report

This report is divided into two volumes. Volume I is a summary report that emphasizes key project methodologies, results, and recommendations. Volume II contains detailed project results from field monitoring of concrete tie temperature and moisture, laboratory experiments, and modeling performed.

2. Concrete Railroad Tie Behavior During Manufacturing and Service

This section of the report summarizes the major elements of the research project. Additional details and technical information is provided in Volume II of this report.

2.1 Concrete Rheology and Behavior of Air Bubbles Under Vibration

The basic understanding of vibration of fresh concrete and its impact on the entrained air system has been advanced through a fundamental study of concrete rheology, fluid mechanics, and bubble behavior in granular fluids. New experiments have demonstrated that common Bingham yield-stress fluid models for concrete are not sufficient for understanding vibration and air bubble rise. Experiments were conducted with surrogate materials that mimic the basic rheological behavior of fresh concrete. Experiments with Carbopol and silicone oil with glass beads underscored the need to acknowledge the granular nature of fresh concrete, and to develop a new modeling approach for concrete rheology that accounts for granular composition.

Granular fluids differ from simple yield-stress fluids in important ways that have practical implications for concrete. This study has demonstrated that the aggregate in fresh concrete plays an essential role in propagating vibrational energy through the concrete mass. Without aggregate, the transmission of vibrational energy is severely damped. The coarse aggregate are more important in this regard than fine aggregate, but the full size distribution as well as volume fraction are important factors. It was also shown that rheological properties are depth-dependent, a fact that is not emphasized in the literature. This suggests that air bubble rise rates change with depth. The depth dependence affects how one would predict time and intensity of vibration, and assess the potential harm that over-vibration might cause to fresh concrete.

It was also shown that vibration has the effect of making granular fluids quasi-Newtonian. If the vibrational energy exceeds the yield stress of the fresh concrete, then air bubbles rise as a function of the local plastic viscosity. The measured yield stress of fresh concrete at rest is largely irrelevant for predicting the movement of air voids and bubbles. Furthermore, the measurement of the viscosity of fresh concrete at a bulk scale (i.e., using a concrete-scale rheometer) is an incomplete view of local conditions that govern air bubble rise. Local conditions that need to be considered are the millimeter-scale fluid properties of cement paste within the concrete that can be expected to vary at the aggregate-paste interfaces.

Another important finding was that the term “radius of action,” that has been common in practice for describing the influence of vibrators in fresh concrete, is a misnomer that needs a new understanding. The experiments and analysis of this project established that “radius of action” is more properly thought to be a “cone of action.” This means that the reach and influence of vibration deep within a sample is much less than can be observed at the surface of fresh concrete. The analysis borrows concepts from soil mechanics and fluid mechanics to establish a new paradigm for modeling fresh concrete behavior.

The model framework developed in this project predicts air bubble rise under uniform vibration. Larger bubbles rise much faster than small bubbles. The model accounts for such differences to predict the full air bubble size distribution with time. As a general finding, the largest air bubbles—air voids that need to be removed to achieve consolidation—are predicted to leave a typical concrete within a few seconds of vibration. Lengthy vibration times may be counter-productive as this can lead to the loss of small air bubbles that are critical for freeze-thaw durability. The parameters that govern vibration and air bubble rise are many, and practitioners need to study their own form geometry, vibration probes, vibration energy, concrete mixers, and other concrete handling procedures to comprehensively assess the stability of entrained air that defines the microstructure of the final hardened concrete products.

2.2 Plant Handling and Vibration

The effects of concrete handling and vibration on the concrete air entrainment system was measured at three concrete railroad tie manufacturing plants. Concrete samples for fresh air content, rheological properties, and hardened air content were made from concrete obtained directly from the mixer, after the concrete was transported to the casting machines, and after vibration. Concrete hardened air measurements showed that concrete sampled from the top of the form after vibration is not necessarily representative of concrete in the whole of the tie and should not be used to make freeze-thaw specimens for quality control testing.

Concrete vibration acceleration and frequency was measured at the plants using form mounted and submersible accelerometers placed in the concrete forms. Results showed that concrete vibrated using form-mounted vibrators could be vibrated for a very long time because the vibration travels along the wires and through the beds in long-line forms. Concrete vibrated using immersion vibrators receiving large accelerations for a shorter time than at plants that used the form-mounted vibrators. Immersion vibrators used for long periods of time can result in significant air loss in the concrete, especially in mixtures with low yield stress.

2.3 Transmission of Vibration Through Concrete

Concrete can be modeled as a fluid phase (cement paste) with a dense suspension of aggregate (sand and coarse aggregate). Models are available in the literature to relate the rheology of a granular fluid to rheology of the simple fluid phase if the volume fraction of aggregate is known. The most common model applied to concrete is the Krieger-Dougherty equation. Such models are useful to estimate rheology of the fluid that governs air bubble rise.

This study required extensive analysis of hardened concrete samples to measure air bubble distribution. Work completed under this project developed improved methods for hardened air analysis (ASTM C457) by using images acquired by a flatbed scanner. These improved methods decrease the measurement time and improve the results of the test through automation.

A laboratory study was executed to explore the propagation of vibration in fresh concrete, mortar or paste samples. It was found that the energy of vibration was more effectively transmitted in the concrete and the mortar samples due to the presence of aggregates. The vibration was not well transmitted in the paste sample. The concrete and mortar samples showed high air loss, whereas the paste sample showed little air loss from the vibration. The results showed that vibrational energy transmission is highest when the aggregate content is high.

2.4 Effects of Vibration Conditions on Concrete Air System

Experimental work was performed to determine the effects of form-mounted vibrator frequency, acceleration, and duration. Two custom vibrating tables were made to rigidly connect to concrete freeze-thaw molds and the bottom container of an ASTM C 231-compliant concrete pressure air meter. Figure 2.1 shows one of the custom vibrating tables. The vibrating frequency of the table was adjusted through electronic controls, whereas the acceleration was controlled by changing the eccentric masses inside the vibrating motor. Concrete mixtures were made and vibrated for 30 seconds or 4 minutes on the vibrating table at different frequencies and acceleration levels and then measured for air content and freeze-thaw durability per ASTM C 666 method A.

Figure 2.1. ASTM C 231-Compliant Container and one ASTM C 666-Compliant Freeze-Thaw Specimen Mounted to Custom Vibrating Table

Long, unreinforced concrete beams were made with a 3 x 4 in. (75 x 100 mm) cross section and cut to 5 different 16 in. (400 mm) length after hardening. These beams were vibrated from one end to measure the effect of vibration distance correlates with freeze-thaw durability.

Higher peak vibration acceleration generally resulted in higher air bubble spacing factors and slightly higher susceptibility to freeze-thaw damage. However, vibration acceleration levels affected total air content more than spacing factor. Vibration frequency increases had a minor effect on concrete air loss. Immersion vibrators were shown to have a local effect on the concrete's susceptibility to freeze-thaw damage. Concrete vibrated for different durations showed that air loss continues with time, but most of the air loss that affects freeze-thaw durability occurs during the first several seconds of vibration. The amount of time it takes to remove unwanted entrapped air from the concrete and consolidate the concrete is dependent on the concrete acceleration transmitted from the vibrator and the concrete rheological properties. Customer concern over bug holes could lead concrete railroad tie producers to vibrate the concrete longer than is necessary to achieve sufficient structural consolidation and could lead to reduced concrete air void spacing factors. In concrete tie freeze-thaw testing, damage did not begin at bug holes.

2.4.1 Chemical Admixtures

Concrete mixtures were made with different combinations of low-range water-reducing admixtures, high-range water-reducing admixtures and air entraining admixtures to determine the effect of chemical admixture combinations on air void stability. The concrete air content was measured per ASTM C 231 using concrete consolidated using of two methods. The first method was to use the standard rodding and tapping procedures described in the standard. In the second method, the concrete sat undisturbed for different periods of time and, was then vibrated in the ASTM C 231 container. Concrete air loss increased as the time between mixing and vibration increased with all mixtures. Air entraining agent type was shown to have little effect on the air void stability with time. Even though the concrete mixtures tested lost air with time, the companion freeze-thaw prism durability was not significantly affected. It was shown that an increase in concrete fluidity could increase air loss and decrease freeze-thaw resistance for concrete mixtures made with some high-range water reducing admixtures.

2.4.2 Air Entrainment Required for Freeze-Thaw Durability

A comparison of air entrainment and concrete properties required to produce freeze-thaw durability showed that a universal concrete air content and spacing factor before vibration does not correlate to durability after vibration. This is important because fresh concrete air measurements are performed before vibration. Concrete with a spacing factor above 0.0087 in. (0.22 mm) after vibration was found to be durable in freeze-thaw tests, regardless of the air entrainment type or dosage, high-range water-reducer type or dosage, vibration amount used, or rheological properties. Spacing factors above that value were found to be inconclusive when comparing freeze-thaw durability, demonstrating that the spacing factor should be used for acceptance, but not rejection, of concrete for freeze-thaw durability.

2.5 Effects of Saw Cutting Pre-Stressed Concrete on Sample Freeze-Thaw Durability

Concrete tie quality control tests for freeze-thaw durability are often performed on small samples excised from concrete railroad ties. Samples tested for freeze-thaw durability according to ASTM C 666 should have cross section dimensions of 3–5 in. (75–125 mm) and length 11–16 in. (275–400 mm). The reinforcement layout for many concrete ties makes it difficult, if not impossible, to extract concrete samples from the pre-stressed tie without cutting through some reinforcement. There is a concern that the release of the pre-stressing forces during saw cutting or inclusion of reinforcement in freeze-thaw samples can influence the results of the ASTM C 666 test and may not accurately demonstrate the performance of the whole tie.

An experimental exercise was conducted to determine the effects of saw cutting, saw cutting pre-stressed concrete, and the presence of reinforcements on freeze-thaw durability. Two sets of three concrete ties were manufactured, and an additional four concrete railroad ties were sampled from the Chicago to St. Louis high-speed rail line. For the concrete railroad ties that were made especially for this project, one set was made with air entrained concrete, and the other was made without any air entrainment to determine if the low water-cement ratio concrete could provide protection against freeze-thaw damage. For each of those two sets, one concrete railroad tie was made with pre-stressing, one was made with wire reinforcement, but without any pre-stressing force applied, and the third without any steel reinforcement. Companion small prisms for ASTM C 666 testing were made from the corresponding concrete batches.

The six pre-stressed concrete ties were cut in half down the middle. One half of the tie was tested through 300 cycles of freezing and thawing. Small prisms were excised from the other half and subjected to ASTM C 666 freeze-thaw testing. Freeze-thaw damage of the large half-tie prisms manifested itself as either micro-cracks that would coalesce and cause concrete crumbling, or as macro splitting cracks that would progress the length of the tie. Freeze-thaw damage was seen in the excised prisms after fewer cycles than in the larger half-tie samples. It was found that saw cutting of reinforcing steel caused damage to small prisms and resulted in failed ASTM C 666 tests. The experimental results of the freeze-thaw durability of saw cut concrete specimens when examined in totality showed that concrete specimens used for freeze-thaw quality control tests should not be saw cut from reinforced concrete products. Saw cut concrete samples that passed the ASTM C 666 freeze-thaw test method were found to be representative of the concrete durability. Saw cut samples that did not pass the ASTM C 666 freeze-thaw test method were found to be inconclusive.

2.6 Field Conditions – Temperature, Humidity, and Degree of Saturation

The actual field condition of concrete crossties is a central issue for assessing the threat of freeze-thaw damage. Crossties are installed on well-drained ballast, but the state of moisture inside the concrete has not been well established in the research literature. Concrete pavements are known to remain wet at their bottom surfaces throughout the year in most climate regions of North America, but data on concrete crossties is limited.

In collaboration with an industry partner, crossties were manufactured with embedded sensors to measure relative humidity and temperature. The crossties were installed in track in Lytton, British Columbia, and at the University of Illinois laboratory in Rantoul, IL. In addition, concrete prisms were fabricated to extend the database on internal conditions of concrete in outdoor environments. Data was collected over many seasons. The configuration of the crossties was varied so the impact of the impermeable pad and rail at the rail seat could be assessed. Models were developed to predict internal relative humidity and temperature profiles by using weather station data including temperature, precipitation, and solar radiation. The experimental data was used to validate the models.

The findings provide a range of practical knowledge that can be useful for assessing the vulnerability of concrete ties to freeze-thaw damage. It was shown that concrete crossties experience high states of moisture even though they are installed on well-drained ballast. While rain easily drains from the ballast, the fine pores of concrete tend to absorb and retain water in the concrete. Concrete water absorption occurs much faster than evaporation. Occasional weather events are sufficient to maintain near saturation levels in the concrete, particularly lower in the ballast where the rock also holds water in its pores and the local air is maintained at high humidity.

Both the Lytton, BC, and Rantoul, IL, sites experience about 100 freeze-thaw cycles per year. A model was developed to predict the number of freeze-thaw cycles when the moisture was high enough to drive freeze-thaw pressure. The data suggests that freezing and high saturation do not often occur simultaneously inside the interior of concrete, suggesting that freeze-thaw pressures do not cause distress deep within concrete. The experiments were less able to characterize the very near-surface moisture condition (i.e., less than 5 mm), but it can be inferred that winter conditions often combined with snow and rain would lead to saturation of surfaces. The data points to freeze-thaw distress as being a surface-intensive distress, such as is seen with surface scaling of concrete flatwork exposed to freeze-thaw environments.

3. Summary of Research Results

This section provides a summary of key findings from this research effort covered in both Volumes I and II. Additional information may be found in Volume II, and the appendices that are separate from the report.

3.1 Modeling Fresh Concrete Behavior and Air Bubble Behavior

Concrete rheology is complex, and the application of vibration significantly changes the perceived yield stress and viscosity. There is significant information documenting rheological studies under quasi-static conditions, but there is little information available to describe the rheological properties of concrete under vibration. This study shows that concrete under vibration has zero yield stress and lower viscosity than would be measured at quasi-static conditions. Therefore, rheological properties measured at rest are not useful for modeling the rise of air bubbles under vibration.

It is essential to use rheology models that capture the granular behavior of concrete. A simple Bingham model fails to account for the role of aggregate that is a key part of vibration transmission. The model proposed in this study predicted important behaviors that were observed in experiments. The granular nature of concrete will lead to a region of fluidization shaped like an inverted cone. This is a departure from the understanding currently present in concrete literature, which discusses the “radius of action”—a term which implies that the action of the vibration is uniform with depth.

The rheological properties of all granular fluids (and concrete) are depth-dependent. This means that the yield stress and viscosity of concrete will vary with depth. A constitutive model for vibrated granular materials predicts Newtonian (constant viscosity) behavior during vibration, and yield-stress behavior without vibration. This is an essential feature of air bubbles behavior under vibration.

The results of the model suggest that it is possible to predict and control the final distribution of air in a concrete system by optimizing the initial distribution of air, concrete properties, and vibration parameters. The proposed model predicts that uniform vibration can be used to eliminate large air voids in freshly-placed concrete, while allowing a population of small air bubbles to endure. While every geometry and concrete is different, the model predicts that the vibration time necessary to remove large air voids from a system is on the order of one minute. Concrete can be designed to be sufficiently viscous under vibration so that small bubbles rise slow enough as to not be driven to the surface. Thus with care, concrete mixtures can be designed to be practically immune to over-vibration problems.

3.2 Basic Behavior of Concrete Under Vibration

Vibration intensity can be measured using accelerometers placed within fresh concrete. Laboratory experiments showed that vibration intensity dissipates as a function of distance from a probe vibrator for fresh concrete and mortar. Vibration does not transmit well in fresh paste, leading to the general finding that aggregate plays a key role in passing vibration through concrete. The point-to-point contact of rigid aggregates facilitates the transmission of vibration through the stiff phases suspended in the fluid paste phase.

The fine aggregate seems to play a stronger role than coarse aggregate in vibration transmission. This seems to arise from typical mixture proportioning of concrete that finds that coarse aggregates represent at most 45 percent of the volume fraction, which is far lower than maximum packing fraction. Thus, the fine aggregate exists all around the coarse aggregate, and it is through the fine aggregate that vibration is conveyed through the fresh material.

Delayed concrete placement and vibration can cause a significant air loss in the concrete, and the loss is linear with time. However, this does not necessarily correspond to a decrease in freeze-thaw performance. This additional air loss caused by the delayed placement and consolidation is minimal if the concrete is placed within the 30 minutes typical of precast concrete railroad tie plants.

Fresh concrete air content before handling and placement is not necessarily a good indicator of freeze-thaw performance. The concrete air void system response to vibration and subsequent freeze-thaw durability is mixture specific.

3.3 Air Entrainment Requirements for Durability

Higher peak vibration acceleration generally results in higher spacing factor and higher susceptibility to freeze-thaw damage. Although increasing the vibration time from 30 seconds to 4 minutes slightly raised the spacing factor, the freeze-thaw durability did not decrease significantly. Alteration to the air void system that affects the concrete freeze-thaw durability was found to occur during the initial vibration.

The spacing factor before vibration was found to be inconclusive as an indicator of a concrete mixture freeze-thaw durability. A low concrete spacing factor after vibration was indicative of good paste freeze-thaw durability, however, a spacing factor above 0.0087 in. was inconclusive. Freeze-thaw testing of concrete with a spacing factor above 0.0087 in. is therefore required to determine its freeze-thaw durability. The relationship between air content before vibration and spacing factor and freeze-thaw durability after vibration is a function of the chemical admixture combination, concrete rheological properties, and vibration, and should be determined for each plant individually.

3.4 Concrete Freeze-Thaw Sample Preparation

The results of the saw cut sample freeze-thaw tests indicated that saw cutting by itself had a minimal effect on freeze-thaw durability, however, saw cutting reinforced concrete samples caused cracking that led to sample failure in freeze-thaw tests not representative of the concrete material durability. Our research also found samples for concrete freeze-thaw quality control should not be excised from pre-stressed concrete ties.

Freeze-thaw damage in large concrete samples tested did not originate at bug holes. Railroads may consider changes in allowable bug holes to reduce the risk of concrete over-vibration.

Freeze-thaw deterioration in concrete ties can appear as micro-cracking at the material level or macro-cracking that initiates at the reinforcement and leads to splitting or cracking of the tie.

3.5 Field Environment of Concrete Crossties

This study developed thermal transport and moisture mass transport models that linked ambient weather station data to the temperature and humidity profiles in crossties. The one-dimensional model proved adequate for prediction purposes, and provided results of similar quality to three-dimensional models that were computationally more demanding.

Experimental data collected in lab and field conditions was used in this study to calibrate the mathematical models. Temperature and humidity inside concrete crossties can be measured with embedded sensors. The models were validated and shown to be successful for predicting temperature and humidity profiles in crossties. The presence of impermeable pad and rail at the rail seat had relatively little impact on the prediction of internal temperature and humidity in the crosstie.

The ballast serves to preserve a state of high humidity below the surface, thus contributing to high levels of humidity in the crosstie. The results in this study indicate that model concrete crossties installed in aggregate ballast are often saturated above 86 percent—meaning that they are susceptible to freezing-thawing damage. In particular, the very near-surface paste is most vulnerable material for freeze-thaw distress as it is the surface that maintains contact with rain/snow/dew water and senses freezing temperatures more frequently.

4. Recommendations for Durable Ties

This study has shown that it is possible to make concrete mixtures that are very resilient to freezing and thawing conditions even if a high level of vibration is applied during fabrication. Some concrete mixture air void systems have been shown to be more tolerant to strong vibration during consolidation. For other mixtures, extreme vibration was shown to have the potential to degrade freeze-thaw durability. Materials, mixture proportions, and properties that contributed to the resiliency of air void systems during vibration can be summarized as follows:

- Concrete admixture system – Concrete air-entraining admixtures are used to stabilize air bubbles that are mixed into the concrete. Concrete made with different air entraining admixtures and high dosages of high-range water reducing admixtures can be very robust and durable in freeze-thaw conditions even after long vibration periods at high acceleration levels that result in relatively low total air content levels. Some combinations of chemical admixtures used in concrete with low yield stresses that typically provide adequate freeze-thaw durability may be less resilient to long vibration periods. Resiliency to vibration may be increased in these cases by increasing total air content or using a different combination of admixture types.
- Rheological properties – An increase in the concrete yield stress may decrease the concrete air loss during vibration.
- Concrete vibration – Some concrete mixtures are vibrated more than necessary for consolidation, and this negatively affects the tie's freeze-thaw performance. More judicious use of vibration may reduce entrained air removal from concrete. The duration of vibration is often based on the elimination bug holes at the concrete surface. Bug holes were shown to have little influence on the freeze-thaw durability in large concrete tie freeze-thaw tests. It may be possible to relax bug hole specifications without compromising the freeze-thaw durability of concrete ties. In fact, this could improve tie freeze-thaw durability by avoiding over-vibration and providing a better-quality air-void system in the concrete.

4.1 Qualification Tests

New mixtures or material sources or brands for use in concrete railroad ties should be prequalified for use in pre-stressed concrete railroad ties to ensure durable freeze-thaw performance. The following tests are recommended.

4.1.1 Coarse Aggregates

- To prevent pop-outs and bulk freeze-thaw deterioration in concrete from aggregates with poor freeze-thaw durability, the freeze-thaw durability of coarse aggregate should be measured before approval for use in concrete mixtures. A potential test method to prequalify a coarse aggregate could be as follows:
  - Test the coarse aggregates in a concrete mixture according ASTM C 666 method A for 300 cycles. The concrete mixture should have a water/cement ratio between 0.4 and 0.45, a fresh air content of 6.5±1.0%, and not contain a water reducing admixture. The coarse aggregates used in this test should be at least 50 percent by mass of the total aggregate content. The concrete should be placed in two layers and consolidated

in the freeze-thaw prism molds using rodding and striking the mold with a mallet 10–12 times for each layer. Vibration should not be used to consolidate concrete for this test. The concrete prisms should be cured in lime water after demolding until 4 days old, and then tested per ASTM C 666 method A.

4.1.2 Concrete Mixture

The relationship between concrete fresh air content after mixing and the concrete freeze-thaw durability after vibration is dependent on the concrete constituent materials, mixture proportions, rheological properties, handling, and vibration. This relationship should be established by the concrete tie producer before use of a new concrete chemical admixture system or significant changes in the concrete mixture proportions. An example of how this could be done is described in the following steps:

1. The base concrete mixture proportions including the water content, cement content, sand, coarse aggregate, and water-reducing admixture dosage are established for the lowest air entrainment dosage used in the study. In this example, that would be 4 percent.
2. Concrete mixtures with 4, 5, 6, and 7 percent air content are made by adjusting the air entraining agent dosage and the total aggregate content while keeping a fixed fine-to-coarse aggregate ratio. The water-reducing admixture dosage, cement content is kept constant. If needed, the water content or water-reducing admixture is adjusted slightly to achieve the target concrete yield stress or other rheological properties. The concrete fresh air content is measured per ASTM C 231 at the time in the handling and placement process anticipated to be used in production. This is typically not done after consolidation because of the difficult in obtaining a representative sample from the top and bottom of the tie because of access problems created by the pre-stressing wires or strands.
3. Concrete is placed in concrete molds that are size-compliant to ASTM C 666 requirements and match-vibrated to the concrete ties. Two concrete prisms for each mixture are made for ASTM C 666 method A freeze-thaw testing and one concrete prism is made to measure the ASTM C 457 hardened air spacing factor.
4. The concrete prisms are wet cured in lime water until 14 days old and tested per ASTM C 666 method A for 300 cycles.
5. The lowest concrete air content that produces an acceptable freeze-thaw durability is chosen to be used as the lower bound air content in concrete quality control testing.
6. The mixture robustness is verified by making the concrete mixture at the upper and lower bound mixing temperatures to be used in production using the lower bound air content and match-vibrating freeze-thaw samples for the temperature extremes. The freeze-thaw durability at these extremes is verified through ASTM C 666 testing.
7. In this example, if the concrete mixture with 4 percent air content meets the desired freeze-thaw durability requirements and 8 percent air content is the maximum air content considered acceptable for abrasion resistance, then the acceptable fresh air content for this mixture would be between 6±2 percent.

4.2 Quality Control Tests

It is not practical to measure the concrete freeze-thaw durability or hardened air content on a daily basis during production. Manufacturing plants need a lower cost test method that provides faster results.

4.2.1 Air Content Limits

One approach is to use air content limits as the primary acceptance criteria if a rigorous testing program is conducted to firmly establish the link between air content and freeze-thaw durability. The lower-bound air content required to achieve freeze-thaw durability determined during the material qualification testing is used as the minimum acceptable air content. The upper-bound air content limit should only be limited to maintain concrete abrasion resistance requirements.

4.2.2 Freeze-Thaw Testing

Concrete made with a concrete hardened air spacing factor after vibration less than 0.0087 in. (0.22 mm) was found in this study to be freeze-thaw durable. Hardened air spacing factor results above 0.0087 in. (0.22 mm) were found to be inconclusive. Consequently, concrete freeze-thaw tests should be conducted for finished concrete tie products that have a spacing factor greater than 0.0087 in. (0.22 mm) in the bottom or top sections of the tie. Concrete freeze-thaw tests should not be conducted on concrete specimens that are saw cut to sizes meeting ASTM C 666 criteria because the saw cutting process could result damage to the concrete. Concrete freeze-thaw prisms tested when the spacing factor is above 0.0087 in. (0.22 mm) should be tested according to ASTM C 666 method A. Concrete freeze-thaw tests should be performed in one of two methods:

Option 1:

Unreinforced prisms made to dimensions specified by ASTM C 666. The concrete prisms should be made using concrete sampled from production. The concrete should be consolidated by match vibrating the concrete to that used in the plants. The vibration energy used in production should match that used in the match vibrating. Depending on the method used to consolidate the concrete in production, match vibration could be accomplished in different ways:

- For production processes that use external form vibrators to consolidate the concrete, steel sample forms could be mounted rigidly to concrete tie forms to experience the same vibration as the ties. Alternatively, the concrete vibration during production could be measured using a submersible accelerometer placed in the center depth and width and directly above the form vibrator location. The concrete prism mold could then be rigidly connected to a table vibrator. The vibration of the table should be adjusted until the measured vibration in the center of the concrete prism matches that measured in the concrete tie cavity.
- For production processes that use immersion vibrators mounted to concrete placement equipment that trails the concrete placing machine, the concrete could be consolidated in one of two ways:
    - The vibrator's maximum velocity is measured when it is out of the concrete. A separate handheld internal vibrator could then be tuned to give an equal maximum velocity when measured out of the concrete. The handheld internal vibrator would be

    inserted into each concrete specimen for at least 15 seconds with care taken to not strike the bottom of the concrete prism with the vibrator.

- Concrete prism molds could be rigidly connected to a table vibrator. The vibration velocity in the concrete immediately next to the concrete immersion vibrator on the placement machine could be measured using a submersible accelerometer. The table vibrator velocity would be adjusted until the velocity measured in the center of the concrete prism mold when mounted on the vibrating table matched the maximum concrete velocity measured by the submersible accelerometer during tie production.
    - For manufacturing plants that use handheld concrete immersion vibrators, the same handheld concrete immersion vibrator used in production should be used to consolidate the concrete prisms used for freeze-thaw testing. The handheld immersion vibrator should be inserted into the concrete for at least 15 seconds, with care taken to not strike the bottom of the concrete prism with the vibrator.

Option 2:

Concrete whole ties could be tested in freeze-thaw using methods like ASTM C 666, adapted to the large size. Whole ties would be wrapped in one layer of burlap and plastic wrap. The ties would then be placed in an automated freeze-thaw chamber for 300 cycles of freezing and thawing. The freeze cycles should be accomplished without the chamber filled with water. For the thaw cycles, the chamber should be flooded with tempered water. At least two freeze-thaw cycles should be accomplished per day. To measure the deterioration, the relative dynamic modulus of elasticity as calculated from the concrete ultrasonic pulse velocity in the concrete in the width direction and vertical direction near the rail seat area should be maintained above 60 percent after 300 freeze-thaw cycles.

5. References

ASTM Standard C 457. (2012). *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete.* West Conshohocken, PA: ASTM International.

ASTM Standard C 666. (2008). *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.* West Conshohocken, PA: ASTM International.

Borchardt, J. K. (2010, July 28). *Railroad Ties: Precast Concrete or Wood?* Retrieved December 29, 2015, from National Precast Concrete Association: http://precast.org/2010/07/railroadties-precast-concrete-or-wood/.

Du, L., and Folliard, K. J. (2005). Mechanisms of air entrainment in concrete. *Cement and Concrete Research, 35*(8), 1463-1471.

Hover, K. (2003). Air in concrete: Expect variability in gaining, losing, and measuring: part 2 of a two part series. *48*(1), 55-59.

Abbreviations and Acronyms

CN	Canadian National Railway
FRA	Federal Railroad Administration
KSU	Kansas State University
UIUC	University of Illinois Urbana-Champaign