

Moisture-Driven Deterioration and Abrasion of Concrete Sleeper Rail Seats

*Submitted for publication in the proceedings of the
9th World Congress on Railway Research*

1 February 2011

John C. Zeman¹, Ryan G. Kernes², J. Riley Edwards^{2,3},
David A. Lange², and Christopher P. L. Barkan²

¹*Farnsworth Group, Inc. (Current Affiliation)
2709 McGraw Dr., Bloomington, IL 61704*

²*Railroad Engineering Program
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 N. Mathews Ave., Urbana, IL 61801
Fax: (217) 333-1924*

Abstract (360 words) + Body (3623 words) + 2 Figures + 2 Tables = 5233 Total Words

John C. Zeman	Ryan G. Kernes	J. Riley Edwards	David A. Lange	Christopher P.L. Barkan
(217) 377-7714	(217) 244-6063	(217) 244-7417	(217) 333-4816	(217) 244-6338
jzeman2@gmail.com	rkernes2@illinois.edu	jedward2@illinois.edu	dlange@illinois.edu	cbarkan@illinois.edu

³ Corresponding author

ABSTRACT

Based on the results of a 2008 railway industry survey on concrete sleepers, rail seat deterioration (RSD) is the most critical problem with concrete sleeper performance on major North American freight railroads. RSD is the degradation of the concrete underneath the rail and results in problems such as wide gauge, insufficient rail cant, and loss of fastening toe load. Currently, mechanisms leading to RSD are not sufficiently understood to allow for effective solutions. The primary causes of RSD appear to be high stresses at the rail seat, relative motion at the rail seat, the presence of moisture, and the presence of abrasive fines. RSD is considered to have five potential mechanisms, and this research investigates three of them: hydraulic pressure cracking, hydro-abrasive erosion, and abrasion. In order to investigate the two moisture-driven mechanisms, a laboratory test setup and procedure were developed to measure the surface water pressure in a laboratory rail seat using rail pads of differing material composition and surface geometry. To evaluate hydraulic pressure cracking, a model of the effective stress in a concrete-sleeper rail seat was created to determine which water pressures on the rail seat surface could lead to damaging pore water pressures in the concrete. Comparing the effective stress model and the measured surface water pressures, hydraulic pressure cracking appears to be a feasible mechanism for RSD given the correct combination of high rail seat loads, sufficient moisture, and a rail pad surface that develops high pressure. The measured surface water pressures were used to estimate the potential water velocity. By comparing these estimates with critical velocities for concrete erosion, it also appears feasible that hydro-abrasive erosion contributes to RSD. Mitigation options for preventing hydraulic pressure cracking are using a rail pad or pad assembly that does not seal water, thereby reducing the occurrence of high impact loads, and using high-strength, air-entrained, low-permeability concrete. Care should be exercised when using pads that do not seal water, as this could contribute to hydro-abrasive erosion or abrasion. Future testing will focus on abrasion in order to evaluate which potential failure mechanism should govern concrete sleeper and fastening system design in order to reduce their life cycle costs.

INTRODUCTION TO RAIL SEAT DETERIORATION (RSD)

Rail seat deterioration (RSD) is degradation underneath the rail on a concrete sleeper. This deterioration leads to track geometry defects such as wide gauge and insufficient rail cant, and allows for accelerated deterioration of the rail-to-sleeper fastening system. Conversely, it has also been noted that fastening system defects (e.g. loss of toe load or insulator material) can lead to RSD. Likely, both the concrete rail seat and the fastening system components undergo wear concurrently.

RSD was first identified by North American railroads in the late 1980's (*T. Johns, unpublished 2009*). In the early-1990's, tests were conducted at the Transportation Technology Center's (TTC's) Facility for Accelerated Service Testing (FAST) to compare the resistance of different combinations of concrete sleepers and fastening system components to RSD [1]. TTC's tests resulted in the identification of certain rail pads and pad assemblies that mitigated RSD to a manageable level, providing solutions that were sufficient for the North American freight loading conditions in the mid-1990's.

Since then, axle loads and rail life have increased due to improved materials and maintenance practices. Consequently, the materials and designs that worked in the past to mitigate RSD are often inadequate today (*R. Reiff, unpublished 2009*). In response to the continued prevalence of RSD on primary freight corridors in North America, members of the American Railway Engineering and Maintenance-of-Way Association (AREMA) Committee 30 (Ties) formed a working group of railroad employees, suppliers, and researchers to address the problem. One of the first actions of this working group was to agree on the factors and causes of RSD (Tables 1 and 2).

Table 1: Relevance of the Causes of RSD to the Potential Concrete Deterioration Mechanisms

Causes	Concrete Deterioration Mechanisms				
	Abrasion	Crushing	Freeze-Thaw	Hydraulic Pressure	Hydro-Abrasive
High stresses at rail seat	✓	✓		✓	✓
Relative motion at rail seat	✓	✓		✓	✓
Presence of moisture	✓	✓	✓	✓	✓
Presence of abrasive fines	✓				✓

Table 2: Summary of Internal and External Factors Related to the Causes of RSD

	High Stresses at the Rail Seat	Relative Motion at the Rail Seat	Presence of Moisture	Presence of Abrasive Fines
Internal Factors	<p><i>Loss of proper rail cant</i></p> <ul style="list-style-type: none"> • Loss of material at rail seat • Loss of material at shoulder • Loss of toe load <p><i>Contact area of pad</i></p> <ul style="list-style-type: none"> • Material properties and surface geometry of rail pad 	<p><i>Looseness of fastening system (loss of toe load)</i></p> <ul style="list-style-type: none"> • Loss of material at rail seat • Loss of material at shoulder • Yielded or fractured clips • Worn insulators <p><i>Scrubbing action</i></p> <ul style="list-style-type: none"> • Poisson's ratio of rail pad 	<p><i>Rail pad seal</i></p> <ul style="list-style-type: none"> • Material properties and surface geometry of rail pad • Looseness of fastening system • Wear of rail seat and rail pad <p><i>Concrete saturation</i></p> <ul style="list-style-type: none"> • Permeability of concrete and rail seat surface 	<p><i>Rail pad seal</i></p> <ul style="list-style-type: none"> • Material properties and surface geometry of rail pad • Looseness of fastening system • Wear of rail seat and rail pad <p><i>Fines from wear of rail seat components</i></p>
External Factors	<p><i>High vertical loads</i></p> <ul style="list-style-type: none"> • Impact loads • Degraded track geometry <p><i>High L/V ratio</i></p> <ul style="list-style-type: none"> • Truck hunting • Over-/under-balanced speeds on curves • Sharp curves • Degraded track geometry <p><i>High longitudinal loads</i></p> <ul style="list-style-type: none"> • Steep grades • Thermal stresses in rail • Train braking and locomotive traction <p><i>Poor load distribution among adjacent rail</i></p> <ul style="list-style-type: none"> • Non-uniform track substructure • Non-uniform sleeper spacing • Degraded track geometry 	<p><i>Uplift action</i></p> <ul style="list-style-type: none"> • Low stiffness of track substructure, higher deflections <p><i>Lateral action</i></p> <ul style="list-style-type: none"> • Truck hunting • Truck steering around curves (push and pull) • Over-/under-balanced speeds on curves • Sharp curves <p><i>Longitudinal action</i></p> <ul style="list-style-type: none"> • Steep grades • Thermal stresses in the rail • Train braking and locomotive traction 	<p><i>Climate</i></p> <ul style="list-style-type: none"> • Average annual rainfall, days with precipitation, humidity, etc. • Average evaporation rate, etc. • Extreme daily or annual temperatures • Number of annual freeze/thaw cycles 	<p><i>Environment</i></p> <ul style="list-style-type: none"> • Wind-blown sand or dust • Moisture to transport the abrasive fines under the rail pad <p><i>Track maintenance</i></p> <ul style="list-style-type: none"> • Ground ballast metal shavings from rail grinding <p><i>Train operations</i></p> <ul style="list-style-type: none"> • Application of locomotive sand for braking (especially on grades) • Coal dust and other abrasive commodities

Table 2 separates the factors that contribute to the causes of RSD into internal and external factors. Some factors are within the realm of concrete sleeper design (internal factors), and others are functions of track alignment, track maintenance, train operations, or the climate/environment (external factors). Analyzing Tables 1 and 2 illustrates the complex interaction of different deterioration mechanisms and causes that contribute to RSD.

In addition to the challenge of diagnosing the mechanisms and causes of RSD, it is difficult to detect RSD without removing the rail and fastening system to examine the concrete rail seat. Maintenance measures currently used to combat RSD are regular replacement of the rail pad, periodic replacement of the fastening components, restoration of the proper rail seat surface with an epoxy or polyurethane coating, or removal of the sleeper from service [2, 3]. A survey of major freight railroads in the US and Canada conducted by the University of Illinois at Urbana-Champaign (UIUC) concluded that RSD was the most critical problem with concrete sleepers on their routes [4]. Prestressed concrete sleepers have the potential to withstand a combination of heavy axle loads and high tonnage that other sleeper materials cannot. Also, ballasted concrete sleeper track or slab track are the preferred methods of track support for high-speed operations, due to their stiff support and tighter geometric tolerances [2, 3]. For these reasons, improving the performance of concrete sleepers will be very beneficial to the railway industry.

Furthermore, learning how to effectively eliminate or mitigate RSD will reduce the risk of concrete sleepers failing prematurely or requiring excessive maintenance. This would lower the life cycle costs and help improve the economic viability of concrete sleepers in comparison to timber sleepers in North America. As a result of improved life cycle savings, higher performing track will enhance the cost efficiency for railways using concrete sleepers to meet the demands of increasing freight tonnages and high-speed rail development in North America.

MECHANISMS OF DETERIORATION

The US and Canadian railways have learned much about RSD since it was first identified in the mid-1980's [5], but the mechanics of the deterioration process are still not wholly understood. Currently, there is evidence that abrasion, freeze-thaw cracking, crushing, hydro-abrasive erosion, and hydraulic pressure cracking may contribute to RSD [5, 6]. Little evidence has been found to suggest that alkali-silica reactivity (ASR) is contributing to RSD, and research and experimental testing at UIUC has ruled out cavitation erosion as a feasible RSD mechanism [4, 5, 7].

The first laboratory test used in this research study was designed to understand the mechanics of the concrete deterioration in RSD by focusing on moisture-driven mechanisms: hydraulic pressure cracking and hydro-abrasive erosion. Future testing will examine abrasion, a mechanism currently believed to be affected, but not driven, by moisture. By understanding which deterioration mechanisms are acting on the concrete, it will be possible to develop more effective methods to prevent or mitigate RSD.

The theory of hydraulic pressure cracking claims that pore pressures in the concrete become large enough that the concrete's tensile strength is exceeded, resulting in micro-cracking and subsequent spalling [5]. In order to evaluate the feasibility of this theory, two elements were examined: the specific pore pressure required to damage the concrete and the expected pore pressure in a typical concrete sleeper. A linear-elastic effective stress model was developed to approximate the pore pressure in saturated concrete resulting from water pressure at the surface [8].

Hydro-abrasive erosion, also called abrasive erosion or suspended particle erosion, refers to concrete wear through the action of flowing water [7]. The potential for hydro-abrasive erosion was evaluated by comparing the theoretical particle flow velocities estimated from the measured surface water pressure to the critical flow velocities found in literature that caused erosion [9].

Abrasion is defined as the wear of concrete particles on the rail seat surface as frictional forces act between the rail pad and the concrete rail seat, which move relative to one another. When combined

with abrasive fines and water that penetrate into the interface between the rail pad and concrete rail seat (pad-seat interface), the frictional forces and relative movement of the concrete sleeper and the fastening system equate to a seemingly ideal situation for the occurrence of abrasive wear.

These three deterioration mechanisms are significantly affected by the ability of the rail pad to form a seal with the rail seat surface of the sleeper [9]. Water underneath the rail pad in a concrete sleeper rail seat may be pressurized or caused to flow, depending on the sealing characteristics of the rail pad [9]. The pressurization of the water could cause hydraulic pressure cracking, while water flow could cause hydro-abrasive erosion [9]. Although water does not drive the abrasion mechanism, anecdotal evidence and literature regarding concrete abrasion resistance indicate that moisture significantly increases the severity of abrasive wear. Thus, the rail pad seal directly influences the potential for abrasion by the intrusion of moisture and fines beneath the rail pad and the potential for hydraulic pressure cracking or hydro-abrasive erosion to occur at the rail seat [9].

The focus of this paper is to summarize the results from laboratory tests undertaken at UIUC to obtain greater insight into the potential moisture-driven failure mechanisms associated with RSD and to introduce a laboratory test for the evaluation of the parameters causing the abrasion mechanism.

LABORATORY TEST RESULTS FOR MOISTURE-DRIVEN MECHANISMS

An original experiment and procedure were developed at the Newmark Structural Engineering Laboratory (NSEL) at UIUC to determine the rail seat surface water pressure. The surface water pressure generated by applying a load on a submerged, mock concrete sleeper rail seat was measured using a pressure transducer [10]. The applied loads varied from 89 kiloNewtons (kN) (20 kilopounds or "kips") to 267 kN (60 kips), with 89 kN approximating the static rail seat load under a 130-metric-ton (286-kip) gross rail car load [2, 9].

Nine rail pads composed of different materials and with different surface geometries were considered in the study, including three types of pad assemblies. The rail pad surfaces tested were flat polyurethane, grooved polyurethane, dimpled polyurethane, flat ethyl-vinyl acetate (EVA), dimpled EVA, dimpled santoprene, a studded pad with a flat plastic bottom, a two-part assembly with a flat plastic bottom, and a three-part assembly with a flat foam bottom underneath a steel plate. Each assembly had a thermoplastic pad in contact with the rail base, which in the experiment was a steel loading plate designed to mimic the base-of-rail loading surface.

After plotting the peak surface pressure for each pad versus the applied load, it was determined that all the rail pads could be organized into one of three groups: flexible (flat and grooved polyurethane, dimpled santoprene), semi-rigid (flat and dimpled EVA, dimpled polyurethane), or assembly with a rigid layer (all three pad assemblies). The pads were placed in these groups solely by their load-pressure behavior, and these names were assigned to the groups in an attempt to explain the differences between them. The experimental load-pressure data were sorted by these pad groups, and mean regression lines were determined for each group (Figure 1). For the case of a perfect seal at the pad-seat interface, the surface pressure would be equal to the load divided by the area of the rail pad, and this is plotted on Figure 1 for comparison, labeled "uniform load stress."

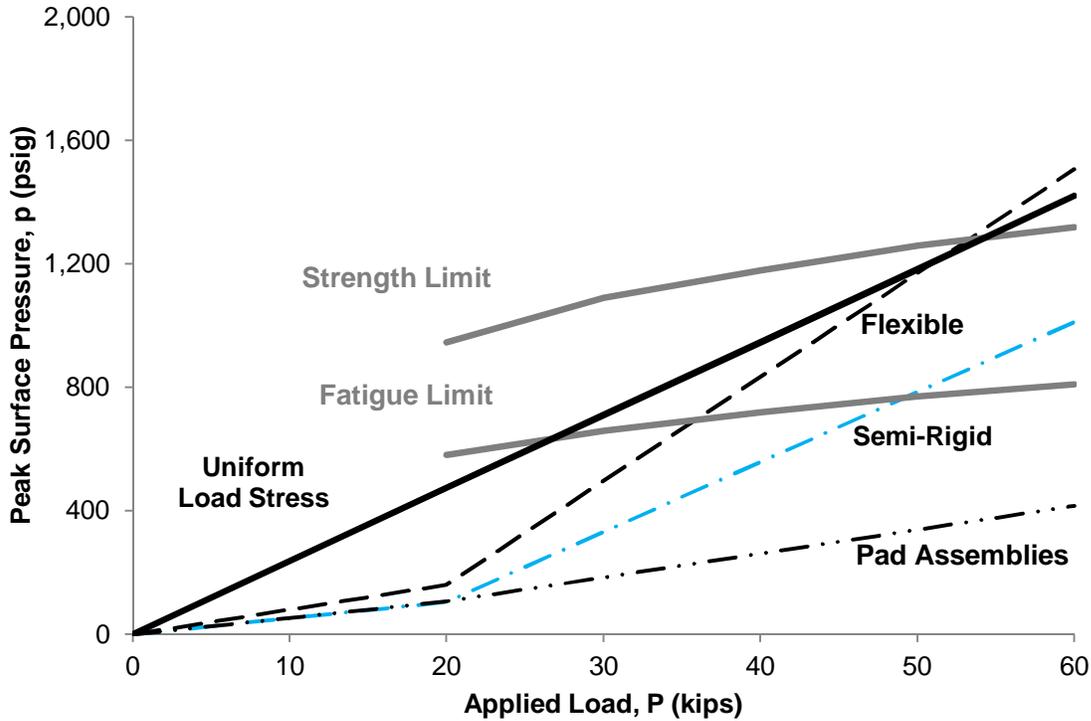


Figure 1: Surface Pressure versus Applied Load, with Load-Pressure Models and Damage Limits

The regression model of pressure versus load for the flexible pads is close to the ideal uniform load stress (Figure 1), suggesting that the flexible pads created a nearly perfect seal. Allowing some of the water to escape or flow rather than to become pressurized may explain the difference between the flexible and semi-rigid pads. These results suggest that some rail pads create more effective seals than others, explaining the difference in their load-pressure behavior. Comparing the empirical models with estimates for concrete damage limits (labeled “strength limit” and “fatigue limit” in Figure 1), it appears that an approach for preventing hydraulic pressure cracking is to use pad assemblies because they do not form effective seals under load [8].

The potential for water flow and hydro-abrasive erosion were estimated from our experimental results. Bernoulli’s equation for pipe flow without losses was used to estimate the maximum surface water velocity as a function of the applied load (representing the total energy) and the water pressure [9]. The resulting estimates for water velocity were scaled down to 72% to estimate the potential suspended-particle velocity (Figure 2) [11]. The lowest threshold of suspended particle velocity in the literature associated with concrete erosion was approximately 50 m/s (165 ft/s), and this value was for flow parallel to the surface, similar to the condition for flow underneath the rail pad [12]. This critical particle velocity was also plotted for comparison (Figure 2).

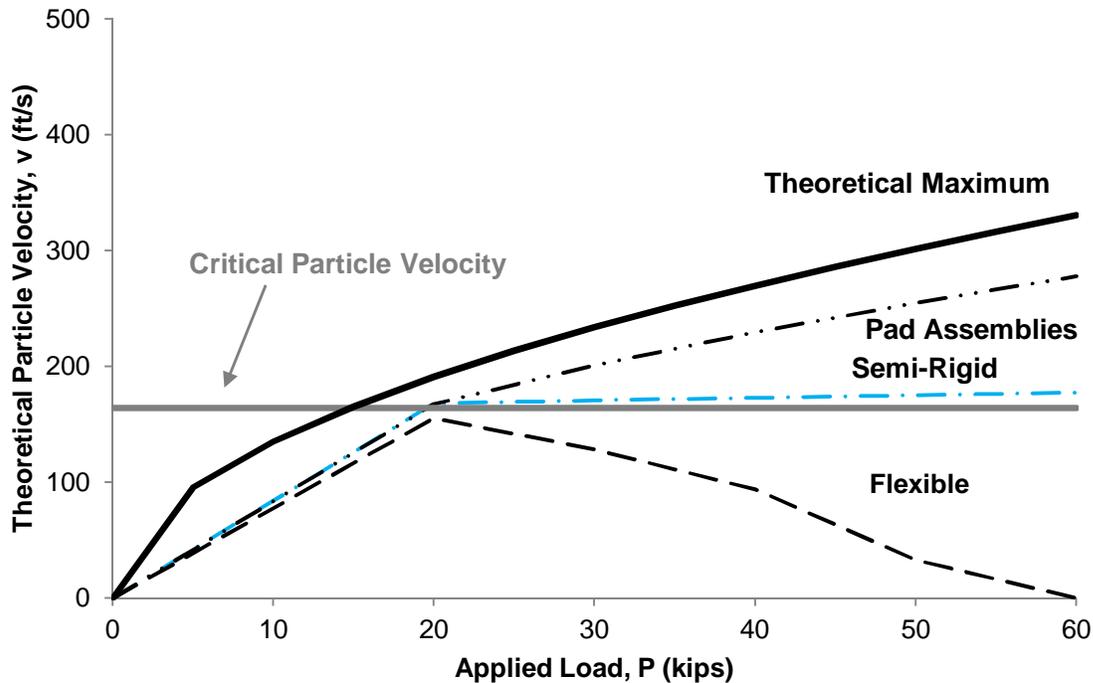


Figure 2: Theoretical Particle Velocity, Scaled as 72% of the Flow Velocity, versus Applied Load

The estimates shown in Figure 2 suggest that hydro-abrasive erosion is a feasible RSD mechanism. It is difficult to predict how much this mechanism might contribute to RSD without conducting experiments that specifically measure the velocity of the particles and the resulting wear in a concrete sleeper rail seat. The estimates of particle velocity suggest that pads with less effective seals have a higher potential for causing hydro-abrasive erosion. To prevent hydro-abrasive erosion, a rail pad should maintain a tight seal both at rest (to minimize intrusion of moisture and fines) and under load (to minimize flow).

The measurements of surface water pressure and the estimates for maximum surface water velocity present conflicting design objectives for rail pads. A tight seal may generate damaging pressure if water seeps under the pad; conversely, an ineffective seal may allow additional intrusion of moisture and fines, as well as damaging flow under load. Further research is needed to understand whether hydraulic pressure cracking or hydro-abrasive erosion and abrasion should dictate the design of the rail pad seal, considering both the loaded and unloaded seal. Moving forward, the approach will be to investigate the parameters that affect abrasion and estimate the frequency with which those conditions occur in track service. Then, the frequency of conditions that lead to abrasion will be compared to the frequency of conditions that lead to the occurrence of other mechanisms. Methods of mitigating the most critical mechanism (the one that has the highest probability of occurring on North American freight corridors) should govern concrete sleeper rail seat and fastening system design. Alternatively, multiple sleeper designs could be manufactured that are specific to the mitigation requirements for various internal and external RSD factors.

FUTURE INVESTGATION OF ABRASION MECHANSIM

Introduction to the Abrasion Mechanism

Abrasion is widely considered to be one of the viable mechanisms that lead to RSD, based on field observations and experimental evidence from existing wear and abrasion tests. RSD was originally called rail seat abrasion (RSA), likely due to the fact that the scrubbing action of the rail pad is visible

during loading cycles and seems to correlate to the rubbing action that has been used to characterize the abrasion mechanism. However, as a result of a better understanding of RSD mechanisms, AREMA recently updated its Manual for Railway Engineering to refer to the degradation of concrete at the rail seat as RSD, recognizing the multiple mechanisms that are capable of producing deterioration. The mechanics of abrasion must be analyzed in order to better understand its influence as an RSD mechanism.

As wheel loads are transferred from the rail to the underlying pad, and subsequently to the sleeper, shear forces act at the pad-seat interface. Slip occurs when the shear forces at the interface overcome the static friction between the pad and rail seat. Each time slip occurs, deformations occur at local contact asperities. If enough local deformation of the concrete surface occurs, individual particles of mortar paste or aggregate can debond and become free from the rail seat. Initially, small particles are worn away, resulting in a surface that appears polished or burnished [13]. Over time, enough particles can be degraded so that a noticeable depth of material is lost, yielding a rough, uneven rail seat.

Abrasion is related to the previously-investigated, moisture-driven mechanisms by its dependence on the seal of the rail pad. The frictional interface between the rail pad and the concrete sleeper rail seat surface is significantly altered by the presence of moisture and abrasive fines that can penetrate into the interface when an effective seal is not achieved. This surface, altered by the presence of an abrasive slurry (fines and moisture), can be a highly abrasive environment. Previous studies have shown that concrete surfaces experience significantly more abrasive wear when they are wet, possibly due to the weakening of mortar paste as it is exposed to moisture [7, 14, 15]. Similarly, the presence of fine materials in standard abrasion resistance tests has accelerated the rate of abrasion. In general, fine particles that are introduced to a frictional interface equate to greater volumes of wear at that interface [16]. According to the American Concrete Institute (ACI) Repair Manual, concrete will only be abraded if the abrading material is harder than the concrete [17]. Considering most rail pad materials are not harder than concrete, abrasive fines from locomotive sand, ground ballast material, coal dust, rail grinding, etc. can be expected to play a major role in abrasion at the rail seat.

Types of Motion Leading to Abrasion

Principles from tribology, an interdisciplinary field aimed at studying interacting surfaces in relative motion, can be applied to the investigation of how and why abrasion occurs at the rail seat. From tribology, the amount of abrasive wear on a surface is proportional to the normal force between the two surfaces and the amount of movement [18]. Additionally, the relative hardness of the interacting materials is important to the rate of wear [18]. These principles will be used in designing the test to understand and evaluate abrasion.

Through experimental testing and field observation, two types of motion have been observed at the pad-seat interface. First, compression of the pad due to axial loading leads to radial expansion of the pad, known as Poisson's effect. This motion at the local contact asperities may be enough to cause wear of the concrete surface, possibly explaining RSD on tangent track where lateral loads are lower. Second, translational motion occurs along the pad-seat interface due to lateral (perpendicular to train motion) and longitudinal (parallel to train motion) loads. High lateral to vertical (L/V) load ratios, such as those experienced on sharp curves, can result in forces that will cause the pad to translate laterally. Alternatively, movement can occur in the longitudinal direction due to the rolling motion of the rail as multiple wheels pass over the sleeper. Because translational motion has the potential for larger displacements, this type of motion will be replicated in the laboratory test.

Experimental Testing of Abrasion

The study of abrasion requires observation of wear after many loading cycles so that the amount of actual deterioration and the rate at which wear occurs can be assessed. Development of a novel laboratory test is underway at UIUC to produce measurable abrasive wear of mock rail seat surfaces. This test will allow for the isolation of parameters that are believed to affect the abrasion mechanism and will facilitate the acquisition of quantitative and qualitative data for each parameter.

The proposed method for executing this test is to use a horizontally mounted actuator to produce displacements of a pad relative to a concrete specimen while a static normal force is applied with a vertically mounted actuator. Replicating the lateral movement at the rail seat during severe track conditions (e.g. loss of toe load) will allow the analysis and study of the abrasion resistance of rail seat surfaces under variable conditions. The test will be more representative of RSD than the current ASTM Standard Tests for abrasion resistance (ASTM C779 and ASTM C627). Also, this setup will allow for variable lateral displacements and adjustable vertical load that will simulate the testing of different L/V ratios. Test parameters will include the normal load, the amount of horizontal displacement of the abrading surface relative to the specimen, the type and amount of abrasive fines, and the moisture condition of the concrete specimen. By testing these parameters, insight into the criticality of abrasion as a RSD failure mechanism will be gained.

Expected Outcomes and Future Research

The rate of abrasive wear is expected to increase as the load and amount of displacement increase. The amount of displacement is expected to be most critical in accelerating abrasion. The presence of surface water is expected to facilitate wear of the concrete specimen; however, little is known about the amount of surface moisture or concrete saturation that is critical for accelerated wear. Unless an additional abrading material (e.g. abrasive particles) is introduced into the test, measurable wear is expected to be limited. After analyzing and understanding the relationships between these variables and the abrasion mechanism, the most critical abrasive conditions will be replicated in order to test various mock concrete sleeper surfaces. In an effort to find solutions for mitigating abrasion of the rail seat, a variety of concrete mix designs, surface coatings, exposed aggregate surfaces, etc. will be tested in the critically abrasive environment.

CONCLUSION

Based on the results of the previous laboratory experiments and the damage limits defined by the effective stress model, hydraulic pressure cracking appears to have the potential to initiate or contribute to RSD as a concrete deterioration mechanism. It appears that the most effective way to prevent hydraulic pressure is to use pads or pad assembly bottoms that do not seal water. The soft foam pads with a rigid metal layer and the hard plastic bottoms developed little surface pressure at the rail seat, with the hard plastic being slightly more effective at minimizing pressure. When thermoplastic pads are in contact with the concrete rail seat, it appears that designing the pad with direct escape channels for the water effectively ejects the surface water upon load application rather than pressurizing it. Thermoplastic pads without escape channels created the highest surface pressures, apparently sealing the water during load application. It seems advisable and relatively simple to incorporate these considerations into future pad and pad assembly designs; however, these design considerations for hydraulic pressure must be balanced with the possibility that allowing water and fines to flow in and out might increase wear due to hydro-abrasive erosion and abrasion.

The potential for hydro-abrasive erosion to damage concrete seems feasible, but more research is needed to understand how important this mechanism is before design recommendations can be made. Like hydro-abrasive erosion, abrasion appears to be a feasible mechanism of RSD. More information is required to understand how abrasive wear initiates and accelerates due to various causes and factors related to track and train conditions. Based on the experience and the opinions of many experts in the industry, abrasion has been selected as the next mechanism for investigation in this study. A laboratory experiment is being developed that will evaluate the parameters that affect the amount and the rate of abrasion of the concrete at the rail seat. By identifying the factors that contribute to RSD, this research will seek to mitigate the effects of abrasion, with an overall goal of improving the performance and service life of concrete sleepers.

ACKNOWLEDGEMENTS

This project is sponsored by a grant from the Association of American Railroads (AAR) Technology Scanning Program. The authors would like to thank David Davis and Richard Reiff of TTCL;

Ernie Barenberg, Grzegorz Banas, and Tim Prunkard of UIUC; Bill Riehl of RailAmerica Inc.; Dwain Jackson of Transducers Direct; the AAR Technology Scanning Committee; and the members of AREMA Committee 30 – Ties and Subcommittee 4 – Concrete Tie Technology for their invaluable contributions to this research. The authors would also like to acknowledge Mauricio Gutierrez-Romero, Mark Dingler, Kevin Kilroy, Hammad Khalil, Charles Gross, Samantha Chadwick, David Marks, and Joseph Rudd from UIUC and Edgardo Santana-Santiago of the University of Puerto Rico at Mayaguez for their work on this project. John C. Zeman has been supported in part by a CN Research Fellowship in Railroad Engineering. J. Riley Edwards has been supported in part by grants to the UIUC Railroad Engineering Program from CN, CSX, Hanson Professional Services, Norfolk Southern, and the George Krambles Transportation Scholarship Fund.

REFERENCES

- [1] Reiff, R., 1995, "An Evaluation of Remediation Technologies for Concrete Tie Rail Seat Abrasion in the FAST Environment," American Railway Engineering Association Bulletin, v 96, bulletin 753, Washington, DC, pp. 406-418.
- [2] Zeman, J.C., J.R. Edwards, D.A. Lange, C.P.L. Barkan, "Investigating the Role of Moisture in Concrete Tie Rail Seat Deterioration," AREMA Conference Proceedings 2009, American Railway Engineering and Maintenance-of-way Association (AREMA), Landover, Maryland, September 2009.
- [3] Zeman, J.C., J.R. Edwards, D.A. Lange, C.P.L. Barkan, "Investigation of Potential Concrete Tie Rail Seat Deterioration Mechanisms: Cavitation Erosion and Hydraulic Pressure Cracking," Proceedings of the Transportation Research Board 89th Annual Meeting, Washington, DC, January 2010.
- [4] Zeman, J.C., J.R. Edwards, D.A. Lange, C.P.L. Barkan, "Failure Mode and Effect Analysis of Concrete Ties in North America," Proc. of the 9th International Heavy Haul Conference, Shanghai, China, June 2009.
- [5] Bakharev, T., Chapters 1, 2, 3, 5, 6, and 7, Microstructural Features of Railseat Deterioration in Concrete Railroad Ties, M.S. Thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois, 1994, pp. 1-28 and 68-97.
- [6] Choros, J., B. Marquis, M. Coltman, "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, Spring Technical Conference 2007, pp. 173-181.
- [7] Zeman, J.C., Hydraulic Mechanisms of Concrete-Tie Rail Seat Deterioration, M.S. Thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois. 2010.
- [8] Zeman, J.C., J.R. Edwards, C.P.L. Barkan, D.A. Lange, 2010b, "Evaluating the Potential for Damaging Hydraulic Pressure in the Concrete Tie Rail Seat," Proceedings of the 2010 Joint Rail Conference, Urbana, Illinois, April 2010.
- [9] Zeman, J.C., J.R. Edwards, D.A. Lange, C.P.L. Barkan, "Sealing Characteristics of Tie Pads on Concrete Crossties," AREMA Conference Proceedings 2010, American Railway Engineering and Maintenance-of-way Association (AREMA), Landover, Maryland, August 2010.
- [10] Zeman, J.C., J.R. Edwards, C.P.L. Barkan, D.A. Lange, "Laboratory Testing to Address the Potential for Damaging Hydraulic Pressure in the Concrete Tie Rail Seat," Proceedings of the Transportation Research Board 90th Annual Meeting, Washington, DC, January 2011.
- [11] Hu, X.G., A.W. Momber, Y.G. Yin, 2002, "Hydro-Abrasive Erosion of Steel-Fibre Reinforced Hydraulic Concrete," *Wear*, v 253, pp. 848-854.
- [12] Goretta, K.C., M.L. Burdt, M.M. Cuber, L.A. Perry, D. Singh, A.S. Wagh, J.L. Routbort, W.J. Weber, 1999, "Solid-Particle Erosion of Portland Cement and Concrete," *Wear*, v 224, pp. 106-112.
- [13] Johns, T., 2010, email correspondence, Tim Johns was the Manager of Rail Products for Exova Canada, Inc. when this research was conducted, 17 November.
- [14] Fwa, T.F. and Low, E.W., "Laboratory Evaluation of Wet and Dry Abrasion Resistance of Cement Mortar," *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 12, No. 2, Winter 1990, pp. 101-106.
- [15] Sonebi, M. and Khayat, K.H., "Testing Abrasion Resistance of High Strength Concrete," *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 23, No. 1, June 2001, pp. 34-43.

- [16] Godet, M., "The Third-Body Approach: A Mechanical View of Wear," *Wear*, v 100, n 1-3, December 1984, pp. 437-452.
- [17] The Concrete Society, "Diagnosis of Deterioration in Concrete Structures," Concrete Society Technical Report No. 54, Section 3.4.6, 2000.
- [18] Halling, J., 1978, *Principles of Tribology*, Macmillan Education, LTD, Houndsmills, Great Britain, pp. 7-8 and 96-103.