

# **Investigation of the Dynamic Frictional Properties of a Concrete Crosstie Rail Seat and Pad and its Effect on Rail Seat Deterioration (RSD)**

*Transportation Research Board 91<sup>st</sup> Annual Meeting*

Submitted: November 15, 2011



Ryan G. Kernes<sup>1</sup>, J. Riley Edwards, Marcus S. Dersch, 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  
Phone: (217) 244-6063  
Fax: (217) 333-1924*

5200 Words, 1 Table, 4 Figures = 6450 Total Word Count

|                             |                       |                       |                     |                         |
|-----------------------------|-----------------------|-----------------------|---------------------|-------------------------|
| Ryan G. Kernes <sup>1</sup> | J. Riley Edwards      | Marcus S. Dersch      | David A. Lange      | Christopher P.L. Barkan |
| (217) 244-6063              | (217) 244-7417        | (217) 333-6232        | (217) 333-4816      | (217) 244-6338          |
| rkernes2@illinois.edu       | jedward2@illinois.edu | mdersch2@illinois.edu | dlange@illinois.edu | cbarkan@illinois.edu    |

<sup>1</sup> Corresponding author

**ABSTRACT**

To meet the demands of increasing freight axle loads and cumulative gross tonnages, as well as high-speed passenger rail development in North America, the performance and service life of concrete railway crossties must be improved. According to a railway industry survey conducted by the University of Illinois at Urbana-Champaign (UIUC), rail seat deterioration (RSD) was identified as one of the primary factors limiting concrete crosstie service life. Abrasion is widely considered to be a viable mechanism leading to RSD; nonetheless, a lack of understanding of the complex interactions affecting the occurrence and rate of abrasion has resulted in a highly iterative design process for concrete crossties and fastening systems. When combined with abrasive fines and water that penetrate into the rail seat and pad interface, the frictional forces and relative movement of the concrete crosstie and fastening system equate to a seemingly ideal situation for the occurrence of abrasive wear. The purpose of this study is to characterize the effect of the dynamic frictional properties between the concrete crosstie rail seat and the bottom of the rail pad in order to better understand the mechanics of abrasion and the magnitude of abrasion as a failure mechanism. This paper includes an investigation of the tribological properties at the interface of the rail seat and pad. Additionally, preliminary results from an experimental evaluation of the frictional coefficient at the rail seat-pad interface are included. By identifying the parameters that contribute to RSD, UIUC's research will seek to mitigate the effects of abrasion with an overall goal of improving the performance of concrete crossties and fastening systems.

## INTRODUCTION

Rail seat deterioration (RSD) is the term used to describe the degradation of material directly beneath the rail pad on the bearing surface of concrete crossties (1). The loss of material at the rail seat results in a stability failure when the fastening system's clamping force on the rail is reduced and track geometry problems such as gauge widening and loss of cant (inclination of rail seat surface) occur (1). These types of track defects increase the derailment risk by altering the ratio of lateral to vertical forces that the wheel imparts into the rail and consequently reducing the stability of the rail. As a result of the problems associated with RSD, the service life of many concrete crossties in service on demanding heavy-axle load railway lines has been reduced.

In order to avoid the premature replacement of concrete crossties well before the intended design life has expired, Class I railways are forced to include rail seat repairs in their capital maintenance plans to prevent track geometry problems. First identified in the 1980's, RSD continues to be a notable problem on North American freight railways as railcar axle loads and rail life cycles increase (1). The labor costs associated with rail seat maintenance is expensive because RSD is difficult to accurately detect and impossible to repair without lifting the rail and removing the pad. If the durability of the materials that compose the rail seat is not sufficient to last as long as rail steel, then interim repairs of the rail seat may be necessary. Thus, increasing the performance and durability of the rail seat materials for concrete crossties is of paramount importance to meet the future requirements of increasing freight tonnages and high-speed rail development (2).

Previous and current research at the University of Illinois at Urbana-Champaign (UIUC) focused on an investigation of the complex physical processes, or mechanisms, that contribute to RSD. As a result of this work, five mechanisms have been identified that have the potential to deteriorate the materials at the rail seat. The RSD mechanisms include abrasion, crushing, freeze-thaw cracking, hydraulic-pressure cracking, and hydro-abrasive erosion (2, 3, 4, 5).

Based on previous research and expert opinion in the North American railway industry, abrasion was selected as the focus of the current detailed investigation. Abrasion is defined as the wear of 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. Though abrasion is widely considered to be a viable mechanism that leads to RSD, a lack of understanding of the complex interaction of parameters that affect abrasion has resulted in a highly iterative process of concrete crosstie and fastening system design. When combined with abrasive fines and water that penetrate into the rail seat and pad interface (seat-pad interface), the frictional forces and relative movement of the concrete crosstie and fastening system equate to an ideal situation for the occurrence of abrasive wear. The mechanics of abrasion must be analyzed in order to better understand its influence as an RSD mechanism (2).

## MECHANICS OF ABRASION AT THE RAIL SEAT

As wheel loads are transferred from the rail to the underlying pad and from the pad to the crosstie, shear forces act at the seat-pad interface (2). Slip occurs when the shear forces at the interface overcome the static frictional force between the bottom of the pad and rail seat (2). Each time slip occurs, strain is imparted into the concrete system. Over time, this strain exceeds the fatigue limit of the concrete material and a brittle failure occurs, dislodging individual particles of mortar paste (2). Initially, microscopic particles are worn away, resulting in a surface that appears polished or burnished (*T. Johns, unpublished*). After many loading cycles, enough particles can be degraded so that a noticeable depth of material is lost, yielding a rough, uneven rail seat surface.

### Parameters Affecting Abrasion Mechanism

Based on the current understanding of the mechanics of abrasion, the primary causes that drive the process are high stresses (i.e. contact pressures), and the motion that occurs between the pad

and the rail seat. The primary factors influencing those causes, and the subsequent rate of abrasion, appear to be the contact properties of the materials at the seat-pad interface. Principles from tribology, an interdisciplinary field aimed at studying interacting surfaces in relative motion, can be applied to the investigation of abrasion in order to more effectively characterize the critical parameters. Based on a literature review of tribology, we suspect that the amount of abrasive wear a surface undergoes is proportional to the normal force between the two surfaces and the amount of movement (7). Additionally, the relative hardness of the interacting materials also affects the rate of wear (7). Based on an extensive literature review, the contact pressure, types of motion specific to the seat-pad interface, and contact properties of materials at the interface present a set of unique engineering challenges that are not fully understood.

### **Contact Properties of Materials at the Rail Seat Interface**

Recognizing the materials that are present at the seat-pad interface and analyzing the behavior of all materials interacting at the interface is critical to understanding the abrasion process. For most concrete crossties in North America, the rail seat is initially composed of concrete mortar paste, fine aggregates, and air voids. The concrete mortar paste surface is composed of a matrix of cement grains that bond to one another as the cement is hydrated (8). As RSD initiates and the cement paste is worn away, coarse and fine aggregate is exposed at the rail seat surface.

Regardless of the cement paste to aggregate ratio at the rail seat, the concrete provides a brittle bearing surface that exhibits a limited amount of elastic behavior. As a result, the surface roughness and hardness are of primary importance to the outcome of the abrasion mechanism. The surface roughness refers to the variability of the profile of the rail seat surface. Alternatively, the surface hardness is the ability of concrete to resist local plastic deformations. For concrete, the roughness and hardness of the surface depend on the quality of the constituents used in concrete crosstie manufacture, the manufacturing methods or processes employed, and nearly every mechanical property of the hardened concrete (4, 9).

Surface coatings of epoxies and urethanes are currently used to restore the rail seat surface in maintenance applications after rail seat surface material is deteriorated. Furthermore, at least one North American railway company is applying a surface coating to new concrete crossties as part of the crosstie manufacturing process in order to increase the durability of the rail seat. Fundamentally, epoxy and urethane materials are expected to exhibit behavior that is different than concrete in the rail seat environment, and these alternative materials are included in our investigation of the abrasion mechanism.

Initially, the rail seat surface is in direct contact with the rail pad. With a goal of attenuating and transferring wheel loads from the rail to the concrete crosstie, a large variety of materials have been used to construct rail pads for North American railway applications. Rubber, santoprene, ethyl vinyl acetate (EVA), polyurethane, reinforced nylons, and many other material combinations have been coupled with various pad geometries in an attempt to protect the rail seat while transferring loads (5).

With respect to the abrasion mechanism, the most important property of the materials that compose the rail pad is the Poisson's Ratio of the pad, or the ratio of lateral strain behavior to vertical strain behavior. The Poisson's Ratio of rail pads is a material property that is correlated to the ability of the pad material to resist internal shear forces under axial compression. The lateral strain forces overcome static frictional forces at the rail seat interface causing slip, or localized movement. A pad with higher internal resistance to shear forces — a lower Poisson's Ratio — exhibits less movement at the contact interface. In addition to Poisson's ratio, pad hardness appears to be an important property in relation to the abrasion mechanism. Pad hardness refers to the local plastic deformation of the materials that make up the pad. Plastic deformation of the pad at local contact asperities can potentially change the pressure distribution at the rail seat, resulting in more damaging pressures (10).

In conjunction with the Poisson's ratio of the pad material, the geometry, loading distribution, and confinement of the pad affect the lateral elasticity, or deflection of the pad perpendicular to the normal load. Although the vertical elasticity, typically referred to as elasticity, of the pad is important for track stiffness and damping, the lateral elasticity of the pad is expected to be a more critical metric in analyzing abrasive behavior of pads on rail seat surfaces. Lateral elasticity directly relates to the amount of shear strain that occurs at the rail seat. A laboratory test to monitor the global lateral elasticity of the pad when measuring the vertical elasticity under compressive loading could be useful in understanding pad behavior and may lead to more prescriptive designs for rail pads in abrasive environments. Furthermore, mathematical models could be used to predict the lateral elasticity of the pad and the shear strain that is transferred to the rail seat for various rail pad designs. Careful consideration of the lateral stiffness should be applied to pad design because of its probable influence on the abrasion mechanism.

While the rail pad plays a critical role in movement at the rail seat, external materials that enter into the seat-pad interface also affect the contact properties. The frictional interface between the rail pad and the 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 by the pad. A perfect seal of the pad, which would eliminate the presence of moisture and fines at the interface, seems unachievable because of the natural porosity of concrete materials and the movement allowed by elastic fastening systems.

Previous studies have shown that concrete surfaces experience significantly more abrasive wear when moisture is present at the contact surface, possibly due to the weakening of mortar paste as it is exposed to moisture (5, 11, 12). Similarly, the presence of fine materials in standard abrasion resistance tests has been shown to accelerate the rate of abrasion (13, 14). In general, fine particles that are introduced to a frictional interface equate to greater volumes of wear at that interface (15). According to the American Concrete Institute (ACI) Repair Manual, concrete will be abraded only if the abrading material is harder than the concrete (16). 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. As a point of reference, silica particles that make up sand are harder than the hardest pad materials, the concrete rail seat, and premium rail steel (17).

### **Dynamic Frictional Properties at the Rail Seat**

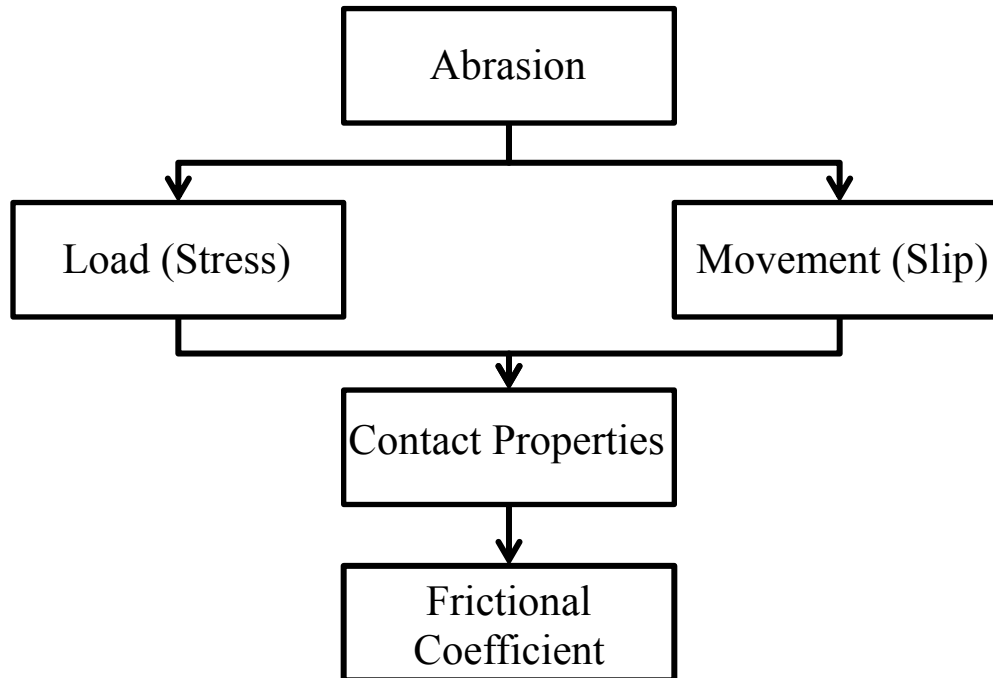
The frictional properties of the seat-pad interface are critical to abrasion because frictional forces resist local movements of the pad. Slip, or relative movement between two surfaces, is opposed by contact friction between the bottom of the pad and the rail seat surface. Additionally, the relative motion of the rail seat and rail pad depends on the frictional forces at the bottom of the rail base and the top of the pad. Determining the optimal contact frictional properties at each interface — at both the top and bottom of the pad, and between the layers of multi-layer pads — to reduce movement and delay the onset of abrasive wear could effectively increase the service life of concrete cross-ties.

One important frictional property at the interface is the static coefficient of friction. As illustrated by the equation below, the magnitude of frictional forces is directly related to the normal force between the two bodies by the coefficient of friction.

$$\text{Frictional Force} = \mu N$$

In this equation,  $N$  stands for the normal force and  $\mu$  represents the frictional coefficient. The static coefficient of friction is the ratio of the force perpendicular to contact required to accelerate a body from rest to the normal force between the two forces.

The frictional coefficient at the rail seat appears to be dynamic for two reasons. First, the frequency of wheel loads is a function of axle spacing and train speed, resulting in repeated loading cycles that are variable. Secondly, the elasticity in the system, facilitated by the flexure of the rail, elastic fastening system, and ballast support conditions, allows the pad to accelerate (move) and then return to its original position. A dynamic friction loop is expected to occur where static friction will give way to kinetic friction and return to static friction under each loading cycle. Moreover, the infiltration of moisture and abrasive fines can alter the frictional coefficient, increasing the variability of the contact properties at the seat-pad interface. Figure 1 shows the predicted relationship between the frictional coefficient and the abrasion mechanism.



**FIGURE 1 Influence Diagram Relating Frictional Coefficient to the Abrasion Mechanism**

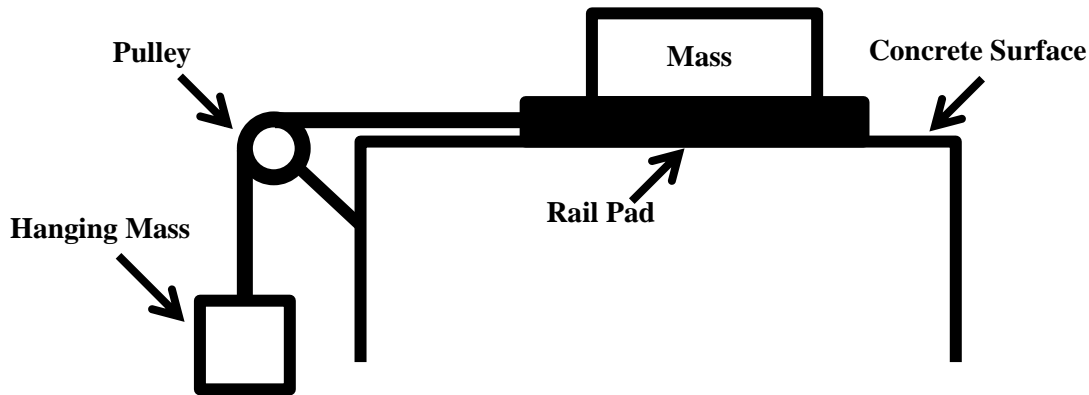
#### **EXPERIMENTAL METHODS OF INVESTIGATING THE ABRASION MECHANISM**

Developing experimental methods for gathering quantifiable data is critical to learning more about the mechanics of abrasion due to the complex interactions contributing to RSD and difficulties in gathering field data. Beyond the abrasion resistance test setup and procedure that is described below, a simplified laboratory study was performed at UIUC to learn about the contact properties of the materials at the seat-pad interface. Additionally, the results from this experiment will be compared to results from future, more representative studies of the dynamic frictional properties at the rail seat.

#### **Estimating the Static Frictional Coefficient of Rail Pads on a Concrete Surface**

The static coefficient of friction between a rail pad and a concrete surface was estimated with a fundamental laboratory experiment at UIUC. A pad was loaded with a known mass and placed on a relatively smooth concrete surface. A lateral force was applied to the pad by tying one end of string to the pad and the other end to a hanging mass. By mounting a pulley to the edge of the elevated concrete surface, the direction of the load provided by the hanging mass was transferred

so that gravity could be used to provide the lateral load on the pad. Figure 2 shows a schematic diagram of the fundamental frictional coefficient test setup.



**FIGURE 2 Test Setup to Estimate Static Frictional Coefficients of Rail Pads on a Concrete Surface**

Three different rail pads were tested with four different contact surface conditions. The first pad was a two-part polyurethane assembly with a flat bottom. In contrast, the second and third polyurethane pads had studded and dimpled geometry, respectively. Sand and water were applied to the interface to modify the surface conditions resulting in four cases: dry, dry plus sand, wet, and wet plus sand. Weight was added to the hanging mass until the pad moved. The weight of the hanging mass required to move the pad was divided by the weight of the loaded pad (normal force), resulting in the experimental static coefficient of friction. For each pad geometry and surface condition combination, three repetitions were conducted, and the average frictional coefficient was calculated. The results from this investigation are shown in Table 1 below.

**TABLE 1 Average Experimental Static Frictional Coefficients of Rail Pads on a Concrete Surface**

| Average Experimental Static Frictional Coefficient |                   |            |      |            |
|--|-------------------|------------|------|------------|
| Geometry of Pad Bottom                             | Surface Condition |            |      |            |
|  | Dry               | Dry + Sand | Wet  | Wet + Sand |
| Flat   | 0.83              | 0.46       | 0.64 | 0.45       |
| Studded  | 0.77              | 0.50       | 0.66 | 0.42       |
| Dimpled  | 0.65              | 0.47       | 0.63 | 0.54       |

The introduction of sand and water to the interface between the pad and the concrete surface decreased the average static frictional coefficient for each trial, regardless of the pad geometry. Sand at the interface reduced the static frictional coefficient by an average of 36%, while water reduced the frictional coefficient by 14%, as compared to the dry surface condition. The static frictional coefficient of the pad with a flat bottom was reduced at a greater rate than the pads manufactured with various geometries. Although the fact that the frictional coefficient can be reduced by over 30% due to the infiltration of water and sand is interesting, this experimental test setup is not representative of the movement and contact pressure of rail seats in service on North American heavy-axle-load freight corridors.

The interesting results and limitations of this experimental test setup have inspired further testing regarding the frictional properties at the seat-pad interface. The relationship between the frictional coefficient and the rate of abrasive wear must be investigated so that the optimal frictional properties can be targeted in the design of concrete crossties and fastening systems to reduce to occurrence of abrasion at the rail seat.

### **Measuring the Abrasion Resistance of Concrete Surfaces**

Abrasion resistance is a term used to describe a material's ability to withstand frictional contact forces and relative movement that have the potential to produce wear. Previous studies have illustrated that the abrasion resistance of concrete materials depends on the quality of materials used, manufacturing/construction practices, and mechanical properties of the finished concrete (5, 9). Increasing the abrasion resistance of the rail seat should be strongly considered as a way of improving the durability and performance of concrete crossties (2).

A number of test methods have been used in North America to compare the relative abrasion resistance of rail seat materials. Previously, the tests have been specified by railways for quality control purposes and employed by crosstie manufactures for research and development purposes. The testing method that is utilized depends on the objectives for performing the test and can be typically divided into two categories; system tests and materials tests. Currently in North America, the American Railway Engineering and Maintenance-of-way Association (AREMA) Test 6: Wear/Abrasion is the recommended method of determining if a rail seat and fastening system have the ability to resist RSD and fastening system component wear under repeated loads (18). Unfortunately, the test is cost prohibitive for prototyping because a full-scale crosstie and fastening system is required for each new design or material improvement. Additionally, the test takes between 10 and 15 days to complete, resulting in very few data points for the funding expended.

Due to the time and cost of AREMA Test 6, several existing materials tests, standardized by the ASTM, were used in the concrete crosstie industry to evaluate the abrasion resistance of rail seats. However, these tests are not representative of the abrasion mechanism at the rail seat interface because they were designed to represent abrasion due to foot traffic, steel wheels, or studded tires on industrial slabs or pavements. Although some of the tests offer the ability to add an abrasive slurry of fine particles and water, the primary parameters of the tests (e.g. pressure, motion, contact properties, etc.) are fundamentally different from the abrasion mechanism that is observed at the rail seat. For example, the continuous motion of the ASTM tests result in rolling friction or kinetic friction that is expected to produce frictional coefficients that remain at relatively static levels throughout the tests.

### **New Laboratory Test Setup and Procedure for Evaluating Abrasion Resistance**

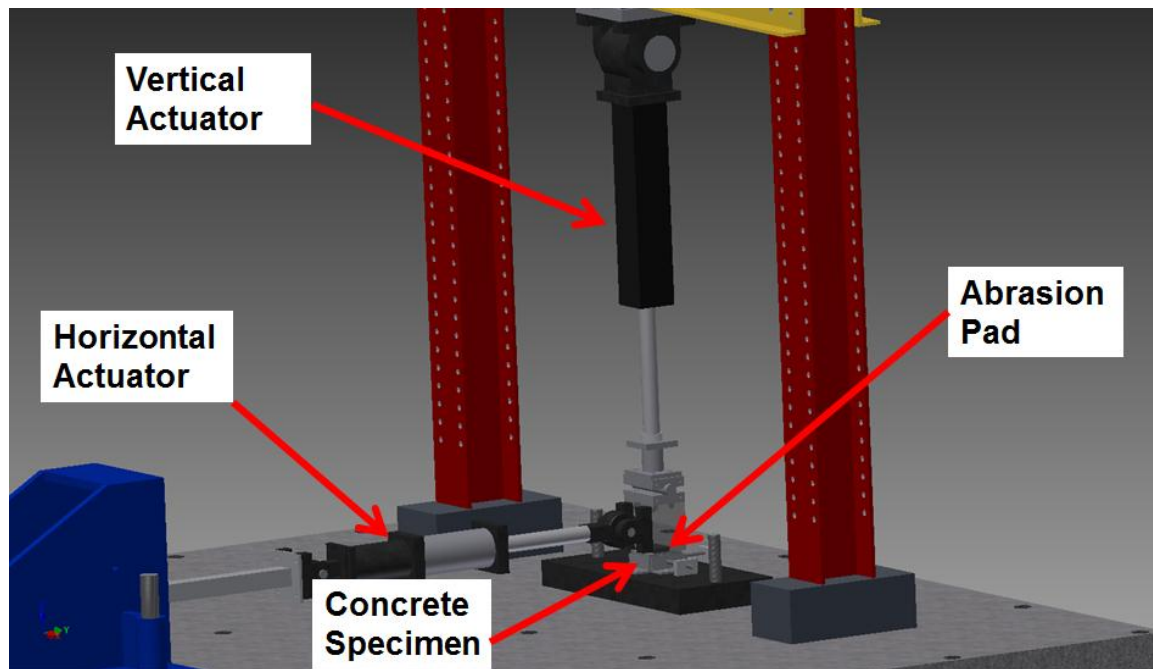
A large gap exists between the full-scale system test (AREMA Test 6) and standardized abrasion resistance tests that have been used to evaluate rail seat surfaces. A laboratory test that is more representative of the rail seat abrasion mechanism than the ASTM standard tests and is easier to execute than AREMA Test 6 will be beneficial to the railway industry.

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. A novel laboratory test and procedure has been developed at UIUC to produce measurable abrasive wear of mock rail seat surfaces. This test is designed to isolate the parameters that are believed to affect the abrasion mechanism and facilitate the acquisition of quantitative and qualitative data for each parameter.

The test utilizes 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. A servo-hydraulic actuator in displacement control provides the force needed to accelerate the pad perpendicular to the normal load and return the pad to its original position.



Simultaneously, an additional servo-hydraulic actuator in force control provides a static normal force on the pad so that representative contact pressures can be maintained. Both actuators are attached to a steel loading head that houses the abrasion pad in a recessed cavity. Mock rail seat specimens that are 6" x 6" x 3" deep are fixed to the floor via a steel base plate and adjustable angle (L-bracket) supports. The pad material is a 3" x 4" x 0.75" thick nylon 6/6 pad. These pads have similar material properties to those of pads that are currently utilized on North American heavy-axle-load freight railways (*S. Tripple, unpublished*). Water and abrasive fines can be added through a channel within the loading head that deposits the slurry (mixture of water and fines) at the edge of the interface between the pad and the specimen. A 3-dimensional (3D) model of the test setup is shown in Figure 3.



**FIGURE 3 Rail Seat Abrasion Resistance Test Setup**

Replicating the translational movement at the rail seat during demanding track conditions and loading scenarios (e.g. loss of clamping force, high lateral and longitudinal forces, etc.) permits the analysis and study of the abrasion resistance of rail seat surfaces under variable conditions. The desire for an accelerated test has resulted in a continuous test where the specimens experience no relaxation of the normal load. Because the concrete specimen is continuously loaded, the loading cycles in this abrasion resistance test should not be correlated to loading cycles on rail seats in the field. Field loading cycles are less damaging because the normal load is relaxed between wheel loads. Test parameters include the normal load (pressure), the amount of horizontal displacement of the abrading surface relative to the specimen, the presence of moisture on the surface of the concrete specimen, and the presence of abrasive fines. Response variables that will be measured include the depth of wear and volume of material lost. 3D imaging system that utilizes a laser to map the physical position of objects in space will be used to determine the amount and position of abrasive wear that occurred on the rail seat specimens during testing. The LVDT transducer housed in the vertical actuator will also provide information related to the depth of wear per test cycle, yielding a measurement for the rate of

abrasion. Additionally, this test setup and procedure will be used to monitor the dynamic frictional properties at the interface between the abrasion pad and the concrete specimen surface.

### **Experimental Frictional Coefficient Measurements**

The displacement and force are monitored in both the lateral and vertical direction for the duration of each abrasion resistance test. The ratio of lateral forces to vertical forces will facilitate the collection of data related to the dynamic frictional coefficient at the contact interface. Initially, the loading head will be accelerated in the lateral direction while the abrasion pad is not in contact with the concrete specimen. The lateral force required to complete a loading cycle — one full stroke and return to original position — will be measured at a rate of ten times the loading rate. This force is called internal friction,  $f_i$ . Next, the concrete specimen will be loaded to a known static load,  $P$ , and the lateral actuator will accelerate the abrasion pad cyclically in the lateral direction. The lateral force necessary to complete a loading cycle in this configuration is called contact friction,  $f_c$ . The equation used for calculating the coefficient of friction is as follows:

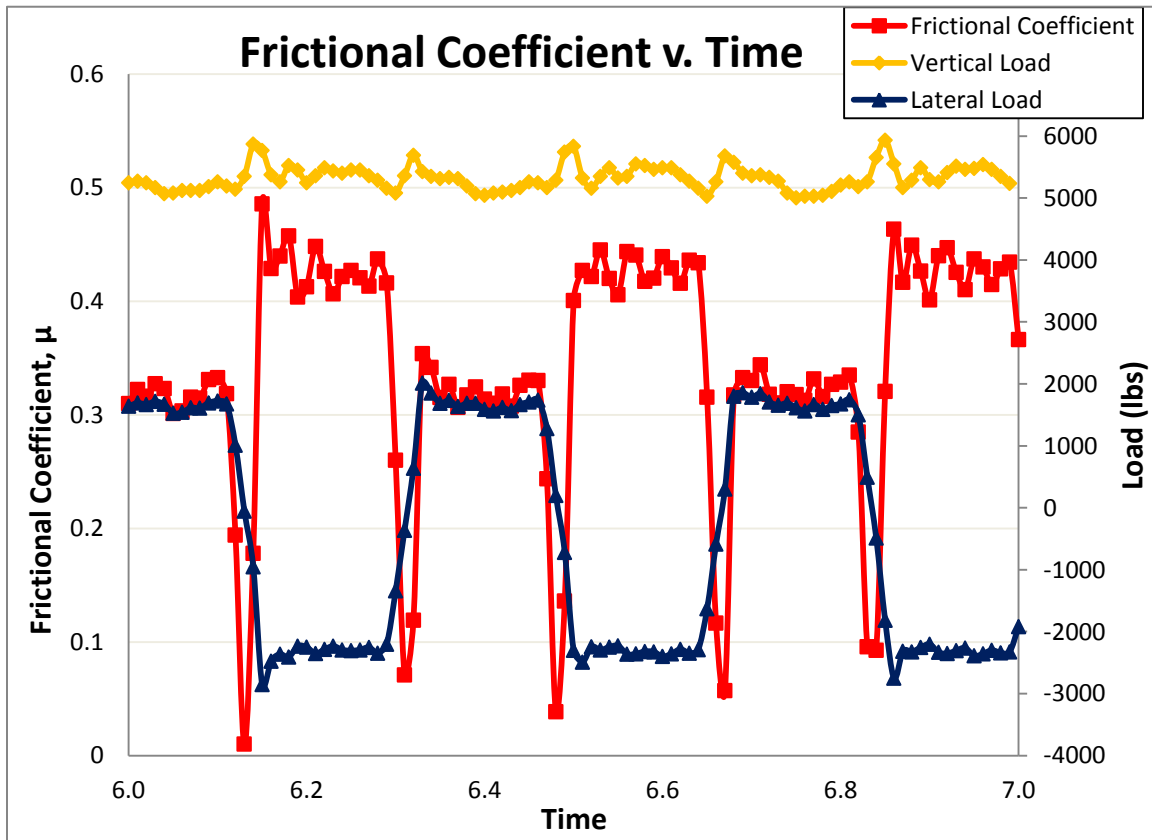
$$\mu = \frac{|f_c - f_i|}{P}$$

### **INITIAL RESULTS AND CONCLUSIONS**

Initial results gathered with a large-scale abrasion resistance test setup and procedure show that the lateral force required to accelerate the pad that is in contact with the concrete specimen changes as loading cycles occur. Based on initial tests with this experimental setup, the internal friction,  $f_i$ , is small relative to the contact friction, and should be neglected. Therefore, the equation for frictional coefficient will be revised as follows:

$$\mu = \frac{|f_c|}{P}$$

As predicted, the force required to accelerate the pad from rest (or to change the direction of motion) is greater than the force required maintain the translational motion. Figure 4 shows the frictional coefficient,  $\mu$ , versus time for three complete loading cycles of the rail seat abrasion resistance test setup. The lateral and vertical loads over the same time duration are also presented in Figure 4. This data was gathered during three loading cycles of an abrasion test that ran for 400 cycles at 3 Hertz (Hz) with a control concrete specimen in contact with a nylon 6/6 abrasion pad. The target normal load was 5 kips, and the total displacement of the pad was 1/8". Water and abrasive fines were not added to the contact interface for this preliminary test.



**FIGURE 4 Frictional Coefficient Over 3 Loading Cycles**

Figure 4 shows the reductions in the coefficient of friction while the pad slides relative to the concrete rail seat. During the three loading cycles displayed in the figure, the pad changes direction 6 times. The lateral force required to accelerate the pad is reduced when the pad begins sliding relative to the concrete specimen, resulting in the reduction of the frictional coefficient, illustrated by the overall negative slope of the frictional coefficient curve between each change in direction (where  $\mu$  goes to zero). Less force is required to retract the actuator, or return pad to its original position, than to extend the actuator. Subsequently, the coefficient of friction was consistently higher as the pad moved in the direction of the extending actuator.

A number of explanations are currently being investigated in order to determine the cause of the directionality of the lateral load required to accelerate the pad. First, the input sine function that was used to control the position of the horizontal actuator may have been offset from the physical midpoint of the test setup. If the midpoint of the path of the pad was not in line with the vertical actuator, then a component of the normal force may have opposed the extension of the horizontal actuator. Second, the concrete specimen, designed to have no inclination (parallel to the bearing plate that supports the specimen), may have been inclined due to abnormalities of the concrete bearing surface on the bottom of the specimen. The test setup and procedure are currently being refined in order to eliminate inconsistencies in the test and to reduce experimental variance.

Initial results also indicate that the maximum value for the coefficient of friction is reduced throughout the duration of a test. Overall, the maximum coefficient of friction for one loading cycle decreases over time during this test.

The properties of the materials (e.g. shear modulus, vertical stiffness, surface roughness, etc.) at the seat-pad interface likely have an impact on the magnitude of displacement of the pad relative to the rail seat. Based on initial results, severity of the displacement of the pad is proportional to the amount of abrasive wear of concrete rail seats. Understanding the basic relationships between material properties, the coefficient of friction, and the rate of abrasion will enable concrete crosstie and fastening system designers to optimize the component designs at contact interfaces.

Future work will include combining the abrasion resistance data with the experimental frictional coefficient characteristics to develop a mathematical model of the seat-pad contact interface, to aid designers in rail seat and fastening system design. The input parameters could include contact pressure, displacement, moisture condition, presence of fines, pad hardness, Poisson's ratio of the pad, concrete strength, curing condition, rail seat roughness, etc. Potential outputs include abrasion resistance, abrasion rate, frictional coefficient characteristics, and the ratio of the frictional coefficient to the rate of abrasion. This model, which will be calibrated with the abrasion resistance test setup, potentially can be verified with data that is accumulated in the field based on a parallel project at UIUC that includes plans for a substantial amount of track instrumentation. With optimal track instrumentation, we may be able effectively gauge how accurately the abrasion resistance test setup and procedure at UIUC represents the abrasion mechanism that occurs in the field. Additionally, we would have a field verified model for contact at the seat-pad interface. An accurate model of the seat-pad interface would allow for the collection of significantly more data and could provide tremendous opportunities for technological advances in concrete crosstie and rail pad design that would result in longer life cycles and/or lower life cycle costs.

The contact pressure, movement, and material properties at the seat-pad interface are expected to be critical to the abrasion mechanism. These parameters are being investigated in parallel with the abrasion resistance testing so that correlations can be made between dynamic frictional properties and the abrasion mechanism. Analysis of these experimental data will advance the understanding of the abrasion mechanism of RSD. By identifying the factors that contribute to RSD, this research will seek to mitigate the effects of multiple RSD mechanisms, with an overall objective of improving the performance and service life of concrete crossties and fastening systems.

## **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 project. Additionally, the authors would like to thank Amsted Rail Inc. and Unit Rail Inc. for providing direction, advice, and experimental testing resources; special thanks to Dave Bowman (Amsted Rail Consultant), Jose Mediavilla (Unit Rail), and Brent Wilson (Amsted Rail). We appreciate the resources provided by BNSF Railway (Tom Brueske), Encore Rail Systems (Fabian Webber), and Pandrol USA (Bob Coats and Scott Tripple). Additionally, many thanks to members of AREMA Committee 30, including John Bosshart, Winfried Bosterling, Tom Brueske, John Clark, Pelle Duong, Tim Johns, Steve Mattson, Thai Nguyen, Jim Parsley, Michael Steidl, and John Zeman. Also we would like to thank Dave Davis and Richard Reiff from TTCL. This work would not have been possible without contributions from Tim Prunkard, Darold Marrow, Don Marrow, Mauricio Gutierrez, Greg Munden, Josh Brickman, Kris Gustafson, Steven Jastrzebski, Andrew Kimmle, Calvin Nutt, Ryan Feeney, Emily Van Dam, and Michael Wnek, all of UIUC.

**REFERENCES**

- 1) Zeman, J.C., J.R. Edwards, D.A. Lange, C.P.L. Barkan, 2010, "Sealing Characteristics of Tie Pads on Concrete Crossties," AREMA Conference Proceedings 2010, American Railway Engineering and Maintenance-of-way Association (AREMA), Landover, Maryland, August.
- 2) Kernes R. G., J.R. Edwards, M.S. Dersch, D.A. Lange, C.P.L. Barkan, 2011, "Investigation of the Impact of Abrasion as a Concrete Crosstie Rail Seat Deterioration (RSD) Mechanism," AREMA Conference Proceedings 2011, American Railway Engineering and Maintenance-of-way Association (AREMA), Landover, Maryland, September.
- 3) Bakharev, T., 1994, 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, pp. 1-28 and 68-97.
- 4) Choros, J., B. Marquis, M. Coltman, 2007, "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, pp. 173-181.
- 5) Zeman, J.C., 2010, Chapters 1, 2, 3, and 6, Hydraulic Mechanisms of Concrete-Tie Rail Seat Deterioration, M.S. Thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois.
- 6) Zeman, J.C., J.R. Edwards, D.A. Lange, C.P.L. Barkan, 2010, "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.
- 7) Halling, J., 1978, *Principles of Tribology*, Macmillan Education, LTD, Houndsmills, Great Britain, pp. 7-8 and 96-103.
- 8) Mindess, S., J.F. Young, D. Darwin, 2003, *Concrete*, 2<sup>nd</sup> ed., Pearson Education Inc., Upper Saddle River, New Jersey, pp. 71.
- 9) Bakke, K. J., 2006, "Chapter 18: Abrasion Resistance." *Significance of Tests and Properties of Concrete and Concrete-Making Materials*. Ed. Lamond, J. F. Pielert, J. H. West Conshohocken, PA: ASTM International, pp. 184-193.
- 10) Gutierrez, M.J., J.R. Edwards, D.A. Lange, C.P.L. Barkan, 2011, "Design and Performance of Elastic Fastening System Assemblies and Measurement of Rail Seat Pressure Distribution for Concrete Sleepers for Heavy-Haul Service," Proceedings of the 9<sup>th</sup> World Congress on Railway Research, Lille, France, May.
- 11) Fwa, T.F. and E.W. Low, 1990, "Laboratory Evaluation of Wet and Dry Abrasion Resistance of Cement Mortar," *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 12, No. 2, Winter, pp. 101-106.
- 12) Sonebi, M. and K.H. Khayat, 2001, "Testing Abrasion Resistance of High Strength Concrete," *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 23, No. 1, June, pp. 34-43.
- 13) Atis, C. D., 2002, "High Volume Fly Ash Abrasion Resistant Concrete." *Journal of Materials in Civil Engineering*. 14.3 (2002):274-7.
- 14) Turk, K. and M. Karatas, 2011 "Abrasion Resistance and Mechanical Properties of Self-Compacting Concrete with Different Dosages of Fly ash/silica Fume." *Indian Journal of Engineering and Materials Sciences*. Vol 18, February, pp. 49-60.
- 15) Godet, M., 1984, "The Third-Body Approach: A Mechanical View of Wear," *Wear*, v 100, n 1-3, pp. 437-452.
- 16) The Concrete Society, 2000, "Diagnosis of Deterioration in Concrete Structures," Concrete Society Technical Report No. 54, Section 3.4.6.

- 17) Williams, J, 2005, *Engineering Tribology*. Cambridge University Press, New York, pp. 179
- 18) *AREMA Manual for Railway Engineering*, 2009, American Railway Engineering and Maintenance-of-Way Association (AREMA), Landover, Maryland, v 1, ch. 30.