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

TRB 13-4271

Transportation Research Board 92nd Annual Meeting

Revised: November 15th, 2012

Amogh A. Shurpali[1], J. Riley Edwards, Ryan G. Kernes, Xiang Liu,
David A. Lange, and Christopher P. L. Barkan

Rail Transportation and Engineering Center - RailTEC
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 N. Mathews Ave., Urbana, IL 61801

5641 Words, 2 Tables, 3 Figures = 6912 Total Word Count

Amogh A. Shurpali[1]
(217) 244-6063
ashurpa2@illinois.edu

J. Riley Edwards
(217) 244-7417
jedward2@illinois.edu

Ryan G. Kernes
(217) 300-2131
rkernes2@illinois.edu

Xiang Liu
(217) 244-6063
liu94@illinois.edu

David A. Lange
(217) 333-4816
dlange@illinois.edu

Christopher P.L. Barkan
(217) 244-6338
cbarkan@illinois.edu

---

[1] Corresponding author

ABSTRACT

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 empirical design process for concrete crossties and fastening systems. The objective of this study is to quantify the abrasion resistance of concrete rail seats by using a variety of concrete mix designs and other materials relevant to the rail industry. To simulate the abrasion mechanism of RSD, a Small-Scale Test for Abrasion Resistance (SSTAR) 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 SSTAR and statistical model will help the rail industry mechanistically design concrete crossties by improving the current understanding of the performance of various concrete abrasion mitigation approaches. Preliminary results show that abrasion mitigation approaches such as the addition of metallic fine aggregates (MFA), steel fibers, and the application of coatings improve the abrasion resistance of concrete specimens.

INTRODUCTION

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 rigorous, 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 material at the contact interface between the concrete rail seat and the rail pad *(1)*. RSD has been identified as one of the primary factors limiting concrete crosstie service life in North American heavy-haul freight infrastructure *(2,3)*. RSD can lead to problems that include fastening system wear and track geometry defects such as loss of cant and gauge-widening that can lead to unstable rail conditions and/or derailments *(4)*. RSD is difficult to detect and 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 cycles of the materials that compose the rail seat and fastening system are 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 *(1,5)*. Going forward, additional RSD research should focus on improving the abrasion resistance of concrete materials as well as the materials used in the manufacture of fastening system components. This research focuses on the development of stronger, more durable materials in the concrete crosstie rail seat, use of various protective surface treatments, and improved manufacturing techniques. Such measures can prevent or delay the onset of RSD and increase the service life of the rail seat.

BACKGROUND

Through previous research on RSD, the University of Illinois at Urbana-Champaign (UIUC) has identified five possible mechanisms having the potential to contribute to RSD. The feasible mechanisms are abrasion, crushing, freeze-thaw cracking, hydraulic-pressure cracking, and hydro-abrasive erosion *(6)*. Of these mechanisms, hydraulic-pressure cracking and hydro-abrasive erosion were investigated at UIUC and found to be feasible mechanisms resulting in RSD *(2,7,8)*. 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 *(8)*. 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 *(9)*. 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 *(9)*. The abrasion mechanism of 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) *(10)*.

In order to better understand the interactions leading to abrasion, two tests were designed and executed at UIUC. First, a Small-Scale Test for Abrasion Resistance (SSTAR) was designed and implemented to understand the effect of various abrasion mitigation approaches such as concrete mix design improvements, alternative curing techniques, and surface treatments on the concrete crosstie rail seat. Second, a Large-Scale Abrasion Test (LSAT) was developed to better understand the mechanics of the abrasion mechanism of RSD by characterizing the frictional forces that resist movement at the contact interface between the concrete crosstie rail seat and the rail pad *(9)*. The focus of this paper is to investigate methods to mitigate the abrasion mechanism of RSD based on experiments performed on the SSTAR.

Mitigation Approaches

As a part of the efforts to improve the abrasion resistance of concrete by improving materials used in the rail seat, many abrasion mitigation approaches were evaluated using the SSTAR. The following descriptions provide background information on the theory and rationale behind selecting these abrasion mitigation approaches.

Air content is believed to have an effect on the abrasion resistance of the concrete rail seat. Air is typically entrained in structural concrete to prevent cracking due to repeated freeze-thaw cycles, and can be expressed as the air void volume in the concrete microstructure. Industry experts have questioned the use of air entrainment in concrete crossties citing the possible adverse effect on the abrasion resistance of the rail seat. According to published literature related to concrete materials, the abrasion resistance of concrete is directly related to concrete compressive strength *(11,12)*. Also, concrete compressive strength is inversely related to the air content *(13)*. Therefore, one would expect that the abrasion resistance of concrete would decrease with increasing air content. However, the trade-off between the abrasion resistance of concrete and air content is not properly understood. UIUC researchers have investigated air entrainment using the SSTAR to determine if there is an optimum air content at which the need for abrasion resistance is balanced with appropriate freeze-thaw considerations.

To bound the complex problem that stems from a multitude of mix design permutations, the air content of a given concrete mixture design was varied by selecting graduated dosages of Air Entraining Admixtures (AEA). The three AEA dosages that were selected for this study were:

1) No AEA – eliminating the air entrainment from the concrete mixture resulted in an air content of 2.2% as measured by ASTM C173,
2) Control specimens – adding a moderate amount of AEA resulted in an air content of 3.5% which is recommended by the American Railway Engineering and Maintenance-of-Way Association (AREMA) for freeze-thaw durability *(14)* , and
3) Additional AEA – adding a dosage of air entrainment that is higher than the dosage of the control mix design resulted in an air content of 6%, which is the recommended average air content for medium/severe environmental exposure conditions by the American Concrete Institute (ACI) *(13)*.

The North American railroad industry has recently increased its use of surface coatings as an abrasion mitigation approach. Epoxy coatings are being used as a preventive RSD mitigation measure. As an example, one major Class I railroad has incorporated the use of epoxy coating into its design specifications for all new concrete crossties. Other Class I railroads are using polyurethane coatings as an RSD repair approach. Preliminary qualitative results from revenue testing have shown that surface coatings can result improvements to the abrasion resistance of rail seat. However, more research needs to be conducted on the engineering principles behind surface coatings in order to maximize their potential to mitigate the abrasion mechanism of RSD.

Self-consolidating concrete is a type of high-performance concrete that exhibits low resistance to flow and moderate viscosity that allows fresh concrete to be placed and compacted properly when extensive reinforcement exists or traditional compactions methods are not available *(15)*. The abrasion resistance of self-consolidating concrete was evaluated due to the advantages of lowering the water-cement ratio, high workability, and the replacement of cement with mineral admixtures (fly ash in this study) which are known to be factors favoring abrasion resistance of concrete *(13,16)*. Also, SCC does not require compaction, which can possibly increase the production rate of concrete crossties while decreasing the production cost.

The abrasion resistance of fiber-reinforced concrete (FRC) was evaluated based on the understanding that FRC has the ability to control cracking. Micro-cracking is suspected to occur in the rail seat due to freeze-thaw cycles and hydraulic pressure *(8,13,16)*. Since FRC may have the potential to mitigate microcracking, we tested FRC in order to investigate its ability to resist abrasion.

Metallic fine aggregates (MFA) are fine metallic shavings that increase the local hardness of the concrete surface. MFA's have been used by pavement manufacturers as an abrasion mitigation approach, and are known to possess significant strength properties *(16,17)*. Additionally, metallic coarse aggregate toppings have been used locally in the rail seat area and tested in revenue service as an RSD mitigation technique *(18)*. Preliminary anecdotal results from field testing of MFA's have shown in improvement in the abrasion resistance of concrete. By evaluating MFA's in this study, we were able to evaluate the validity of this abrasion mitigation approach.

METHODOLOGY

A prioritized list of abrasion mitigation approaches 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 *(19)*. Research and testing using the SSTAR was divided into two phases. Phase 1 involved testing of abrasion mitigation approaches that were being evaluated for their abrasion resistance by the concrete materials industry *(20)*. The list of abrasion mitigation approaches was enhanced and further refined in Phase 2 by removing approaches from Phase 1 that did not show an improvement in abrasion resistance. Also, the Phase 2 experimentation reflected more recent RSD mitigation approaches being researched and used in revenue service by the North American concrete crosstie industry.

In Phase 1, all specimens that were tested were prepared in the concrete materials laboratory at UIUC, except for the specimens with surface coatings. A concrete crosstie manufacturer prepared the concrete specimens with surface coatings. In Phase 2, all specimens were prepared by concrete crosstie manufacturers. The concrete crosstie manufacturers were involved in the production of test specimens to minimize variability in casting methods and to obtain concrete mix designs that were representative of current industry practices.

The following concrete abrasion mitigation approaches were tested to quantify the abrasion resistance of each approach: supplementary cementitious materials (mineral admixtures), fibers, metallic fine aggregates (MFA), self-consolidating concrete (SCC), variable curing conditions, and the application of various surface treatments (coatings). This paper will focus on the results from Phase 2. Please refer to a previous publication for more details on test results from Phase 1 *(20)*.

SMALL - SCALE TEST FOR ABRASION RESISTANCE (SSTAR)

Motivation

When investigating component-level behavior within the system, limitations to large-scale abrasion resistance testing, which typically requires relatively more time and resources to operate, can present significant challenges. These challenges limit the breadth, depth, and effectiveness of a parametric study to identify ways of mitigating the abrasion mechanism in RSD. The aforementioned limitations and lessons learned from the design of previous tests led UIUC researchers to the development of the SSTAR. The SSTAR was designed with the following characteristics and attributes: 1) ability to isolate the abrasion mechanism, 2) ability to quantify the abrasion resistance of various concrete abrasion mitigation approaches, 3) simple and economical operation, and 4) ability to conduct short duration tests that will facilitate the collection of large volumes of data.

The SSTAR was designed to be similar to the current industry standard abrasion tests, with modifications incorporated to represent some elements of RSD in the field *(21,22)*. The SSTAR is not completely representative of field conditions for several reasons, which must be controlled (to the extent feasible) and understood when interpreting data. One difference is the continuous, rotational loading of concrete in the SSTAR as opposed to cyclic loading under normal field conditions. Another difference is that the interaction between steel and concrete which occurs in SSTAR is different from the interaction between polymer materials and concrete as seen in the field. Nevertheless, the SSTAR is a simplified tool that aims to provide quantitative results that compare the abrasion resistance of various abrasion mitigation approaches. Furthermore, it should not be considered a system-level test, but rather a qualification test for concrete rail seat materials prior to full-scale or revenue testing. Moreover, the SSTAR allows researchers to quickly obtain large amounts of data, which is critical in constructing an empirical model of rail seat wear, one of the primary objectives of this research project *(19)*.

Test Setup

The SSTAR was constructed by modifying a lapping machine that is typically used to sharpen tools or create flat, smooth surfaces on machined metal parts, and polish rocks in the realm of geotechnical engineering (**Figure 1**). The lapping machine is comprised of a revolving steel plate with concrete specimens loaded in three counter-rotational rings that rest on top of the plate. 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 weighing 4.5 pounds (pounds) [2 kilograms] is placed on top of each specimen to provide a normal load. To represent the influence of three-body wear, an abrasive slurry of water and sand is applied to the lapping plate throughout the test at a uniform rate 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 to support a sand storage container. Holes were drilled at the bottom of the sand storage container and wooden platform to ensure proper alignment.

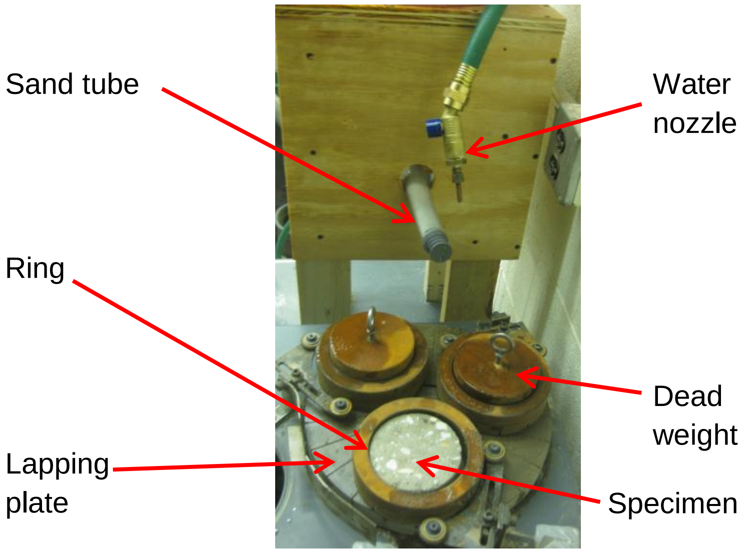

FIGURE 1 SSTAR Setup and Abrasive Slurry Conveyance Equipment

Test Protocol

To ensure confidence in the test results, nine specimens (or replicates) were tested for each abrasion mitigation approach. It should be noted that the abrasion resistance test was conducted after curing the concrete for 28 days. First, the concrete specimens were marked to identify the wearing surface (the as-cast surface). Also, locations where thickness readings were to be taken were marked. Initial thicknesses at the four marked locations were obtained using a vernier caliper. Three specimens were then placed in the lapping machine rings, the dead weight was applied, and the test was started. At the same time, an abrasive slurry of water and manufactured sand was introduced into the specimen-lapping plate interface. The manufactured sand used in this research is Ottawa sand and 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 total test duration was 100 minutes, with thickness measurements taken at regular time intervals.

After testing, the wear depth (i.e., the difference between initial and final thicknesses taken at every time step using vernier calipers) was plotted with respect to testing duration to represent the progression of abrasion with time (wear rate curves). The wear rate 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 were published in 2012 *(19)*.

RESULTS AND DISCUSSION

Specimens containing 3.5% air by volume are called “control specimens”. The differences in abrasion resistance of concrete specimens are measured relative to the control specimens. Also, all comparisons between abrasion resistances of control specimens and other abrasion mitigation approaches are done at the end of the test (i.e., 100 minutes). The wear rate is defined as the ratio of wear depth over testing duration and is depicted by the slope of wear rate curves in **Figure 2**. As the wear curves shift downward towards the x-axis (i.e., wear rate decreases), the corresponding abrasion mitigation approach shows higher abrasion resistance. Each data point represents the average wear depth value obtained from nine specimens. Error bars representing two standard errors (both positive and negative) in wear depth are shown on all the data points.

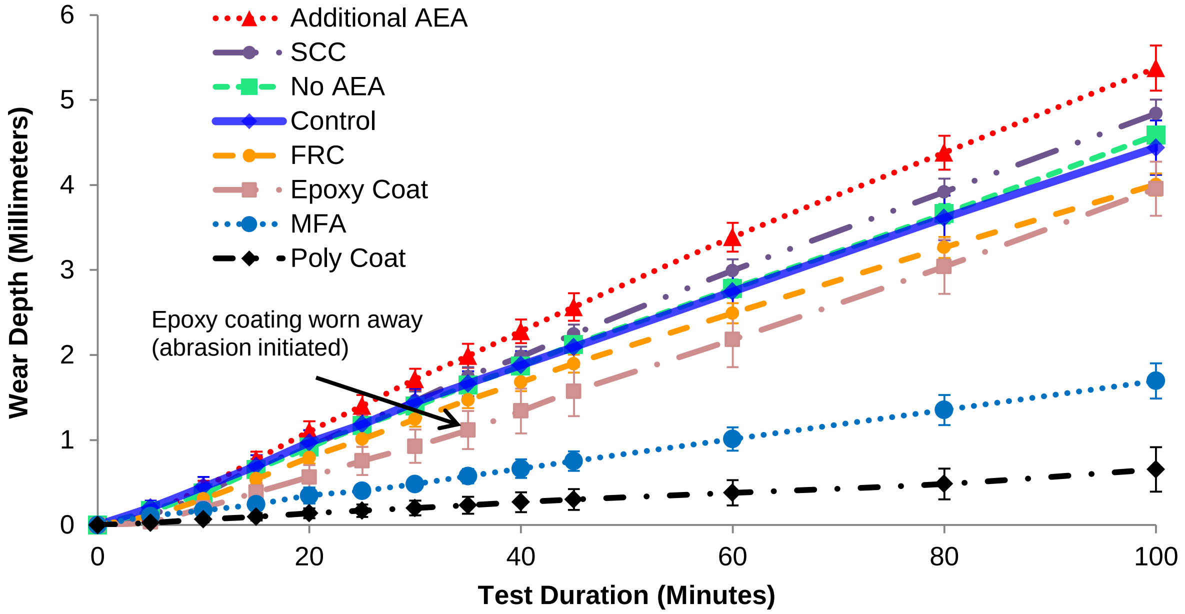

FIGURE 2 Wear Rate Curves of Various Abrasion Mitigation Approaches

Air Content

Data from the SSTAR appears to support the hypothesis that abrasion resistance of concrete is directly correlated with the compressive strength. It was observed that the compressive strength of specimens with additional AEA (6% air content) was 22% less than that of specimens without any AEA (2.2% air content). This reduction in compressive strength probably led to a 15% decrease in abrasion resistance of specimens with additional AEA compared to specimens without AEA **(Figure 3)**.

Also, there was no appreciable difference in the abrasion resistance of control specimens relative to specimens cast without AEA. This may be explained by the fact that air is naturally entrapped into the concrete matrix during mixing and consolidation, even when no AEA is added during casting. Also, there was only a 7% reduction in compressive strength of control specimens (9,800 psi) relative to specimens without AEA (10,500 psi).

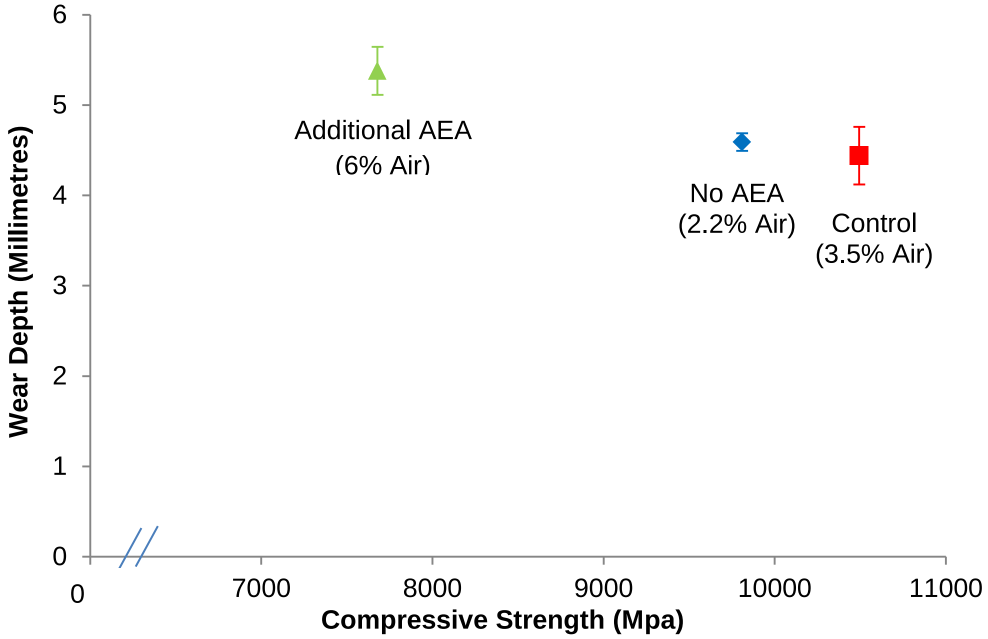

Figure 3 Effect of Compressive Strength on Abrasion Resistance

Surface Coatings

Data from the SSTAR shows that epoxy coating delayed the onset of abrasion, and provided an 11% increase in abrasion resistance relative to the control specimens **(Figure 2)**. The epoxy coating developed cracks, after which it quickly disintegrated and added to the abrasive slurry. This phenomenon can likely be attributed to the hardness of the epoxy coating layer as observed while testing. After the epoxy coating wore away, the abrasion of concrete material started and the wear rate of the specimens was similar to that of the control specimens. This is evident from **Figure 2** where the epoxy coating is completely worn after 35 minutes. After the coating was lost, the wear rate increased from 0.03 millimeters per minute to match the wear rate of control specimens at 0.05 millimeters per minute.

Data from SSTAR showed that the polyurethane coating exhibited the least abrasion of all of the mitigation measures tested in Phase 2. It was observed that the specimens with polyurethane coating showed 85% higher abrasion resistance compared to the control specimens. In some instances, the polyurethane coating remained intact throughout the duration of the test. One reason that the polyurethane coating may have performed better than epoxy coating is that it was observed to be significantly less hard compared to epoxy coating. The additional hardness of the epoxy may have resulted in a brittle layer that cracked under significant shear stress in the SSTAR.

Self-Consolidating Concrete (SCC)

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)**. This reduction in abrasion resistance is likely related to the 5% decrease in compressive strength of the SCC specimens compared to the control specimens.

Fiber-Reinforced Concrete (FRC)

Results from the SSTAR showed that there was an improvement of 10% in the abrasion resistance of FRC specimens relative to control specimens **(Figure 2)**.

Metallic Fine Aggregate (MFA)

The MFA specimens exhibited exceptional abrasion resistance, and minimal wear of concrete was observed at the end of tests. The MFA specimens had the second best abrasion resistance after the polyurethane coated specimens, showing a 62% increase in abrasion resistance as compared to the control specimens **(Figure 2)**. These results are in agreement with the literature and limited anecdotal evidence related to the field performance.

Table 1 summarizes the percentage change in abrasion resistance of various specimen types relative to the control specimens. A negative sign before the numbers in the last column indicates a reduction in the abrasion resistance (greater depth of wear) relative to that of the control specimens.

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	-22.0
Self-Consolidating Concrete (SCC)	-9.0
Metallic Fine Aggregate (MFA)	62.0
Fiber-Reinforced Concrete (FRC)	10.0
Polyurethane coat	85.0
Epoxy coat	11.0

STATISTICAL MODELING OF ABRASIVE WEAR

There are two objectives for the analysis of the data at discrete intervals: forecasting future wear rate and characterizing the wear rate *(23)*. With regard to this research, forecasting would entail predicting (extrapolating) wear data as a function of time based on data obtained previously. Data generated from the SSTAR is in a time-ordered sequence (time series), wherein wear depths are recorded at discrete time intervals. This time-series analysis can be extended to predict field wear rates on a concrete crosstie rail seat as a function of loading cycles, provided relevant data is available from actual field conditions. However, such data are not currently available. 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 rates as a function of loading cycles (or number of train passes). This would be a helpful tool to model crosstie degradation and optimize crosstie maintenance/replacement schedules while ensuring minimum costs. In addition to this, a descriptive model can be used to optimize concrete mix designs 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. In this study, statistical modeling was mainly used as a tool to compare and rank abrasion resistances of various abrasion mitigation approaches over a period of time.

An ordinary regression model (or ordinary least squares (OLS) method) with time as the independent variable is not suitable for describing time series for two reasons.

First, the observations making up the time series are usually dependent. This is true in the context of this research, as periodic wear depth measurements are taken on the same specimen resulting in the wear measurements being dependent on wear measurements taken previously. Second, forecasting future values entails extrapolation of historical data for which regression models are not suitable and can lead to inaccurate forecasts *(23)*. 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.

Numerical Example

What follows is a statistical modeling example that illustrates 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)
ε_{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: Parameter estimates

TABLE 2 Autoregressive Parameter Estimates

Variable	DF	Estimate	Standard Error	t Value	Pr > |t|
X_1 (β_1)	1	0.0505	0.000697	72.36	<.0001
$X_1\ X_2$ (β_2)	1	-0.0085	0.001710	-5.01	0.0002

Step 3: 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 abrasion resistances of the CONT and FRC specimens.

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

CONCLUSIONS

SSTAR is capable of producing quantifiable abrasion of concrete specimens in an accelerated environment. Also, based on the results obtained from SSTAR, the experimental test setup proved to be a reliable alternative to existing abrasion resistance tests and provided repeatable data. This is illustrated from **Figure 2** where the error bars representing two standard errors do not indicate a wide scatter of data. Through experimental testing using the SSTAR, researchers at UIUC have successfully compared 21 abrasion mitigation approaches through material improvements (Phases 1 and 2). Also, a statistical model was developed to describe the abrasion mechanism of concrete. This was helpful in comparing the relative abrasion resistance of various abrasion mitigation approached as well as predicting wear rates.

Data from SSTAR in Phase 2 shows that the abrasion resistance of concrete can be improved with the addition of steel fibers, application of polyurethane and epoxy coatings on the rail seat surface, and using MFA's in the rail seat. Increasing the air content appeared to have a negative effect on the abrasion resistance of concrete probably due to a reduction in the compressive strength of concrete. Surface treatments in the form of epoxy and polyurethane coatings improved the abrasion resistance of the specimens significantly. Polyurethane coatings performed significantly better than epoxy coatings, likely due to the differences in material properties such as hardness. Minimal wear was observed on the surface of the concrete specimens topped with MFA's upon completion of the abrasion tests. SCC showed no significant improvement in abrasion resistance despite the presence of elements of various effective abrasion resistance approaches present within the SCC mix design.

FUTURE WORK

As a part of an effort to develop a simplified industry-standard abrasion resistance test for concrete crossties, data obtained from SSTAR 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.

Further materials experimentation will be conducted to understand the effect of various coating parameters like coating thickness, temperature, and curing method. Although MFA and FRC improved the abrasion resistance of concrete, more research must be done on the effect of harder metallic materials on the abrasion resistance of the rail seat as well as the softer rail pad.

Aggregate properties are critical to the abrasion resistance of concrete *(16,24)*. To study the effect of varying aggregate proportion on the abrasion resistance of concrete, the relative proportion of aggregate in the concrete mix will be varied. The coarse 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 the control specimens. Also, the water/cement ratio will be held constant to minimize variation in the other properties of hardened concrete. In addition, an image analysis will be utilized to characterize the effect of variability in the area of coarse aggregate that is exposed to the abrasion resistance of concrete specimens as abrasion progresses *(25)*. Another research project is underway at UIUC which aims to evaluate the performance of high performance concrete (HPC) mix designs in concrete crossties. This will be done by conducting a comprehensive array of tests to evaluate the durability of concrete crossties. Results from this project will supplement the conclusions from our study related to the abrasion resistance of various rail seat materials.

ACKNOWLEDGEMENTS

The authors would like to express sincere gratitude to the Association of American Railroads (AAR) Technology Scanning 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, Bill Holberg, Greg Grissom, Eric Gehringer, Rob Loomis, 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, Brennan Caughron, and Samuel L. Sogin, all of UIUC. J. Riley Edwards has been supported in part by grants to the UIUC Rail Transportation and Engineering Center (RailTEC) from CN, CSX, Hanson Professional Services, Norfolk Southern, and the George Krambles Transportation Scholarship Fund.

REFERENCES

1. 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.
2. Zeman, J. C., *Hydraulic Mechanisms of Concrete-Tie Rail Seat Deterioration*, University of Illinois at Urbana-Champaign, 2010.
3. Van Dyk, B. J., Dersch, M. S. and Edwards, J. R., *International Concrete Crosstie and Fastening System Survey – Final Results*, Urbana: 2012.
4. 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.
5. 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.
6. 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.
7. 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.
8. Bakharev, T., *Microstructural Features of Railseat Deterioration in Concrete Railroad Ties*, University of Illinois at Urbana-Champaign, 1994.
9. 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.
10. 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.
11. Witte, L. P. and Backstrom, J. E., *Some Properties Affecting Abrasion Resistance of Air-Entrained Concrete*, Proceedings, ASTM International, Concshohocken, PA: 1995, p. 1141.
12. Hadchti, K. M. and Carrasquillo, R. L., *Abrasion Resistance and Scaling Resistance of Concrete Containing Fly Ash*, Austin: 1988.
13. Mindess, S. Young, F. J. and Darwin, D., *Concrete*, Upper Saddle River: Pearson Education, Inc., 2003.
14. American Railway Engineering and Maintenance-of-Way Association (AREMA), *Manual for Railway Engineering*, Manual for Railway Engineering, 2012.
15. Khayat, K. H., *Workability , Testing , and Performance of Self-Consolidating Concrete*, ACI Materials Journal, 2000, pp. 346–354.
16. Gencel, O. Sabri Gok, M. and Brostow, W., *Effect of Metallic Aggregate and Cement Content on Abrasion Resistance Behaviour of Concrete*, Materials Research Innovations, vol. 15, Apr. 2011, pp. 116–123.
17. Wiley, C. N., *Chemical Abstracts*, Chemical Abstracts, Volume 3, Easton, Pa.: American Chemical Society, 1909, p. 2495.
18. Philip J. McQueen Corporation, *Railseat Abrasion of Concrete Ties-Summary Report of the Problem and Existing Solutions*, San Rafael: 2006.

19. Shurpali, A. A. Edwards, J. R. Lange, D. A. Barkan, C. P. L. and Van Dam, 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.
20. 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*, 2013.
21. Turkish Standards Institution, *TS 699*, Ankara.
22. BSI, *British Standard BS 812-113:1990 Testing Aggregates. Method for Determination of Aggregate Abrasion Value (AAV).*
23. Miller, R. B. and Wichern, D. W., *Intermediate Business Statistics: Analysis of Variance, Regression, and Time Series*, Madoson: 1977.
24. Frith, D. J. Morian, D. A. Stoffels, S. M. and Saboundjian, S., *Hard Aggregate Resistance to Studded Tires*, Transportation Research Record: Journal of the Transportation Research Board, vol. 1874, 2004, pp. 19–28.
25. Chermant, J., *Why Automatic Image Analysis ? An Introduction to This Issue*, vol. 23, 2001, pp. 127–131.