Investigation of the Mechanics of Rail Seat Deterioration (RSD) and Methods to Improve the Abrasion Resistance of Concrete Sleeper Rail Seats

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Abstract

A sustained increase in gross rail loads and cumulative freight tonnages on heavy haul railways, as well as increased interest in high and higher-speed passenger rail development, is placing an increasing demand on railway infrastructure and its components. Rail seat deterioration (RSD) refers to the degradation of the material at the contact interface between the sleeper rail seat and the pad that protects the bearing area of the sleeper. RSD continues to be identified as one of the primary factors limiting concrete sleeper service life, particularly in heavy haul operations. This study's focus is to characterize the frictional forces that resist movement at the contact interface between the concrete rail seat and the bottom of the rail pad and determine the most effective methods of increasing the abrasion resistance of rail seat materials. This paper includes results from two laboratory experiments performed at UIUC using test setups and protocols that are designed to isolate the abrasion mechanism and facilitate the acquisition of quantitative and qualitative data related to the frictional properties of rail pad materials sliding on a concrete surface under various normal loads and the abrasion resistance of rail seat materials. Increasing the service life of railway track components will facilitate capacity building on heavy haul, mixed-traffic, and passenger railways around the world by reducing maintenance costs and decreasing the demand for maintenance windows.

1.0 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 stringent, and track occupancy time is at a premium. Improvements in concrete crosstie and fastening system designs also help address the need to reduce track maintenance windows, thereby gaining rail capacity. Before these advancements are realized, several design and performance challenges must be overcome, including Rail Seat Deterioration (RSD) and fastening system wear and fatigue.

RSD refers to the degradation of the concrete material at the contact interface between the crosstie rail seat and the rail pad [1]. RSD has been identified as one of the primary factors limiting concrete crosstie service life in North America, particularly in heavy haul freight infrastructure [2,3]. RSD can lead to problems such as loss of cant, gauge-widening, fastener system wear, and other track geometry deficiencies that create the potential for unstable rail conditions and/or derailments [4]. RSD is difficult to detect and impossible to repair without lifting the rail and removing the rail pad through a labor-intensive and costly repair process that results in track outages, traffic disruptions, and increased operating costs. One of the primary maintenance challenges facing the rail industry is the lack of compatibility between life cycles of infrastructure components. If the life cycle of the materials that compose the rail seat and fastening system is not sufficient to match the life cycle of the rail, interim repairs of the rail seat may be necessary.

2.0 Background

The University of Illinois at Urbana-Champaign (UIUC) has identified five possible mechanisms having the potential to contribute to RSD. These are abrasion, crushing, freeze-thaw cracking, hydraulic-pressure cracking, and hydro-abrasive erosion. Out of these mechanisms, hydraulic pressure cracking and hydro-abrasion were investigated at UIUC and found to be feasible mechanisms resulting in RSD [3,5,6]. 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 materials as two or more surfaces move relative to one another [6]. 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 pad slips relative to concrete 4) strain is imparted on concrete matrix, 5) the harder surface cuts or ploughs into the softer surface. The abrasive mechanism in RSD is further complicated and potentially accelerated due to the occurrence of three-body wear that results from the formation of an abrasive slurry made up of fines and water in addition to the two interacting surfaces (i.e. rail seat and rail pad) [7]. A lack of understanding of the complex interactions affecting the severity of abrasion has resulted in an iterative design process for concrete crossties and fastening systems.

In order to improve our understanding of the interactions leading to abrasion, two tests were designed and executed to understand and mitigate the abrasion mechanism in concrete sleeper rail seats. First, a Large-Scale Abrasion Test (LSAT) was developed to understand the mechanics of abrasion by characterizing the frictional forces that resist movement at the contact interface between the concrete rail seat and the bottom of the rail [8]. Next, a Small-Scale Abrasion Resistance Test (SSART) was designed to understand the effect of various concrete mix designs, curing conditions, and surface treatments on the abrasion resistance of the concrete rail seat. This test will enable us to propose methods to mitigate the abrasive mechanism of RSD.

3.0 Laboratory Test Results for Mechanics of Abrasion

3.1 Large-Scale Abrasion Test Setup

The LSAT is made up of a test frame and two servo-hydraulic actuators. 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 concrete rail seat specimens that are 152 millimeters (mm) x 152 mm x 76 mm (6” x “6” x 3”) deep are fixed to the floor via a steel base plate and adjustable angle supports. The pad materials are 76 mm x 102 mm x 19 mm (3” x 4” x 0.75”) thick blocks of generic nylon 6/6 and polyurethane, approximately a quarter of the area of a typical rail pad. Water can be added through a channel within the loading head and can be deposited at four edges of the pad through grooves in the top of the loading head cavity. Ottawa sand can be applied manually to the contact interface with a small measuring cup. A photograph of the test setup is shown below in **Figure 1**.

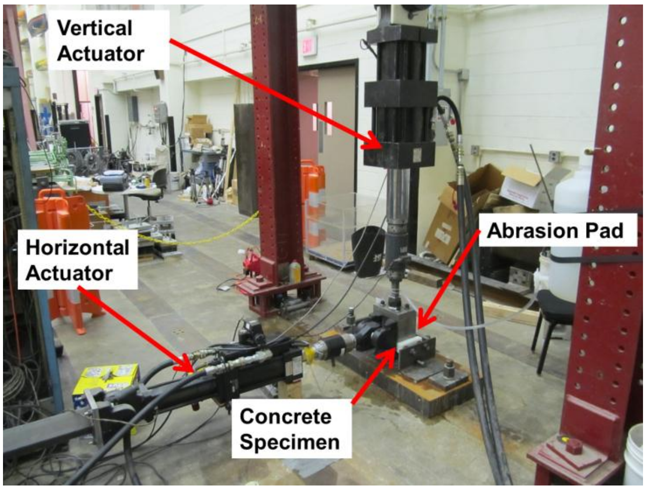


FIGURE 1: Large-Scale Test Setup

Initially, deterioration tests were performed to verify that measurable abrasion could be caused with the test setup and to understand which input parameters were most critical to the severity of abrasion. Significant abrasion of the concrete specimens was achieved under a variety of normal loads, displacements, load rates, and applications of sand and water. The deterioration tests lasted three hours and accumulated between 32,000 and 64,000 loading cycles.

Efforts to correlate input parameters such as magnitude of displacement and normal force with the severity of abrasion (wear depth) proved exceedingly difficult. Due to the rigidity in the loading head and position of the actuators, the perpendicular contact angle between the pad and the concrete surface was difficult to maintain. As a result, the pressure distribution was not uniform and variability existed from test to test. Furthermore, the heterogeneity of the concrete surface added to the variability because the wear depth appeared to depend on the random distribution of large and small aggregates in the concrete. Also, heat effects appeared to be affecting the behavior of the materials as they interacted, leading to severe plastic deformation of the pad materials. In order to understand the mechanics of abrasion, additional variables were isolated and the testing protocol was simplified.

Based on observations made during the deterioration tests, the frictional relationships that exist between rail pad materials and mock concrete rail seats appeared to change throughout the tests and vary based on a number of factors. Friction at the rail seat and rail pad interface appears to have an effect on the movement of the pad relative to the rail seat, the load transfer of wheel loads as they move from the top of rail through the fastening system components into the rail seat, and the abrasive wear behavior of both the pad and rail seat materials. Contrary to the deterioration tests where many thousands of loading cycles were necessary to understand the severity of progressive abrasion, observations related to the frictional characteristics can be made after any number of loading cycles. As a result, the testing procedure was designed to simulate a single train pass. It was hypothesized that the coefficient of friction would be reduced as the magnitude of the normal load on the pad was increased and the number of loading cycles during a single simulated train pass increased.

3.2 Testing Protocol

A testing protocol with the objective of simulating a single pass of a 100-car unit coal train was implemented by applying 400 loading cycles to the pad and concrete specimen, representing 100 four-axle rail cars. For each individual pad and concrete specimen, 400 lateral load cycles were applied at a frequency of 3 cycles per second using the horizontally mounted actuator. The magnitude of the displacement of the pad was fixed at 3 mm (1/8”). These constraints were specified to reduce the number of variables relative to the deterioration tests.

In order to monitor the effects of temperature on the frictional behavior of the pad materials, the temperature of the pad surface was measured with an infrared thermometer before each test and immediately after the final (i.e. 400th) loading cycle. After the initial temperature, T_i, was measured, the normal load was applied to the pad with the vertical actuator. After approximately 2 minutes and 14 seconds, or 400 cycles in the lateral direction, the test was stopped. Once the loading head was retracted and the hydraulic system was turned off, the surface of the pad was scanned continuously and the maximum detected temperature was recorded as T_f. Before the next test was started, the pad was allowed to cool to within one degree of its initial temperature.

The following fundamental equation was used to calculate the coefficient of friction (μ) at five different instances during each test:

$$\mu = |\boldsymbol{F}|/\boldsymbol{P}$$

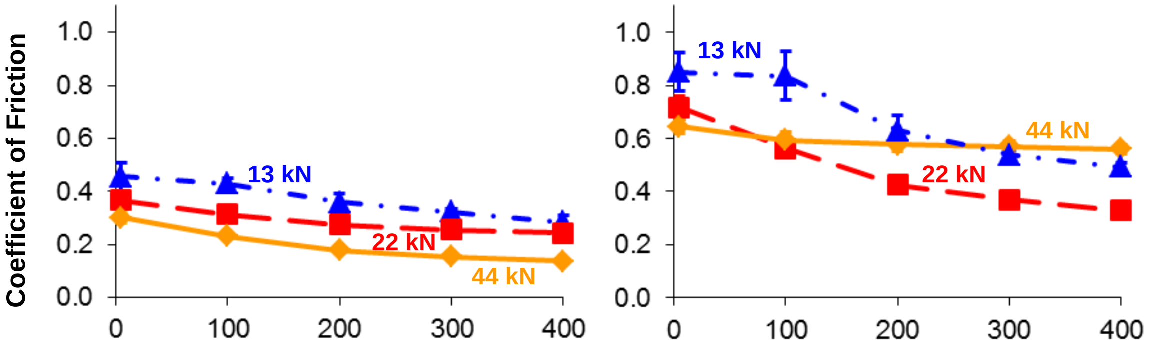
where F is the force required to initiate lateral sliding under vertical normal load P. The ratio of lateral load to vertical load was plotted at loading cycle 5, 100, 200, 300, and 400. The peak value for coefficient of friction (COF) during the cycle, between the changes in direction of the loading head, was selected as the COF value for the loading cycle.

A series of tests were conducted to evaluate the effect of increasing normal load on the COF between the pad and concrete surface. Normal loads of 13 kN (3 kips), 22 kN (5 kips), and 44 kN (10 kips) were applied to both pad types to represent 53 kN (12 kip), 89 kN (20 kip), and 179 kN (40 kip) rail seat loads, respectively. Each pad and concrete specimen was tested 4 times at each load magnitude. For these tests where the normal force on the pad was varied, no water or sand was added to the contact interface.

3.3 Results & Discussion

The normal load tests yielded a number of interesting results. First, the COF values decreased as the magnitude of the normal force on the pads increased. The correlation was more pronounced for the nylon 6/6 pads than polyurethane pads. The nylon 6/6 pads displayed similar sliding behavior at 13 kN, 22 kN, and 44 kN based on physical observations, but the frictional response of the pads under 44 kN normal loads yielded lower COF values. **Figure 2a** shows the mean values for all friction tests for each normal force with error bars that represent two standard errors for nylon 6/6 pads.

The COF values recorded at 44 kN were consistently lower than those under a 13 kN and 22 kN load, including those recorded on the same specimen. The higher contact stresses may have caused more deformation at local contact points, thus smoothing the contact interface between the nylon 6/6 and concrete surfaces. Deformation of surface asperities due to the increase in force has been shown to lead to a reduction in the coefficient of friction of polymers in other studies [9].



(a) (b)

FIGURE 2: Mean Coefficient of Friction for a) Nylon 6/6 Pads and b) Polyurethane Pads under 13 kN, 22 kN and 44 kN Normal Loads

The correlation between normal load and COF was not as apparent for tests with polyurethane pads. **Figure 2b** shows the mean values for all friction tests for each normal force with error bars that represent two standard errors for polyurethane pads. The COF values at loading cycles 5 and 100 were lower under 44 kN loads than at 13 kN loads, but no clear trend is visible at load cycles 200, 300, and 400. During the tests with a normal load of 44 kN, observations of the pad under loading revealed that minimal sliding of the pad relative to the concrete was occurring. Instead, the pad appeared to be absorbing all of the shear strain internally (i.e. within its own thickness), such that gross slip of the pad relative to the concrete was barely visible.

The second trend that was observed during the friction tests is that the coefficient of friction decreases with subsequent loading cycles. For both pad materials tested, a noticeable decline in the COF was consistently observed from cycle 5 to cycle 400. The decline in COF over time during a simulated train pass is most likely due to the buildup of thermal stresses at the contact interface. **Table 1** lists the average temperatures measured before and after each friction test.

The temperature build up at the contact interface resulted in severe plastic deformation of the pad materials. At the primary load bearing contact points, the material appeared to soften, leading to plastic flow and severe deformation. The increase in temperature of the 44kN test on polyurethane was significantly lower than in tests run with 13 kN normal loads. The average temperature of 44 kN tests was 93° C compared to 130° C for 13 kN tests. Additionally, less plastic deformation was visible on the pad surface after the 44 kN tests where minimal gross sliding was observed during the tests. Due to the combination of less slip, lower temperatures, and less deterioration, the COF values for pads tested at 44 kN remained relatively constant.

TABLE 1 Mean pad temperature of pads in degrees Celsius

Normal Force	Nylon 6/6		Polyurethane	
kN	T_i	T_f	T_i	T_f
3	24	155	24	130
5	24	151	24	121
10	24	172	24	93

Previous research has shown that the COF and wear behavior of polymers depend on the temperature of at the contact interface [9]. It is hypothesized that the shear strength of the pad material is likely being reduced as the temperature is increasing. Once the shear strength of the pad is reduced, less force is required to move the pad in a tangential direction relative to the normal load due to the lateral force being absorbed as internal shear. Additionally, plastic deformation and tearing of the material can occur due to a decrease in shear strength of the material at local contact points.

4.0 Laboratory Test Results for Improved Rail Seat Materials

4.1 Background

The LSAT presents a novel approach to the RSD problem, and includes representative component materials (e.g. nylon and concrete) and conditions that are representative of the field (e.g. rail seat pressures, abrasive slurry). However, there are limitations to large-scale testing, which requires more time and resources to operate, and can present challenges when investigating component level behavior within the system. These challenges limit the breadth, depth, and effectiveness of a parametric study to identify ways of mitigating RSD. The aforementioned limitations and lessons learned from previous test development led UIUC researchers to the development of a simplified test known as the Small-Scale Abrasion Resistance Test (SSART).

The SSART was designed with the following characteristics: 1) the ability to isolate the abrasion mechanism, 2) ability to quantify the abrasion resistance of different concrete specimens, 3) be comparatively simple and economical to operate, and 4) allow for shortened testing durations that will facilitate the collection of large volumes of data.

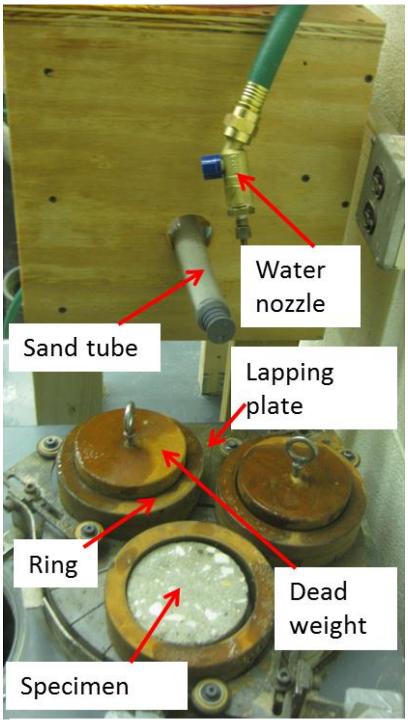


FIGURE 3: SSART Test Setup

4.2 SSART Test Setup

The SSART was constructed by modifying a lapping machine that is typically used to sharpen tools or create flat, smooth surfaces on machined metal parts, and for rock polishing in geotechnical engineering (**Figure 3**). The lapping machine is comprised of a revolving steel plate with concrete specimens loaded in three counter-rotational rings that rest on the plate and are held in place relative to the rotating disk. The three rings are held in place on the lapping plate by small rubber wheels attached to the main frame. This allows the circular specimens to revolve around their center while still maintaining the same position relative to the revolving lapping plate. A dead weight weighting 2 kg (4.5 pounds) is placed on top of each specimen. To represent the influence of water and fines that is often seen in the field, an abrasive slurry of water and Ottawa sand is applied to the lapping plate throughout the test to abrade the concrete surface that mates against the lapping plate.

4.3 SSART Test Protocol

In order to have satisfactory confidence in our test results, nine specimens (or replicates) were tested for each mix-design. The concrete specimens are marked to identify the wearing surface (i.e. the as-cast surface). Initial thicknesses at four marked locations are obtained using a pair of vernier calipers. Three specimens are then placed in the lapping machine rings, the deadweight is applied, and the test is started. At the same time, the abrasive slurry is introduced into the specimen-lapping plate interface.

After testing, the wear depth data (i.e. difference between initial and final thicknesses) is plotted with respect to testing duration to represent the progression of abrasion with time. Further details regarding the rationale behind the development of the test, test apparatus construction, specimen production, test protocol and preliminary results from previous testing can be found in a previous publication [10].

A test matrix containing a prioritized list of specimens was developed based on the opinion 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 [10]. While most specimens in the test matrix were prepared at UIUC, some were prepared by concrete crosstie manufacturers to obtain concrete mix designs and coating procedures that were reflective of current industry standards. The following concrete mix designs and materials were tested to quantify their abrasion resistance: supplementary cementitious materials (mineral admixtures), fibers, variable curing conditions/methods, and the application of various surface treatments (i.e. coating, grinding). Grinding is the process wherein the top layer of cement paste is ground to expose a plane and hard aggregate surface.

4.4 Results and Discussion

First, samples were cast using a concrete mix design that is representative of a mix used for the manufacture of concrete crossties in North America. Specimens cast with this control mix design (and cured in 100% humidity) will hereafter be referred-to as “control specimens”. Any change in abrasion resistance is measured relative to the control specimens. Wear depth is used as a metric to quantify abrasion and is the inverse of abrasion resistance. As curves shift downward on the graph, the surface material shows higher abrasion resistance. **Figure 4** shows wear rate curves for specimens wherein each data point represents the average value of data obtained from 9 specimens. Error bars representing two standard errors (positive and negative) in wear depth are shown on all data points. The following approaches were found to improve the abrasion resistance of concrete: certain amounts of fly ash, silica fume, submerged curing (not curing in humidity), addition of steel fibers, grinding the top cement paste surface and epoxy coating on the rail seat surface.

Curing condition seems to have an impact on the abrasion resistance of concrete. Submerged specimens cured in a pool of water showed an approximately 7% abrasion resistance over the control specimens (**Figure 4b**). This observation gains significance because curing techniques used in sleeper manufacture vary throughout the world. While sleepers in North America are allowed to cure while stacked in open air, countries like India and some European nations submerge sleepers in pools of water while curing [11].

In North America, epoxy coatings are frequently used as a reactive RSD repair material and/or preventative RSD mitigation measure. Preliminary qualitative results from revenue testing have been promising according to Class I railroads. Data from the SSART shows that epoxy coating improves the abrasion resistance of concrete by approximately 10% relative to control specimens (**Figure 4d**). It was also observed that the epoxy coating quickly disintegrated and added to the abrasive slurry once it developed cracks. The abrasive wear rate matched that of control specimens after the epoxy coating was completely lost. This phenomenon can likely be attributed to the hardness and smooth finish of the brittle epoxy coating layer. However, the use of an epoxy coating could still be cost effective if it delays the onset of RSD, and increases the life cycle of concrete crossties. Additionally, grinding was evaluated for its abrasion resistance. The improvement in abrasion resistance due to grinding was 13.5% greater than that of the epoxy coated specimens.

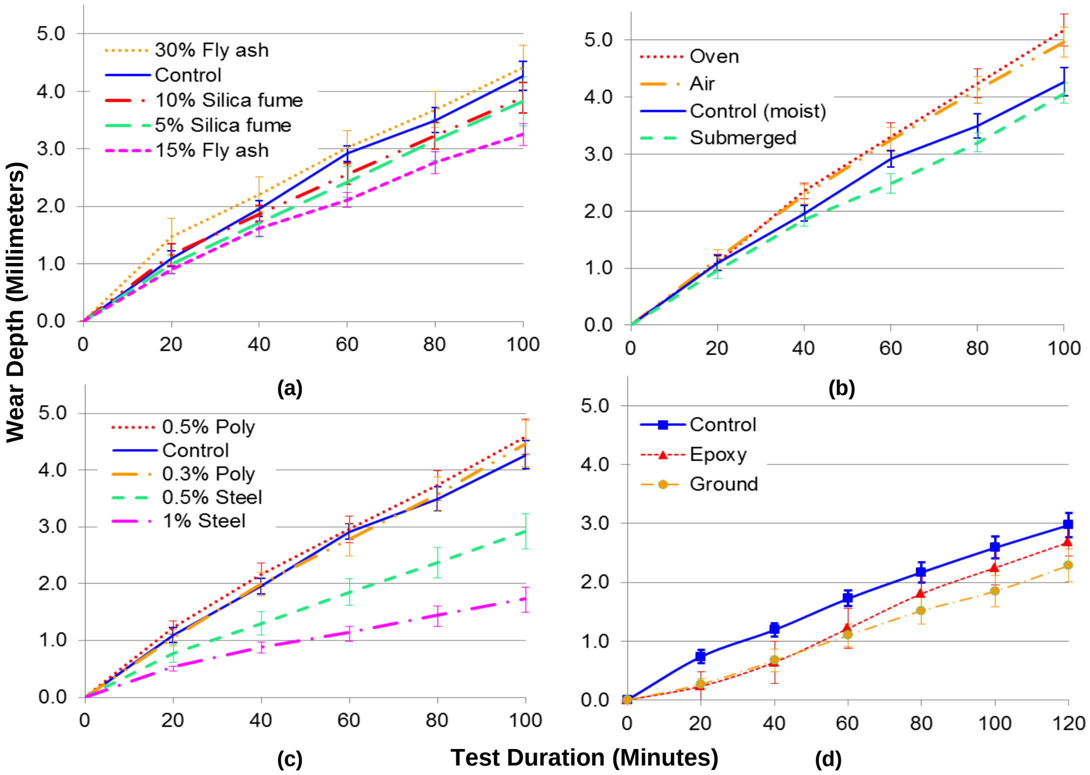


FIGURE 4: Wear Depth Dependence on a) Addition of Mineral Admixtures, b) Curing Conditions, c) Addition of Fibers, d) Surface Treatment

Fiber-reinforced concrete (FRC) was also evaluated for its abrasion performance based on the widespread understanding that FRC has a very strong ability to reduce cracking [12]. Results from the SSART showed that FRC specimens with steel fibers gave the best abrasion performance among all other specimen types with improvements as much as 40% (0.5% Steel) and 65% (1% Steel) (**Figure 4c**).

Mineral admixtures like fly ash are being used in the concrete sleeper industry in order to increase strength and resistance to Alkali Silica Reaction (ASR). Data from SSART showed that the addition of small amounts of silica fume (5%) and fly ash (15%), specified by percentage of cement replacement by weight, improved the abrasion resistance by 13% and 30% respectively (**Figure 4a**). This improvement can be attributed to reduced water-to-cement (w/c) ratios and the densification of the concrete matrix caused by these mineral admixtures without affecting the slump of fresh concrete.

5.0 Conclusions

The Large-Scale Abrasion Test confirmed that abrasion is a feasible RSD mechanism. Additionally, the frictional force that resists the translation of the pad relative to the sleeper rail seat may be reduced as normal loads increase and as heat builds up in the pad. Through experimental testing using the SSART, researchers at UIUC have successfully compared 13 approaches to improving the abrasion resistance of the rail seat. Data from SSART illustrates that the abrasion resistance of the rail seat surface can be improved with the addition of optimal amounts of fly ash and silica fume, advantageous curing conditions, addition of steel fibers, grinding top cement paste layer off to expose hard aggregate surface, and epoxy coating of the surface. The knowledge gained from this research will be used to formulate specific recommendations to mitigate the adverse effects of RSD in future, both from the rail pad as well as the concrete materials standpoint.

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