USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project 0931Y04

Investigation of Material Improvements to Mitigate the Abrasive Wear Mechanism of Concrete Crosstie Rail Seat Deterioration (RSD)

By

J. Riley Edwards
Research Scientist and Senior Lecturer
University of Illinois at Urbana-Champaign
Jedward2@illinois.edu

and

David A. Lange
Professor
University of Illinois at Urbana-Champaign
dlange@illinois.edu

DISCLAIMER

Funding for this research was provided by the NEXTRANS Center, Purdue University under Grant No. DTRT07-G-005 of the U.S. Department of Transportation, Research and Innovative Technology Administration (RITA), University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

USDOT Region V Regional University Transportation Center Final Report

TECHNICAL SUMMARY

NEXTRANS Project No. 0931Y04 November 10, 2014

Investigation of Material Improvements to Mitigate the Abrasive Wear Mechanism of Concrete Crosstie Rail Seat Deterioration (RSD)

Introduction

To meet the increasingly stringent design and performance requirements due to increasing cumulative gross tonnages from heavy-haul freight operations, along with increased high-speed inter-city passenger rail development, improvements in concrete crosstie designs are needed. Rail Seat Deterioration (RSD) continues to be identified as one of the primary factors limiting concrete crosstie service life in North America. RSD refers to the degradation of material at the contact interface between the concrete crosstie rail seat and the rail pad that protects the bearing area of the crosstie. Industry experts consider abrasion to be a viable mechanism leading to RSD. A lack of understanding of the complex interactions affecting the severity of abrasion has resulted in an iterative design process for concrete crossties and fastening systems. The objective of this study is to quantify the abrasion performance of rail seats by using a variety of concrete admixtures and materials. To simulate the abrasive wear mechanism of RSD, a Small-Scale Abrasion Resistance Test (SSART) was designed by researchers at UIUC. Additionally, a theoretical framework to model and predict abrasive wear was developed using statistical techniques. Data obtained from the SSART and the statistical model will help the rail industry mechanistically design concrete crossties by improving the current understanding of the performance of concrete crosstie mix designs. Preliminary results show that the addition of metallic fine aggregates (MFA), steel fibers, and the application of coatings improve the abrasion resistance of concrete specimens.

Findings

Through experimental testing using the SSART, researchers at UIUC have successfully compared 21 approaches to improving the abrasion resistance of the rail seat through rail seat material improvements (Phases 1 and 2). Data from SSART in Phase 2 shows that abrasion resistance of concrete can be improved with the addition of steel fibers, polyurethane and epoxy coating on the rail seat surface, and using metal shavings as fine aggregates in the top portion of rail seat. Also, a theoretical framework to describe the abrasive wear process as well as predicting abrasive wear depth was successfully developed, and will be further refined under future testing.

Recommendations

Based on data obtained through experimentation, the abrasion resistance of concrete can be improved with the addition of steel fibers, polyurethane and epoxy coating on the rail seat surface, and using metal shavings as fine aggregates in the top portion of rail seat. These findings have been applied by one major railroad, but field performance results are not available to date.

As a part of a continued effort to develop a simplified industry-standard abrasion resistance test for concrete crossties, data obtained from SSART should be correlated with the data from AREMA Test 6 (Wear and Abrasion) on the Pulsating Load Testing Machine (PLTM) at UIUC. AREMA Test 6 is the industry standard crosstie and fastening system wear/deterioration test, and is the only AREMA test that is capable of generating RSD.

Additionally, image analysis should be utilized to characterize the effect of variability in exposed area of coarse aggregate on the abrasion resistance of concrete specimens as abrasion progresses. As a part of this work, the relative proportion of aggregate in the concrete mix will be varied to see if there is an effect on abrasion resistance of concrete. The aggregate proportion in the mix will be changed without affecting the cement paste to aggregate ratio so as to not dilute the binding properties relative to control specimens. At the same time, the water/cement ratio and coarse aggregate to fine aggregate ratio will be held constant to minimize change in the other properties of hardened concrete.

Finally, given that experimental testing of all possible permutations of abrasion mitigation approaches is not feasible, statistical modeling of wear rate should be furthered.

Contacts

For more information:

J. Riley Edwards
Senior Lecturer and Research Scientist
University of Illinois at Urbana-Champaign
1201 NCEL, MC-250
205 N. Mathews Ave., Urbana, IL 61801
(217) 244-7417
jedward2@illinois.edu

David A. Lange
Professor
University of Illinois at Urbana-Champaign
2129b NCEL, MC-250
205 N. Mathews Ave., Urbana, IL 61801
(217) 333-4816
dlange@illinois.edu

NEXTRANS Center
Purdue University - Discovery Park
3000 Kent Ave
West Lafayette, IN 47906

nextrans@purdue.edu
(765) 496-9729
(765) 807-3123 Fax

www.purdue.edu/dp/nextrans

ACKNOWLEDGMENTS

The authors would like to express sincere gratitude to the Association of American Railroads (AAR) Technology Outreach Committee and the NEXTRANS Region V Transportation Center for sponsoring this research. Additionally, the authors would like to thank VAE Nortrak and KSA for providing critical resources for the laboratory experimental work. A special thanks goes to Steve Mattson from VAE Nortrak for providing direction, advice, and encouragement. Many thanks to the members of AREMA Committee 30, including John Bosshart, Greg Grissom, Eric Gehringer, Ryan Rolfe, and Pelle Duong. Thanks to Greg Frech and Emily Van Dam for performing much of the experimental testing. This work would not have been possible without contributions from Tim Prunkard, Darold Marrow, Don Marrow, Marcus Dersch, Brandon Van Dyk, Sam Sogin and Chris Rapp, all of UIUC. J. Riley Edwards has been supported in part by grants to the UIUC Rail Transportation and Engineering Center (RailTEC) from CN, Hanson Professional Services, and the George Krambles Transportation Scholarship Fund.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure and Table Page

CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

To meet the increasingly stringent design and performance requirements due to increasing axle loads and cumulative gross tonnages from heavy-haul freight operations, along with increased high-speed inter-city passenger rail development, improvements in concrete crosstie designs are needed. These improved designs are especially critical on joint heavy-haul freight and high-speed passenger rail infrastructure, where loading demands are highest, track geometric requirements are most stringent, and track occupancy time is at a premium. Improvements in concrete crosstie and fastening system designs also help address the need to reduce track maintenance windows, thereby gaining rail capacity. Before these advancements are realized, several design and performance challenges must be overcome, including rail seat deterioration (RSD).

RSD refers to the degradation of the concrete material at the contact interface between the concrete rail seat and the rail pad (Kernes et al., 2011). RSD has been identified as one of the primary factors limiting concrete crosstie service life in North America, particularly in heavy-haul freight infrastructure (Edwards et al., 2012; Zeman, 2010). RSD can lead to problems such as loss of cant, gauge-widening, fastening system wear, and other track geometry deficiencies that can lead to unstable rail conditions and/or derailments (Zeman et al., 2009). RSD is difficult to detect and impossible to repair without lifting the rail and removing the rail pad through a labor-intensive and costly repair process that results in track outages, traffic disruptions, and increased operating costs. A primary maintenance challenge facing the rail industry is the lack of compatibility between life cycles of infrastructure components. If the life cycle of the materials that compose the rail seat and fastening system is not sufficient to match the life cycle of the rail, interim repairs of the rail seat may be necessary.

Previously, RSD research and industry design practices have focused on mitigating the wear of concrete through pad design improvements and various fastening system design modifications, with very little focus on concrete mix design enhancements (Kernes et al., 2011; Moody, 1987). Wheel impact load detectors (WILD) have been successfully used as a preventive measure to detect any out of round wheels, but they have not noticeably lowered the likelihood of RSD (Moody, 1987). Going forward, additional RSD research should focus on improving the performance of concrete materials as well as the materials used in the manufacture of fastening system components. One of the most viable areas of research focuses on the development of stronger, more durable materials in the concrete crosstie and/or concrete rail seat to prevent or delay the onset of RSD and increase the service life of the rail seat (Kernes et al., 2011).

A field of study that has implications on the life of the rail seat is tribology, which is the science and engineering of interacting surfaces that are in relative motion. Significant research has been performed to investigate the tribological interaction between two surfaces, but the majority of this research falls within the mechanical engineering domain (e.g. metal-polymer-composite interactions) as opposed to the realm of civil engineering. The objective of this study is to use the principles of tribology to further understand the polymer-to-concrete interaction at the rail seat - rail pad interface.

1.2 Study objectives

The University of Illinois at Urbana-Champaign (UIUC) has identified five possible mechanisms having the potential to contribute to RSD. These are abrasion, crushing, freeze-thaw cracking, hydraulic-pressure cracking, and hydro-abrasive erosion (Joh, et al., 2010). Of these mechanisms, hydraulic pressure cracking and hydro-abrasion were investigated at UIUC and found to be feasible mechanisms resulting in RSD (Zeman 2010; Choros et al., 2007; Bakharev, 1994). According to another study, RSD resembled damage that is typically caused by abrasion, with hydraulic pressure cracking and freeze-thaw cracking also being identified as possible contributors (Bakharev, 1994).

Previous research at UIUC focusing on RSD has been centered on the moisture-driven mechanisms of RSD. The work described in this paper seeks to build on previous research by focusing on the abrasion mechanism of RSD. Abrasion is defined as the wear of a material as two or more surfaces move relative to one another (Kernes et al., 2011). Abrasion is a progressive failure mechanism and occurs when; 1) cyclic motion of the rail base induces shear forces, 2) shear forces overcome static friction, 3) the rail pad slips relative to the concrete, 4) strain is imparted on concrete matrix, and 5) the harder surface cuts or ploughs into the softer surface. The abrasive mechanism in RSD is further complicated and potentially accelerated due to the occurrence of three-body wear. Three-body wear occurs as a result of an abrasive slurry (e.g. abrasive fines and water) that often exists in addition to the two interacting surfaces (i.e. rail seat and rail pad). (Dwyer el at., 1993). This further complicates the process of abrasion.

In order to better understand the interactions leading to abrasion, two tests were designed and executed to mitigate the abrasion mechanism in concrete crosstie RSD. First, a large-scale abrasion resistance test was developed to better understand the mechanics of the abrasive RSD failure mechanism by characterizing the frictional forces that resist movement at the contact interface between the concrete rail seat and the bottom of the rail (Kernes et al., 2011). Secondly, a Small Scale Abrasion Resistance Test (SSART) was designed and implemented to understand the effect of various concrete mix designs, curing conditions, and surface treatments on the abrasion resistance of the rail seat. This test will provide guidance for methods to mitigate the abrasive mechanism of RSD, and is the focus of this paper.

1.3 Organization of the research

The remainder of the research is organized as follows. Chapter 2 provides an explanation of phases and use of SSART. Chapter 3 provides an explanation of the laboratory test results from each concrete mix. Chapter 4 explains the approaches to statistical modeling. Chapter 5 summarizes the research and its contributions, and provides future research directions.

CHAPTER 2. METHOLOGY

This chapter introduces SSART and provides an explanation of phases and use of SSART. Section 2.1 states the order of the test matrix. Section 2.2 introduces the background of SSART. Section 2.3 describes the test set up of SSART. Section 2.4 discuss the test protocols.

2.1 Prioritization

A test matrix containing a prioritized list of specimens was developed based on the opinions of industry experts, results from the latest industry research and testing aimed at RSD mitigation, and literature in the domain of abrasion resistance of concrete materials (Shurpali et al., 2012).

Research and testing using the SSART was divided into two phases. Phase 1 involved testing of specimens that were being evaluated for their abrasion resistance by concrete crosstie manufacturers or the larger concrete materials industry (Shurpali et al., 2013). The test matrix was further refined in Phase 2 by removing specimens from Phase 1 that did not show an improvement to the abrasion resistance. Also, the Phase 2 test matrix reflected more recent RSD mitigation approaches being researched by North American concrete crosstie industry.

In Phase 1, while most specimens in the test matrix were prepared at UIUC, certain specimens with surface treatments (e.g. epoxy coatings) were prepared by concrete crosstie manufacturers (Shurpali et al., 2013). Specimens were cast by a concrete crosstie manufacturer to minimize variability in casting methods and to obtain concrete mix designs that were reflective of current industry practices.

In both phases, the following concrete mix designs and treatments were tested to quantify their respective abrasion resistance: supplementary cementitious materials (mineral admixtures), fibers, metallic fine aggregates (MFA), self-consolidating concrete (SCC), variable curing conditions/methods, and the application of various surface treatments (coatings).

2.2 SSART Background

There are limitations to large-scale abrasion resistance testing, which typically require more time and resources to operate, and can present challenges when investigating component level behavior within the system. These challenges limit the breadth, depth, and effectiveness of a parametric study to identify ways of mitigating RSD. The aforementioned limitations and lessons learned from the design of previous tests led UIUC researchers to the development of the SSART. The SSART was designed with the following characteristics and attributes: 1) ability to isolate the abrasion mechanism, 2) ability to quantify the abrasion resistance of different concrete specimens, 3) be comparatively simple and economical to operate, 4) allow for shortened testing durations that will facilitate the collection of large volumes of data, and 5) ensure the harder surface cuts or ploughs into the softer surface to generate abrasion.

The SSART was designed to be similar to the current industry standard abrasion tests for other materials, with modifications incorporated to better represent the crosstie materials and field conditions (Turkish Standards Institution; BSI, 1990). It was also designed as a pre-qualification test for the American Railway Engineering and Maintenance-of-way Association (AREMA) Test 6 – Wear and Abrasion.

2.3 SSART Test Setup

The SSART was constructed by modifying a lapping machine that is typically used to sharpen tools or create flat, smooth surfaces on machined metal parts (Figure 1). The lapping machine is comprised of a revolving steel plate with concrete specimens loaded in three counter-rotational rings that rest on the plate and are held in place relative to the rotating disk. The three rings are held in place by small rubber wheels attached to the main frame. This allows the circular specimens to revolve around their center while still maintaining the same position relative to the revolving lapping plate. A dead weight weighting 4.5 pounds (pounds) [2 kilograms] is placed on top of each specimen.

To represent the influence of water and fines that is often seen in the field, an abrasive slurry of water and sand is applied to the lapping plate throughout the test to abrade the concrete surface that mates against the lapping plate. Water is delivered to the lapping plate through a plastic tube, with a valve that is used to control the flow rate. A raised wooden platform was constructed and a sand storage container was placed on the platform. Holes were drilled at the bottom of the container and wooden platform ensuring proper alignment. Sand is applied to the lapping plate at a uniform rate using a plastic tube.

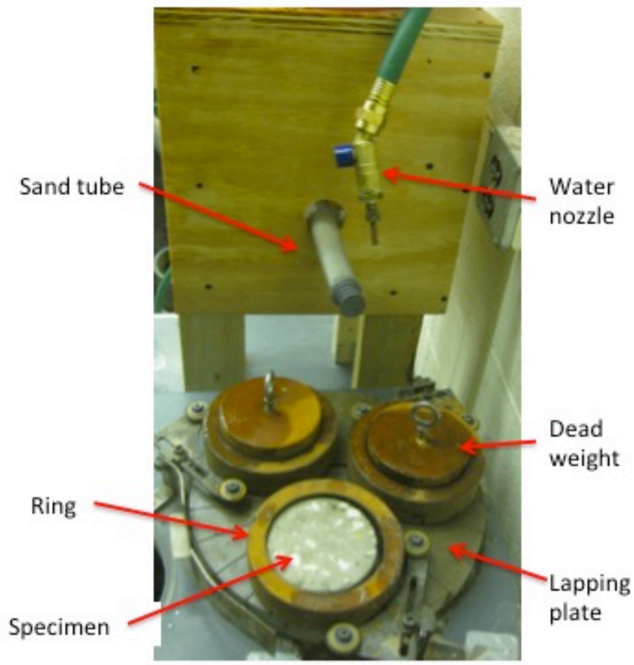

Figure 1 SSART and Abrasive Slurry Conveyance Equipment

2.4 SSART Test Protocol

To ensure confidence in our test results, nine specimens (or replicates) are tested for each mix-design. The concrete specimens are marked to identify the wearing surface (i.e., the as-cast surface). Also, points where thickness readings are to be taken are marked. Initial thicknesses at the four marked locations are obtained using a vernier caliper. Three specimens are then placed in the lapping machine rings, the dead weight is applied, and the test is started. At the same time, an abrasive slurry of water and Ottawa sand is introduced into the specimen-lapping plate interface. Ottawa sand has a gradation of 20-30, which indicates that the sand particles pass through a nominal sieve opening size of 841 microns and retained on a nominal sieve opening size of 596 microns. The test is run for a total of 100 minutes, with thickness measurements taken every five minutes for the first 45 minutes of the test and every 15 minutes until the end of the test. After testing, the wear depth (i.e., the difference between initial and final thicknesses) is plotted with respect to testing duration to represent the progression of abrasion with time (wear rate curves). Also, the cumulative wear depth at the end of the test is plotted as a function of compressive strength of specimens.

It should be noted that wear depth is used as a metric to quantify abrasion resistance of concrete instead of weight and/or volume loss. This is done to counter the variability induced by the weight/volume loss measurements due to absorption of water by the concrete specimens during testing. Further details regarding the rationale behind the development of the test, test apparatus construction, specimen production, test protocol, and preliminary results from previous testing can be found in a previous publication (Shurpali et al., 2012).

The SSART is not completely representative of field conditions for several reasons, which must be both controlled (to the extent feasible) when testing and understood when interpreting data. These issues may be mitigated as the understanding of the field environment and lab capabilities are further refined. One difference is the rotational loading of concrete in the SSART as opposed to cyclic loading under normal field conditions.

Another difference is the steel-concrete interaction in the SSART rather than polymer-concrete interaction seen in the field. With this being said, the SSART is a simplified tool that aims to provide quantitative results that compare the abrasion performance of a specimen as a function of concrete mix design and/or surface treatment. Also, it is not a system-level test and was designed as a qualification test for concrete rail seat materials prior to full-scale or revenue testing. Moreover, the SSART allows researchers to quickly obtain large amounts of data, which is critical in constructing an empirical model of concrete wear rate, one of the primary objectives of this research project (Shurpali et al., 2012).

CHAPTER 3. MITIGATION APPROACHES: THEORY, RESULTS, AND DISCUSSION

Chapter 3 contains an explanation of the mitigation approaches used for each specimen. The effect of air content is mentioned in 3.2. In section 3.3, the effect of surface treatment is presented. The result from self-consolidating concrete (SCC) is noted in section 3.4. Evaluation of fiber-reinforced concrete (RFC) is discussed about in section 3.5, and the use of Metallic Fine Aggregate (MFA) is covered in section 3.6.

2.5 Methodological Framework

First, samples were cast using a concrete mix design that is representative of a mix used for the manufacture of concrete crossties in North America. Specimens cast with this control mix design (i.e., specimens with 3.5% air content by volume) will hereafter be referred-to as "control specimens". Any change in abrasion resistance is measured relative to the control specimens. Figure 2 shows wear rate curves for specimens wherein each data point represents the average value obtained from the nine specimens. Error bars representing two standard errors (both positive and negative) in wear depth are shown on all data points. Wear depth is used as a surrogate term for abrasion, or the inverse of abrasion resistance. As the wear curves shift downward on the graph, the mix design shows higher abrasion resistance based on SSART testing. Table 1 summarizes the percentage change in abrasion resistance of various specimen types relative to control specimens. After Phase 1, the following approaches were found to improve the abrasion resistance of concrete: including certain amounts of fly ash and silica fume, submerged curing (not moist curing), adding steel fibers, grinding the top surface, and applying an epoxy coating on the rail seat surface. This paper provides detailed results from Phase 2 of testing. Please refer to a previous publication for more details on test results from Phase 1 (Shurpali et al., 2013).

Table 1 Change in Abrasion Resistance Relative to Control Specimens

Specimen Type	Change in Abrasion Resistance (%)
0% Air	-3.4
3.5 % Air	_
6% Air	-21.2
SCC	-9
MFA	62
FRC	10
Polyurethane coat	85
Epoxy coat	11

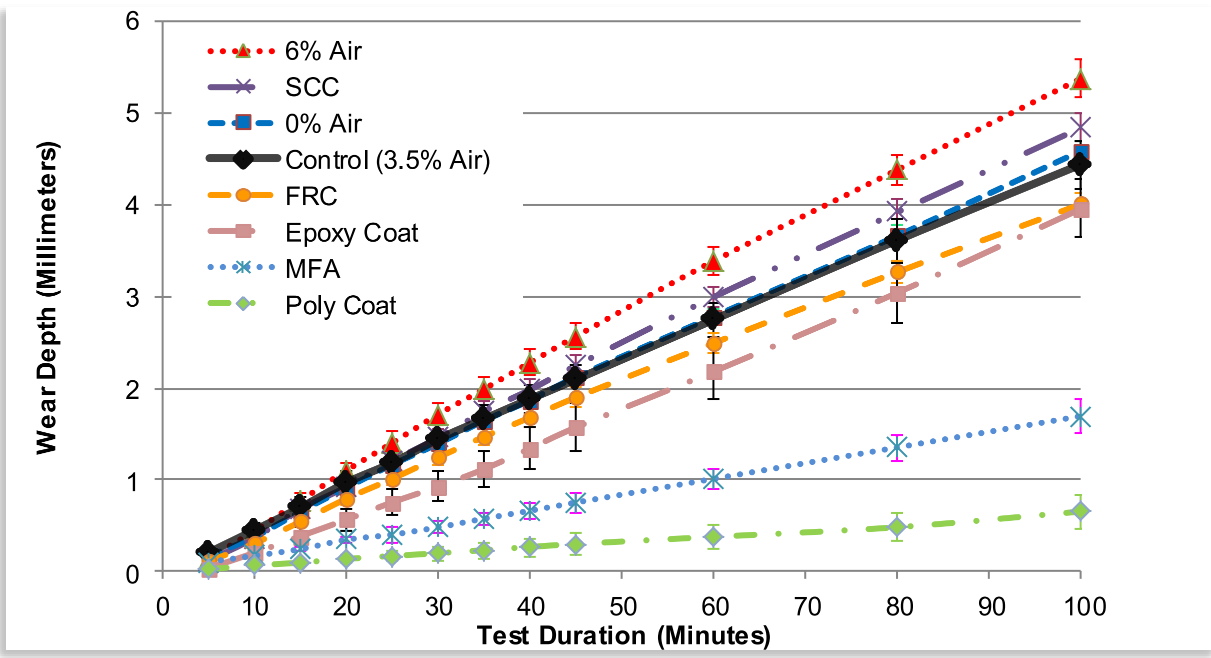

Figure 2 Wear Rates of Various Approaches of Abrasion Mitigation (28-day)

2.6 *Effect of Air Content*

Air is typically entrained in structural concrete to prevent cracking due to repeated freeze-thaw cycles, and is reported as the air void volume in the concrete microstructure.

Air entrainment has been used in the manufacture of concrete crossties within North America. However, questions have been raised on the merit of air entrainment in concrete crossties citing its possible adverse effect on abrasion resistance of the rail seat. It is well-established and understood that abrasion resistance is directly related to concrete compressive strength (Witte et al., 1995; Hadchti et al., 2003). With this knowledge, one would expect that the abrasion resistance of concrete would decrease with increasing air content. This is due to the understanding that concrete compressive strength is inversely related to the air content (Mindess et al., 2003). However, the trade-off between abrasion resistance of concrete and air content percentage is not properly understood. UIUC researchers have investigated air entrainment using the SSART to determine if there is an optimum air content at which the abrasion resistance reaches a maximum. At the same time, neither the compressive strength nor the freeze-thaw durability of concrete should be adversely affected as local optimization considering only abrasion resistance may have adverse system-level effects on the crosstie and fastening system.

To bound the complex problem that stems from a multitude of mix design permutations, air-content (by volume) was varied from a minimum of approximately 0% (reflective of no air entraining admixtures) to a maximum of 6%. An intermediate air content of 3.5% was also chosen to reflect the nominal value of air content used in the North American concrete crosstie industry (AREMA, 2012). Results from SSART seemed to be inconclusive in terms of the effect of air content on abrasion resistance of concrete. It was found that specimens with air content of 3.5% performed better compared to specimens with 0% air and 6% air (Table 1). Out of all samples tested, the samples with 6% entrained air proved to be the least resistant to abrasion, and showed 21.2% more wear than the control specimens. The lower abrasion resistance of the specimens with 6% air content may be due to reduction in compressive strength. Additionally, it is still not clear why specimens with 0% air performed poorly relative to control, given the expected increase in compressive strength relative to the 3.5% air entrained samples (Figure 2). More research needs to be done to study the effect of air content on abrasion resistance of concrete, by increasing the number of mixes with unique air contents that are tested, and attempting to hold compressive strength constant.

2.7 *Effect of Surface Treatment*

In North America, epoxy coatings are experiencing widespread use as a reactive RSD repair material and/or preventative RSD mitigation measure. As an example, one major Class I railroad has incorporated the use of an epoxy coating into its design specifications for the manufacture of concrete crossties. Preliminary qualitative results from revenue testing have been promising according to the railroad, but there exists room for improvement. Data from the SSART shows that epoxy coating delays the onset of abrasion, and provided an 11% increase in abrasion resistance as compared to the control sample (Figure 2). It was also observed that the epoxy coating quickly disintegrated and added to the abrasive slurry once it developed cracks. However, after the epoxy coating was worn away, the abrasive wear rate matched that of control specimens. This phenomenon can likely be attributed to the hardness and smooth finish of the brittle epoxy coating layer. However, the use of an epoxy coating could still be cost effective if it delays the onset of abrasive RSD, and decreases the life cycle cost of concrete crossties.

Polyurethane coatings were also evaluated for their abrasion performance. Like epoxy coatings, there is no consensus in the industry on the effectiveness of polyurethane coatings as an abrasive RSD mitigation technique. Data from SSART showed that polyurethane coating resulted in the least abrasion of all of the mitigation measures tested in Phase 2, 85% less than the control specimens. One reason that the polyurethane coating may have performed better than epoxy coating is that it was observed to be significantly less brittle than the epoxy coating.

2.8 *Self-Consolidating Concrete (SCC)*

Self-consolidating concrete (SCC) was evaluated for its abrasion resistance due to the advantages of lowering the water-cement ratio, mineral admixture content (fly ash in this research) and high workability. SCC does not require compaction, which can decrease the production cost of concrete crossties. However, it was observed that SCC did not improve the abrasion resistance of concrete, and showed a 9% reduction in abrasion resistance relative to the control specimens (Figure 2).

2.9 Fiber-Reinforced Concrete (FRC)

Fiber-reinforced concrete (FRC) was evaluated for its abrasion performance based on the widespread understanding that FRC has the ability to reduce cracking (Mindess et al., 2003). Results from the SSART showed that there was an improvement of 10% in the abrasion resistance of FRC specimens (Figure 2). This observation of modest improvement differed from Phase 1 results wherein FRC specimens were observed to be one of the best performers with a 65% improvement in abrasion resistance (Shurpali et al., 2013). This difference in observations can possibly be attributed to the difference in the manufacturing source and concrete materials between Phase 1 and Phase 2.

2.10 Metallic Fine Aggregate (MFA)

Metallic fine aggregates (MFA) have been used by French pavement manufacturers, and are known to possess significant strength and resistance to abrasion (Wiley et al., 1909). Additionally, MFAs have been used locally in the rail seat area and tested in revenue service as an RSD mitigation technique. Preliminary anecdotal results from field testing of MFA's have been encouraging. Results from SSART were in agreement with the qualitative field performance information, which is reflected by the fact that MFA specimens were the second best performers after polyurethane coating, showing a 62% increase in abrasion resistance as compared to the control specimens (Figure 2).

2.11 Relationship between Compressive Strength and Abrasion Resistance

Figure 3 provides data on cumulative wear depth at the end of the test as a function of concrete compressive strength for all specimen types. There was no clear correlation between abrasion resistance and compressive strength, which is not in agreement with existing literature (Witte et al., 1995; Hadchti et al., 1988). For example, in case of MFA specimens, the abrasion resistance seems to be higher than FRC specimens, even though the compressive strength of FRC specimens was lower. This shows that there are most likely additional factors contributing to the abrasion resistance of concrete beyond its compressive strength.

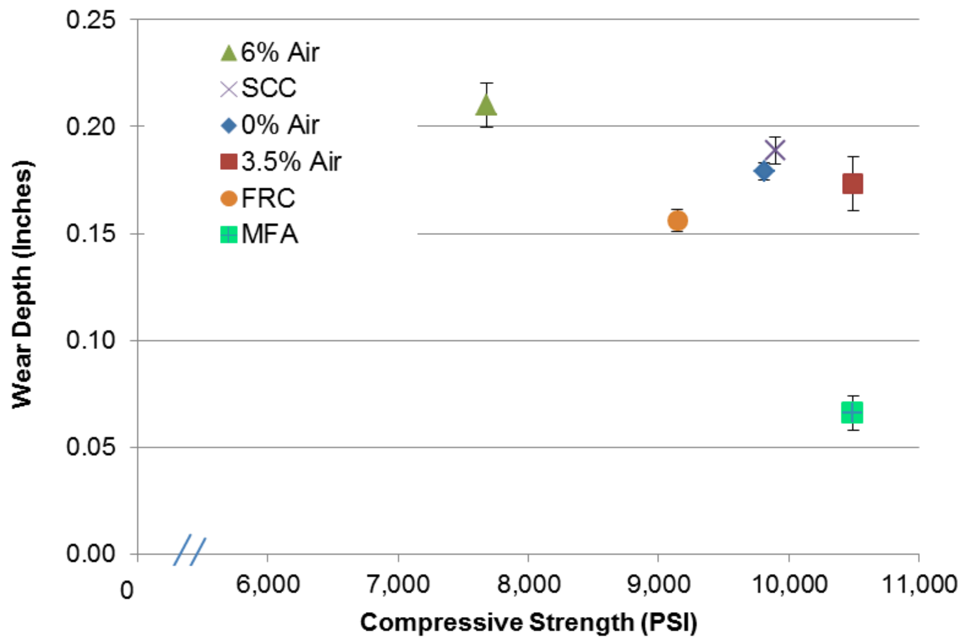

Figure 3 Relationship Between Compressive Strength and Abrasion Resistance

Overall, with the exception of the relationship between abrasion resistance and compressive strength, the results obtained through testing were in agreement with the relevant literature (Mindess et al., 2003). This lends credibility to the results obtained from SSART and gives insight into a prioritized list of tests to be performed on AREMA Test 6 (Wear and Abrasion) or in future revenue testing.

CHAPTER 3. STATISTICAL MODELING OF ABRASIVE WEAR

Chapter 3 provides an explanation of the modeling approaches and reasoning behind the development of the model. Additionally, a sample calculation is shown in section 3.2.

3.1 Approaches

Data generated from the SSART is in a time-ordered sequence (time series) wherein wear depths are recorded at discrete time intervals. There are two objectives for the analysis of our data at discrete intervals: characterizing the rate of wear and forecasting future wear values (Miller et al., 1977). With regard to this research, forecasting would entail predicting (extrapolating) wear data as a function of time based on the data obtained. This time-series analysis can be extended to predict field wear depths and rates on a concrete crosstie rail seat as a function of loading cycles, provided relevant data is collected under actual field conditions. Thus, the analyses performed as a part of this work should be considered as a theoretical framework to demonstrate the possibility of predicting actual in-service wear depths as a function of loading cycles (or number of train passes). In addition to this, a descriptive model can be used to optimize concrete mix design by combining various abrasion mitigation approaches. However, this would require further testing that examines the interaction effects between various combinations of abrasion mitigation techniques and concrete mix designs.

For two reasons, an ordinary regression model (or ordinary least squares (OLS) method) with time as the independent variable is not suitable for describing time series. First, the observations making up the time series are usually dependent. This is true in this research context, as periodic wear depth measurements are taken on the same specimen. Recall that one of the assumptions underlying the regression model is that the errors, and hence the observations, are not correlated. Second, forecasting future values entails extrapolation of historical data for which regression models are not suitable and can lead to inaccurate forecasts (Miller el at., 1977). Based on the aforementioned reasons, the authors decided to develop and use a first order auto regressive model (AR1) to model the wear behavior of the concrete specimens.

3.2 Numerical Example

What follows is statistical modeling example that provides a comparison of relative abrasion resistance of control specimens (CONT) and FRC specimens (FRC):

Step 1: Model development

The model was developed using the following equation,

$$Y_{ij}=\beta_1 T_{ij}+\beta_2 T_{ij} D_{ij}+\varepsilon_{ij}$$

Where,

Y_{ij} = wear depth at i^{th} time period and j^{th} replicate

β_1, β_2 = parameter coefficients

T_{ij} = i^{th} time period for j^{th} replicate

D_{ij} = dummy variable (0 = CONT, 1 = FRC)

e_{ij} = statistical error term at i^{th} time period for j^{th} replicate

Three possible hypotheses exist when comparing relative abrasion resistances of FRC specimens and control specimens:

If $\beta_2 = 0$, no difference of wear rate between CONT and FRC (null hypothesis)

If $\beta_2 < 0$, wear rate of CONT is greater than FRC

If $\beta_2 > 0$, wear rate of CONT is less than FRC

Step 2: Detect auto-correlation

The Durbin-Watson Test was conducted to examine the null hypothesis that there is a correlation between the errors at adjacent time periods. Dublin-Watson (D-W) test shows that the first order auto-correlation exists ($P < 0.0001$). This further justifies the need for using the AR(1) model over ordinary least squares (OLS) method.

Step 3: Parameter estimates

Table 2 Autoregressive Parameter Estimates

Variable	**DF**	**Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
x2 ($\beta 1$)	1	0.0505	0.000697	72.36	<.0001
x1x2 ($\beta 2$)	1	-0.0085	0.001710	-5.01	0.0002

Step 4: Interpretation

From Table 2, we can see that $\beta 2 < 0$, which means that the wear rate of CONT is greater than wear rate of FRC showing that FRC improves abrasion resistance relative to control specimens. Also, we can conclude that there is a statistically significant difference between the wear rates of the CONT and FRC specimens.

Step 5: Model diagnostics

The comparison of test wear depth (empirical data) and the predicted wear depth using the AR(1) modeling approach is shown in Figure 4. The model appears to fit the empirical data well.

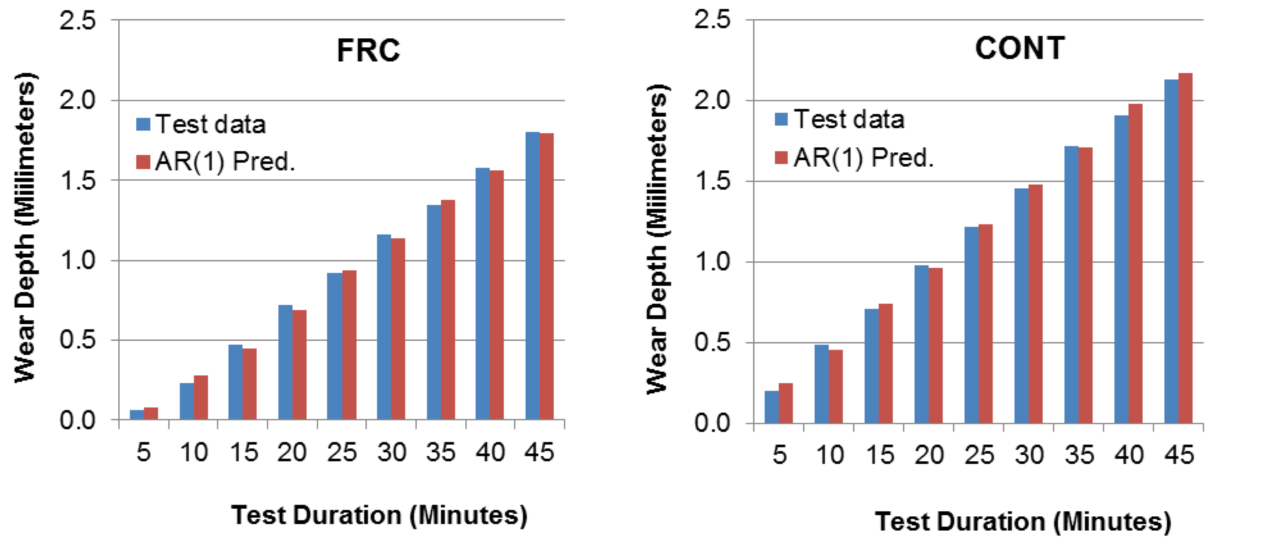

Figure 4 Comparison between Wear Depth Predictions from AR(1) Model and Experimental Data for CONT and FRC

The goodness-of-fit of the AR(1) versus ordinary least squares (OLS) is compared by metrics known as the mean absolute deviance (MAD) and mean-squared predictive error (MSPE). Lower values of MAD and MSPE indicate better the goodness of fit.

$$MAD = \frac{\sum_{i=1}^{N} | y_i^{pred} - y_i^{obs} |}{N} \quad (3)$$

$$MSPE = \frac{\sum_{i=1}^{N} (y_i^{pred} - y_i^{obs})^2}{N} \quad (4)$$

Where:

y_i^{pred} = the predicted wear depth at ith time period

y_i^{obs} = the observed wear depth at ith time period

Table 3 below presents the comparison of AR(1) and OLS in terms of the fit of the model. While MAD (AR1) at 0.026 is lower than MAD (OLS) at 0.044, MSPE (AR1) at

0.00092 is less than MSPE (OLS) at 0.00372. Thus, AR(1) shows an better goodness-of-fit of the tested data, using both MAD and MSPE. As mentioned earlier, this is because OLS model is based on the assumption of independent observations, which is not appropriate for the testing procedures in this study.

Table 3 Goodness of Fit of AR (1) Model Relative to OLS

					MAD		**MSPE**	
Test	**Predicted**		**Residual**		**Absolute**		**Squared Residual**	
	AR(1)	**OLS**	**AR(1)**	**OLS**	**AR(1)**	**OLS**	**AR(1)**	**OLS**
0.205	0.252	0.241	-0.047	-0.036	0.047	0.036	0.00224	0.00128
0.488	0.460	0.482	0.028	0.006	0.028	0.006	0.00076	0.00003
0.710	0.741	0.722	-0.031	-0.012	0.031	0.012	0.00094	0.00015
0.980	0.965	0.963	0.015	0.017	0.015	0.017	0.00023	0.00028
1.223	1.234	1.204	-0.011	0.019	0.011	0.019	0.00013	0.00035
1.455	1.477	1.445	-0.022	0.010	0.022	0.010	0.00048	0.00011
1.723	1.711	1.686	0.012	0.037	0.012	0.037	0.00014	0.00137
1.910	1.977	1.926	-0.067	-0.016	0.067	0.016	0.00452	0.00027
2.135	2.168	2.167	-0.033	-0.032	0.033	0.032	0.00111	0.00103
0.063	0.081	0.192	-0.019	-0.130	0.019	0.130	0.00035	0.01680
0.232	0.280	0.384	-0.048	-0.152	0.048	0.152	0.00226	0.02304
0.472	0.452	0.576	0.020	-0.104	0.020	0.104	0.00041	0.01080
0.720	0.691	0.769	0.029	-0.049	0.029	0.049	0.00087	0.00235
0.925	0.936	0.961	-0.011	-0.036	0.011	0.036	0.00012	0.00127
1.165	1.141	1.153	0.024	0.012	0.024	0.012	0.00057	0.00015
1.348	1.380	1.345	-0.032	0.003	0.032	0.003	0.00102	0.00001
1.580	1.563	1.537	0.017	0.043	0.017	0.043	0.00027	0.00184
1.805	1.795	1.729	0.010	0.076	0.010	0.076	0.00011	0.00575
					0.026	**0.044**	**0.00092**	**0.00372**

The above example illustrates three useful points: 1) the abrasion resistances of various specimens can be compared over a period of time, 2) the abrasive wear rate that results from SSART testing can be described using a statistical model, and 3) wear depth can be extrapolated over a reasonable period of time.

CHAPTER 4. CONCLUSIONS

Chapter 4 provides a summary of this research effort, highlights its contributions, and proposes directions for future research.

4.1 Summary

Through experimental testing using the SSART, researchers at UIUC have successfully compared 21 approaches to improving the abrasion resistance of the rail seat through rail seat material improvements (Phases 1 and 2). Data from SSART in Phase 2 shows that abrasion resistance of concrete can be improved with the addition of steel fibers, polyurethane and epoxy coating on the rail seat surface, and using metal shavings as fine aggregates in the top portion of rail seat. Also, a theoretical framework to describe the abrasive wear process as well as predicting abrasive wear depth was successfully developed, and will be further refined under future testing.

4.2 Future research directions

As a part of an effort to develop a simplified industry-standard abrasion resistance test for concrete crossties, data obtained from SSART will be correlated with the data from AREMA Test 6 (Wear and Abrasion) on the Pulsating Load Testing Machine (PLTM) at UIUC. AREMA Test 6 is the industry standard crosstie and fastening system wear/deterioration test, and is the only AREMA test that is capable of generating RSD. Ultimately, this research will help in formulating design recommendations for the industry to mitigate RSD from a materials standpoint.

Additionally, image analysis will be utilized to characterize the effect of variability in exposed area of coarse aggregate on the abrasion resistance of concrete specimens as abrasion progresses. As a part of this work, the relative proportion of aggregate in the concrete mix will be varied to see if there is an effect on abrasion resistance of concrete. The aggregate proportion in the mix will be changed without affecting the cement paste to aggregate ratio so as to not dilute the binding properties relative to control specimens. At the same time, the water/cement ratio and coarse aggregate to fine aggregate ratio will be held constant to minimize change in the other properties of hardened concrete.

Given that experimental testing of all possible permutations of abrasion mitigation approaches is not feasible, statistical modeling of wear rate will continue with the objective of improved ability to predict the effect of various abrasion mitigation approaches. This can be addressed by using scientific experimental design methods and using Statistical Analysis Software (SAS) so a prioritized list of possible combinations of various elements can be generated and the test matrix can be consolidated.

REFERENCES

10th International Heavy Haul Association Conference, New Delhi, 2013.

American Railway Engineering and Maintenance-of-Way Association (AREMA), Manual for Railway Engineering, Manual for Railway Engineering, 2012.

Bakharev, T., Microstructural Features of Railseat Deterioration in Concrete Railroad Ties, University of Illinois at Urbana-Champaign, 1994.

BSI, British Standard BS 812-113:1990 Testing Aggregates. Method for Determination of Aggregate Abrasion Value (AAV).

Chermant, J., Why Automatic Image Analysis ? An Introduction to This Issue, vol. 23, 2001, pp. 127–131.

Choros, J., Marquis, B., and Coltman, M., Prevention of Derailments Due to Concrete Tie Rail Seat Deterioration,, Proceedings of the ASME/IEEE Joint Rail Conference and the ASME Internal Combustion Engine Division, 2007, pp. 173–181.

Dwyer-Joyce, R. S., Sayles, R. S., and Ioannides, E., An Investigation into the Mechanisms of Closed Three- Body Abrasive Wear, WEAR, vol. 175, 1993, pp. 133–142.

Hadchti, K. M., and Carrasquillo, R. L., Abrasion Resistance and Scaling Resistance of Concrete Containing Fly Ash, Austin: 1988.

Joh, S.-H., Hwang, S. K., Kang, T.-H., Park, C.-S., and Lee, I.-W., Nondestructive Identification of Freezing-Induced Cracks in Concrete Sleepers of High-Speed Railways in South Korea, Transportation Research Record: Journal of the Transportation Research Board, vol. 2159, Dec. 2010, pp. 98–109.

Kernes, R. G., Edwards, J. R., Dersch, M. S., Lange, D. A., and Barkan, C. P. L., Investigation of the Dynamic Frictional Properties of a Concrete Crosstie Rail Seat and

Pad and Its Effect on Rail Seat Deterioration (RSD), Proceedings of the Transportation Research Board 91st Annual Meeting, Washington, DC, January, 2011.

Kernes, R. G., Edwards, J. R., Dersch, M. S., Lange, D. A., and Barkan, C. P. L., Investigation of the Impact of Abrasion as a Concrete Crosstie Rail Seat Deterioration (RSD) Mechanism, American Railway Engineering and Maintenance of Way Association (AREMA) conference proceedings, 2011.

Miller, R. B., and Wichern, D. W., Intermediate Business Statistics: Analysis of Variance, Regression, and Time Series, Madoson: 1977.

Mindess, S., Young, F. J., and Darwin, D., Concrete, Upper Saddle River: Pearson Education, Inc., 2003.

Moody, H. G., Wheel Load Detector Extends Life of Concrete Railroad Ties, Transportation Research Board of the National Academies, vol. 257, 1987, pp. 18–23.

Shurpali, A. A., Edwards, J. R., Lange, D. A., Barkan, C. P. L. and VanDam, E., Laboratory Investigation of the Abrasive Wear Mechanism of Concrete Crosstie Rail Seat Deterioration (RSD), Proceedings of the ASME/ASCE/IEEE 2012 Joint Rail Conference, Urbana: 2012.

Shurpali, A. A., Kernes, R. G., Edwards, J. R., Dersch, M. S. Lange, D. A., and Barkan, C. P. L., Investigation of the Mechanics of Rail Seat Deterioration (RSD) and Methods to Improve Rail Seat Abrasion Resistance in Concrete Sleepers,

Turkish Standards Institution, TS 699, Anakara.

Van Dyk, B. J., Dersch, M. S., and Edwards, J. R., International Concrete Crosstie and Fastening System Survey – Final Results, Urbana: 2012.

Wiley, C. N., Chemical Abstracts, Chemical Abstracts, Volume 3, Easton, Pa.: American Chemical Society, 1909, p. 2495.

Witte, L. P., and Backstrom, J. E., Some Properties Affecting Abrasion Resistance of Air-Entrained Concrete, Proceedings, ASTM International, Concshohocken, PA: 1995, p. 1141.

Zeman, J. C., Edwards, J. R., Dersch, M. S., Lange, D. A., and Barkan, C. P. L., Failure Mode and Effect Analysis of Concrete Ties in North America, International Heavy Haul Association Conference, 2009.

Zeman, J. C., Hydraulic Mechanisms of Concrete-Tie Rail Seat Deterioration, University of Illinois at Urbana-Champaign, 2010.