Proceedings of the ASME/ASCE/IEEE 2012 Joint Rail Conference
JRC2012
April 17-19, 2012, Philadelphia, Pennsylvania, USA

JRC2012-74107

LABORATORY INVESTIGATION OF THE ABRASIVE WEAR MECHANISM OF CONCRETE CROSSTIE RAIL SEAT DETERIORATION (RSD)

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ABSTRACT

Currently, there are divergent design and performance demands on railway infrastructure components due to increasing freight axle loads and cumulative gross tonnages, as well as increased investment in high-speed passenger rail development in North America. The divergence in loading and performance demands on shared infrastructure arises from the fact that while high-speed passenger trains exert lower loads at relatively high speeds, freight trains exert high loads at relatively low speeds. Improvements in infrastructure component designs are needed to achieve increased durability and tighter geometric tolerances. According to a rail industry survey administered by University of Illinois at Urbana-Champaign (UIUC), Rail Seat Deterioration (RSD) is the principal performance problem limiting the service life of concrete crossties in North America. Rail infrastructure researchers and industry experts agree that abrasive wear may occur due to relative motion between the rail pad and concrete crosstie rail seat, potentially resulting in RSD. The complex tribological process of abrasion is further complicated and expected to be accelerated by the presence of abrasive fines and moisture, creating 3-body wear. Lack of understanding of the abrasion mechanism has resulted in a sub-optimal and iterative design of ties, causing reduced service life. This paper summarizes our efforts in understanding the effect of changing the mix design of concrete on the abrasion resistance of the rail seat which will eventually help us in modeling abrasive wear in RSD by constructing a mathematical relationship between the rail seat wear rate and input parameters including concrete mix design, mechanical/tribological properties of materials involved, normal load applied, presence of moisture, abrasive fines. To simulate abrasive wear in RSD, a simple experiment is being carried out using a rotating wheel (lapping machine) capable of abrading concrete samples as a part of UIUC's Small-Scale Abrasion Resistance Test (SSART). The objective of this research is to develop wear performance curves (e.g. wear versus load/time/cycles) for lab specimens developed from concrete crosstie mix designs that are currently being used in the industry, as well as for the evaluation of new mix designs. These data will help the rail industry in mechanistically designing concrete crossties by improving the understanding of materials used for concrete crosstie mix designs, with the objective of decreasing life cycle costs for the tie and fastening system. Preliminary SSART results are

in agreement with relevant literature documenting the relationships between concrete mix designs and curing conditions and the resulting rate of abrasion.

INTRODUCTION

Rail seat deterioration (RSD) refers to the degradation of concrete material under the rail pad on the concrete crosstie rail seat. RSD can lead to problems with the stability of the rail, loss of cant, gauge-widening, and other track geometry deficiencies that create the potential for derailments (1, 2). Previously, RSD research has focused on mitigating the wear of concrete through pad design improvements and other fastening system alterations, with minor focus on mix design enhancements (3). Wheel Impact Load Detectors (WILD) were also used as a preventive measure, albeit with limited success (3). Going forward, additional RSD research should focus on improving the performance of concrete materials as well as the materials used to manufacture fastening system components. The possibility exists to use stronger, more durable, materials in the concrete tie and/or concrete rail seat to prevent or delay the onset of RSD and increase the life of the rail seat to match the life of the rail steel (1).

According to previous and current research conducted at the University of Illinois at Urbana-Champaign (UIUC), five possible mechanisms have been identified 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 found to be feasible mechanisms for RSD (4, 5, 6, 7). According to another study, the damage due to RSD resembled abrasion, with hydraulic pressure cracking and freeze-thaw cracking also being identified as possible contributors (5).

Previous research has focused on the moisture-driven mechanisms of RSD, and this work seeks to build on previous research by focusing on the abrasion mechanism of RSD. 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 (1).

Modeling abrasive RSD involves knowledge of tribology, a multi-disciplinary field studying the science of interacting surfaces in relative motion (1). This paper presents initial research into the contact mechanics of abrasive RSD as well as the initial testing to understand the effects of using innovative materials in concrete tie and/or rail seat mix designs. Extensive research has been performed investigating the tribological interaction between two surfaces. However, the majority of this research falls within the mechanical engineering domain (machines: metal-polymer-composite interactions) as opposed to civil engineering applications. However, it is of our interest to study the interaction at the rail seat - rail pad interface (concrete-rubber/polymer and other similar material pairs). Furthermore, the majority of the existing abrasion models that have been developed are empirical in nature.

The objective of modeling abrasive RSD is to predict the concrete wear occurring at the rail seat. This will be achieved by constructing a mathematical relationship between wear rate and various input parameters including, but not limited to, concrete mix design, applied load, mechanical/tribological properties of materials, and the presence of moisture and abrasive fines. A representative model will help us to: (a) evaluate various combinations of concrete mix design parameters in an efficient and cost-effective manner, (b) mechanistically design the mix design of rail seat which also has a bearing on design of other components of the crosstie and fastening system such as rail pads, clips, shoulders, and insulators, and (c) increase the durability of the concrete rail seat to increase service life and reduce maintenance costs. The abrasive wear leading to RSD is considered to be a closed three-body wear phenomena (8). Three-body wear is a phenomenon wherein particles are interposed between the two surfaces. In other words, the process whereby a particle becomes trapped between two surfaces, and removes material from one or both, can be classified as closed three-body abrasive wear (8). In the application of concrete crossties, the third-party bodies are composed of various aggregate particles, steel particles, and moisture.

EXISTING INDUSTRY STANDARD ABRASION RESISTANCE TESTS

Existing abrasion resistance tests typically focus on either the system as a whole or the specific materials within a component. At the system level, the American Railway Engineering and Maintenance-of-way Association (AREMA) developed a Wear and Abrasion resistance test (AREMA Test 6) designed specifically for concrete crossties and fastening systems (9). This test allows tie and fastener designers to gather data on individual component wear as a part of a system test.

At the materials level, there are three ASTM standards, containing five tests for evaluating the abrasion resistance of concrete, but each has drawbacks to being used in the rail seat – rail pad domain. ASTM C779, Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces, contains three sub-methods for testing. Method A is the revolving discs method. Three revolving steel discs, each rotating about their own axis and an axis central to all three are placed on the concrete, while abrasive slurry is added. Method B has three sets of steel dressing wheels that continuously roll over the concrete specimen. Abrasive slurry is also added during this test. The dressing wheel method is designed to test abrasion due to impact forces, such as steel wheels on a concrete warehouse floor. Method C is the ball bearings method. A series of ball bearings are moved around a wet, abrasive-covered concrete surface. All three tests require wear depth measurements at varying time increments (10). However, ASTM C779 has several drawbacks with respect to the need to replicate the rail pad and concrete tie interface. Firstly, all three methods require complicated test setups that are not easily obtained or constructed. Secondly, the test set-ups and protocols tend to focus on impact abrasion between steel and concrete, not a polymer rail pad on concrete. Finally, the results from methods B and C have high coefficients of variation.

The fourth test to evaluate the abrasion resistance of concrete is found in ASTM C944, Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces, by the Rotating-Cutter Method, and subjects concrete specimens to a rotating cutter (11). The last relevant ASTM standard abrasion resistance test is ASTM C418, Standard Test Method for Abrasion Resistance of Concrete by Sandblasting, which utilizes a sandblaster to abrade the surface of a concrete specimen, and then the volume of concrete removed is determined by pressing clay into the surface of the specimen (12).

In addition to ASTM standards, Turkey and Great Britain have standards that are commonly used to test the abrasion resistance of concrete. Turkish standard TS 699 and British Standard BS 812-113 are similar to one another and involve a concrete specimen being applied to a rotating steel wheel and loaded. Abrasive slurry and water can also be applied to the wheel, and the depth of wear is recorded after a set amount of time (13, 14).

While AREMA Test 6 is a representative test for full-scale concrete crosstie and fastening systems, it presents a challenge in isolating one variable due to the system focus of the test. Within the concrete crosstie research domain, several problems need to be studied that are not currently addressed by the existing tests, which primarily focus on steel-on-concrete abrasion. In case of concrete crossties, there is an intermediary rail pad between the steel and concrete surfaces. Additionally, most concrete abrasion resistance tests focus on rolling or circular motion, which does not accurately reflect the lateral and vertical motion of the rail pad on the concrete rail seat as it is cyclically loaded by a high tonnage freight trains.

LARGE-SCALE ABRASION TESTING AT UIUC

To improve the understanding of the mechanics of abrasive RSD in a manner representative of field conditions and to overcome the drawbacks mentioned above, the development of a large-scale abrasion test has been undertaken at UIUC. The test setup consists of two actuators; one mounted vertically and the other mounted horizontally (Figure 1). This setup is capable of testing abrasion resistance of various rail seat concrete mix designs and rail pad combinations while varying normal loads, displacement, and frequency of loading. The test also incorporates abrasive slurry (e.g. fines and water) at the rail seat to rail pad interface. In addition to being representative of field conditions and giving accurate and realistic wear patterns, the large-scale abrasion resistance test at UIUC has the potential to facilitate greater understanding of the frictional properties at the seat-pad interface, energy dissipation rate at the seat-pad interface, and other properties that are not sufficiently understood. Initial results look promising given aggressive abrasion has been successfully recreated on concrete specimens.

SMALL-SCALE ABRASION RESISTANCE TESTING (SSART) AT UIUC

Since the large scale abrasion resistance test presents a novel approach to a system problem that includes the rail pad and rail seat, UIUC researchers noted the need for a simplified test which; a) is more economical to operate, b) can cause aggressive and expedited abrasion on concrete specimens, and c) can rapidly generate large quantities of data. Such an abrasion resistance test would be similar to the current industry standards abrasion tests described above, with modifications to better represent the tie and rail pad loading conditions. It would also be a pre-qualification test for the large-scale abrasion resistance test.

It was decided to use a lapping machine to carry out this experimental testing regime. A lapping machine is typically used to sharpen tools or create flat, smooth surfaces on a variety of machined metal parts, such as bolts. The lapping machine is comprised of a revolving steel disc with concrete specimens loaded and held in place relative to the disc. In general, the principles employed by the lapping machine are the same as the British and Turkish abrasion resistance standards. Throughout the test, an abrasive slurry is applied to the lapping plate, which abrades the concrete surface that mates against the lapping plate. However, there are several differences between the traditional abrasion resistance set-up and the lapping machine. The steel disc with the lapping machine is loaded with three specimens at a time. The specimens fit into circular rings which are held in place on the lapping plate by small rubber wheels. This allows the circular specimens to rotate around their center while still maintaining the same position relative to the lapping plate. This is different from the other standards, which use square specimens held rigidly in place on the rotating wheel. Additionally, the loads applied and revolutions per minute (RPM) of the lapping machine are slightly less than those used in the British and Turkish abrasion resistance standards.

SSART CONSTRUCTION AND MODIFICATION

Lapping is a machining operation in which two surfaces are rubbed together with an abrasive material placed between them. The lap or lapping plate in this machine is circular disk on the top of the machine that is 12 in. (30 cm) in diameter (Figure 2). On top of the lapping plate are three rings of 6 in. (15 cm) diameter and 1.5 inches (3.8 cm) deep. The specimens are placed inside these rings. A dead weight weighing 4.5 lbs. (2 kg) is then placed on top of each specimen. In operation, the rings are stationary relative to the lapping plate beneath them. An abrasive slurry, representative of what is found in the field, is introduced at the lapping plate-specimen interface to accelerate abrasion (15).

The original lapping machine was designed to deliver diamond slurry to the lapping plate using a pump and a metal bar with tubing. The lapping machine has been modified to provide a delivery mechanism for the abrasive slurry throughout the test. In the modified system, water is delivered to the lapping plate through a plastic tube. A raised wooden platform was constructed and a sand storage container was placed on the platform. Holes were drilled at the bottom of the container and wooden platform making sure that they were aligned. Sand is applied at a uniform rate to the lapping plate via a plastic tube passing through the hole.

The SSART is not completely representative of field conditions for several reasons, which will be mitigated as our understanding of the field environment and lab capabilities are further refined. Reasons include non-cyclic loading and metal-concrete interaction rather than metal-rubber/polymer pad interaction. However, as mentioned earlier, the SSART is a simplified tool to compare/validate data obtained from large-scale abrasion testing. Moreover, it is critical to have large quantity of data in order to construct an empirical model representing wear rate, one of the ultimate objectives of this research project.

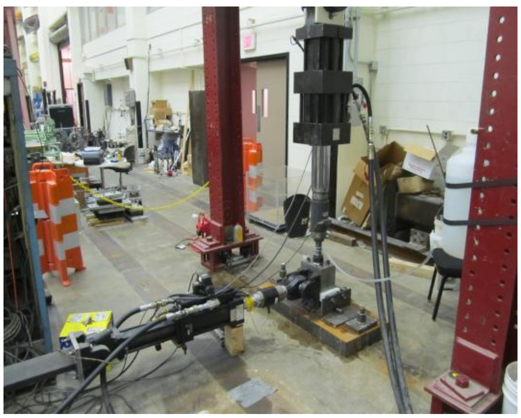

FIGURE 1. LARGE-SCALE ABRASION TEST AT UIUC

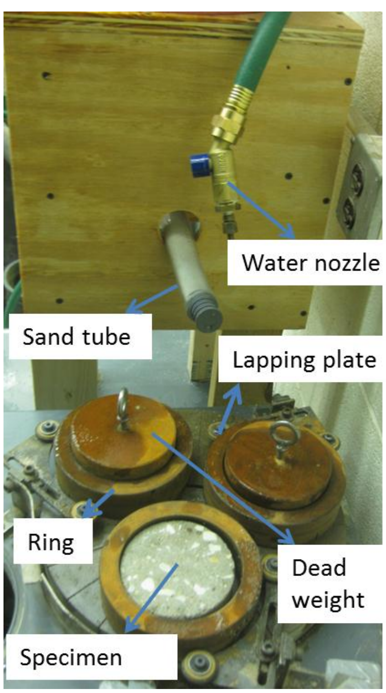

FIGURE 2. SSART AND ABRASIVE SLURRY CONVEYANCE EQUIPMENT

SPECIMEN PRODUCTION

Concrete mix design and batching

To understand the effect of material properties on the rate of rail seat wear (abrasion), UIUC is exploring variations in mix designs. Initially, a literature review on mitigation of concrete abrasion was conducted, which identified several potential mixes with the objective of characterizing and minimizing abrasion.

Witte and Backstrom, as well as many other concrete materials researchers, considered compression strength as one of the most important factors contributing to the abrasion resistance of concrete (16). However, the abrasion resistance is a function of water-to-cement (w/c) ratio of concrete and not only its compressive strength (17). Stiffer mixes are more abrasion resistant than leaner mixes (18). Water-reducing admixtures, by virtue of their positive effect on water-cement (w/c) ratio, increase the compressive strength of concrete, which increases the abrasion resistance of concrete.

Several studies have shown increased abrasion resistance when a small percentage of the cement was replaced with silica fume. Optimal replacement appears to be approximately 5% (14). There are conflicting reports regarding the effect of the addition of fly ash on the abrasion resistance of concrete (14, 18, 19). This issue will be investigated further through additional experimental testing at UIUC. Compaction, finishing, and curing techniques also have a great impact of the compressive strength and abrasion resistance of concrete (18).

Concrete specimens 8 in. (20 cm) long and 4 in. (10 cm) in diameter are cast and cured. This is followed by saw-cutting one inch from the as-cast surface of the specimen. The as-cast surface is abraded and studied during testing. These one-inch thick concrete specimens will hereafter be referred to as the test “specimens”. More details on various concrete mix design parameters used for testing are provided in Appendices A and B.

TEST PROTOCOL

The specimens are marked to identify the wearing surface (i.e. the as-cast surface). Also, points where thickness readings would be taken are marked. Initial weight and thicknesses at the four marked locations on the specimen are obtained using a digital scale and vernier calipers respectively. Three specimens are then placed in the lapping machine rings, deadweight is applied and the test is started. At the same time, an abrasive slurry of water and Ottawa sand (having a gradation of 20-30, i.e. sand particles passing through a nominal sieve opening size of 841 microns and retained on a nominal sieve opening size of 596 microns) is introduced into the specimen-lapping interface. The test is run for 2 hours with weight and thickness measurements taken every 20 minutes throughout the test and again at the end of the test. Before taking measurements, the surface of the specimen is cleaned using pressurized air to remove excess surface moisture and abrasive fines. The air nozzle is placed approximately at 5 in. (10 cm) from the specimen surface and air is blown for approximately 20 seconds. Care is taken to be consistent with the distance of nozzle from the specimen surface and the cleaning duration so as to reduce any variability in the reading obtained. Also, the nozzle is not held too close to the specimen to ensure no internal moisture is lost. The specimens are rotated to different rings every time the test is stopped to reduce inter-ring variability.

PRELIMINARY RESULTS AND DISCUSSION

The results obtained were in agreement with the relevant literature. This lends credibility to the SSART results and insight into tests which should be conducted in the future. Note that each data point in the following graphical representations is an average value of data obtained from three separate tests (i.e. nine specimens). Error bars representing the scatter (standard deviation) in wear depth readings are also included in all the plots. Due to lack of time, all tests were conducted after curing for 7 days. However, through tests conducted after 28 days, the correlation between various parameters was found to be approximately similar. Also, *wear depth* is used as a surrogate term for *abrasion resistance*. These two parameters are inversely proportional to each other.

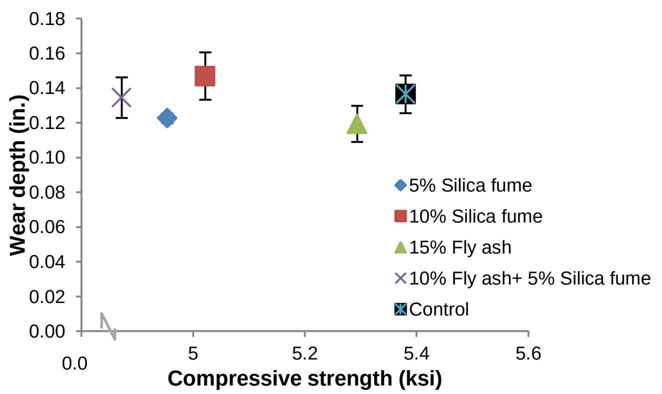

FIGURE 3: WEAR DEPTH DEPENDENCE ON ADMIXTURE TYPE AND PROPORTION

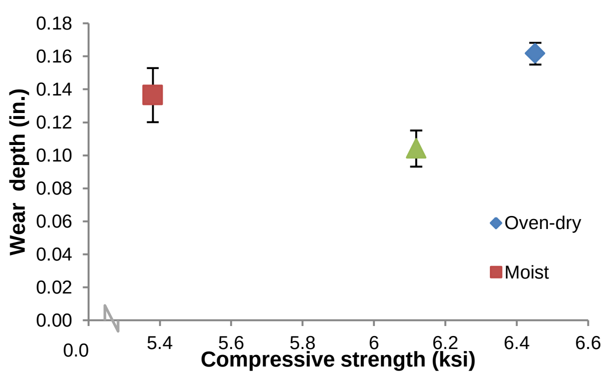

FIGURE 4: WEAR DEPTH DEPENDENCE ON CURING CONDITION

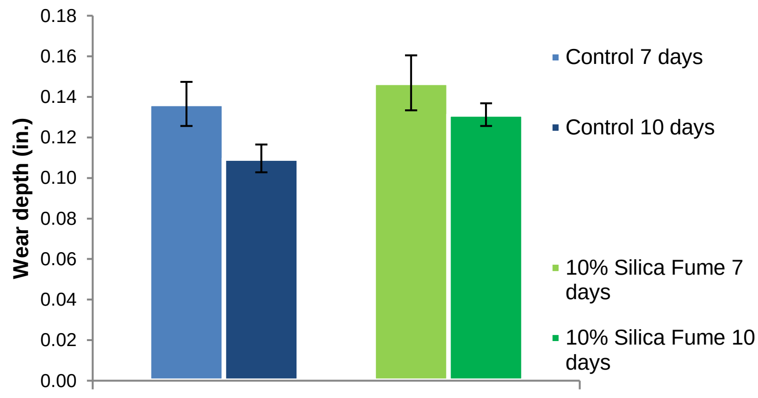

FIGURE 5: WEAR DEPTH DEPENDENCE ON CURE TIME

Effect of silica fume and fly ash

Addition of small amounts of silica fume and fly ash reduces the w/c ratio without affecting the slump of the mix. This increases the strength of concrete and thus improves the abrasion resistance of the specimens. Preliminary test results show there is a decrease in wear depth by 12-15% (compared to average wear depth of control specimens) when small amounts of silica fume (5%) and fly-ash (10%) were added (Figure 3).

Effect of curing conditions

The wear depths of specimens which were cured in submerged conditions were lower than those recorded from specimens cured in moist and oven-dry conditions. This occurs because the cement has adequate water to hydrate and gain strength in submerged conditions. As mentioned previously - while holding curing conditions constant - as strength increases, abrasion resistance also increases (16). However, preliminary results showed the wear depth of the oven-dried specimens was the greatest though its compressive strength was found to be the highest (Figure 4). Therefore, it appears that oven curing could lead to inferior resistance to abrasion. The detrimental effect appears to be due to the fact that it produces a non-uniform distribution of hydration products, leaving weak zones in the cement that govern the strength (20). Further testing is needed to determine the exact effect of curing conditions on the mix design.

Effect of cure time

It was found that wear rate was inversely proportional to curing time. In other words, the strength of concrete (and hence abrasion resistance) goes up with time. Test results verified this and wear depth decreased as curing time increased from 7 days to 10 days for both control specimens (blue) and specimen with 10% silica fume (green) (Figure 5). Another observation was that when silica content was increased to 10%, the wear depth was higher relative to control specimens at the same cure time.

A more thorough experimental analysis of curing times and admixture content is needed to reach a definitive conclusion about the optimal method of curing concrete crossties to mitigate abrasion.

CONCLUSIONS AND FUTURE WORK

A large number of complex materials interactions make understanding RSD extremely challenging, and lends itself to a regression analysis. Isolating the abrasion mechanism by means of laboratory tests facilitates better understanding of abrasive RSD. It is believed that the SSART can help further our understanding of methods to improve the abrasion resistance of the concrete rail seat by isolating the effect of using different mix designs (by using innovative materials). This will help in formulating design recommendations for the industry for mitigating RSD from a materials standpoint. The SSART can cause aggressive abrasion of concrete specimens and can quickly generate a large quantity of data which will help in constructing a mathematical model representing abrasive RSD. The SSART will also provide a way to compare/validate data from the large-scale abrasion test at UIUC.

In addition to modeling abrasive RSD, this test will be used to rank various mix designs for rail seats by drawing wear depth vs. time (cycles) curves. Once a model representing abrasive RSD is constructed, it can be extended and developed further to predict wear rates in the large scale abrasion test. The modified model will eventually be calibrated and validated against field conditions.

Many mix-design parameters will be tested in the future, including air-entrainment and use of harder aggregates. Air entraining is typically done in all concrete structures to prevent cracking due to freeze-thaw cycles. The same concept has traditionally been incorporated in concrete crosstie manufacturing. However, there has been a debate in the North American railroad industry on the merit of entraining air in concrete crosstie manufacturing. This is because there is a trade-off between percentage air-content and compressive strength of concrete. The strength of concrete goes down as the air-content increases. It is known that as the strength goes down, the abrasion resistance too goes down (16). Thus, air entraining has to be studied in greater detail to determine the optimum air-content at which the abrasion resistance is maximum without compromising on the strength of concrete as well as maintaining the freeze-thaw cracking resistance to acceptable standards.

Aggregates are probably the most important factor contributing to abrasion resistance of concrete. In fact, some studies suggest that in most air-entrained concretes, while silica fume can slightly improve concrete abrasion resistance, the effect of coarse aggregate is more significant (21). Also, abrasion resistance in high-strength concretes with very low w/c is largely determined by that of the coarse aggregate (21). Harder, more angular aggregates tend to offer improved abrasion resistance (18). Potential aggregates include high quality quartz, granite, basalt, traprock, emery, and metallic aggregates (22). A report on RSD suggests that using metallic aggregate topping at the rail seat while casting the crosstie has shown significant reduction in RSD problems (23). The same study also suggested that the increase in initial costs due to metallic aggregates can be easily offset by savings achieved due to reduction in maintenance/replacement costs of rail seats. Therefore, studying the effect of various aggregated used in rail seat deserves merit.

Surface-treatments like UV epoxy coatings on rail seats and grinding the rail seat to expose hard aggregate will also be studied in greater detail to understand their effect on abrasion.

ACKNOWLEDGEMENTS

The authors would like to express sincere gratitude to the Association of American Railroads (AAR) Technology Scanning Program and the NEXTRANS Region V Transportation Center for sponsoring this research project. Additionally, the authors would like to thank VAE Nortrak (Steve Mattson) and Amsted RPS (Jose Mediavilla) for providing resources, advice and direction. Additionally, we would like to express our appreciation to members of AREMA Committee 30, including John Bosshart, Winfried Bosterling, Tom Brueske, John Clark, Pelle Duong, Tim Johns, Mark Hammonds, Scott Tripple, Thai Nguyen, Jim Parsley, Michael Steidl, and John Zeman. Finally, thanks to Tim Prunkard, Darold Marrow, Don Marrow, Marcus Dersch, Ryan Kernes, Brandon Van Dyk, Christopher Rapp, Calvin Nutt, Ryan Feeney, Kris Gustafson, all of UIUC.

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APPENDIX A

TEST MATRIX CONTAINING DETAILS OF VARIOUS CONCRETE MIX-DESIGNS BEING TESTED USING SSART AT UIUC

Design mix code	Admixtures (%)				FRC		Curing condition				Air entraining (Target air voids %)			Surface treatment		Baseline mix
	Silica fume		Fly Ash													
	5	10	15	30	Poly	Steel	Moist	Submerged	Oven dry	In air	0	5	10	UV epoxy	Ground	Control
1	x						x									
2		x					x									
3			x				x									
4				x			x									
5									x							x
6								x								x
7							x									x
8										x						x
9											x					x
10												x				x
11													x			x
12															x	x
13															x	x
14					x											x
15																x

Note:

1) The number of specimens required for testing is nine along with three specimens required for compression testing and one for contingencies (which sums up to 13).

2) Control mix-design details given in the table below. Control specimens are cured for 28 days in moist curing conditions.

3) Testing related to the test-matrix is currently progressing at UIUC.

APPENDIX B

CONCRETE MIX DESIGN FOR CONTROL SPECIMENS

Concrete Mixture Design		
Material	**Unit**	**Quantity**
Cement (Type I)	lbs/yd^3	640
Coarse Aggregate	lbs / yd^3	1809
Fine Aggregate	lbs / yd^3	1218
Water	lbs / yd^3	205
Air Entraining	oz / yd^3	2.3
HRWR	oz / yd^3	50.0
Target Air Content	%	6.0
Target W/C		0.32
Target Slump	in	3.0