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Improving the Abrasion Resistance of Concrete to Mitigate Concrete Crosstie Rail Seat Deterioration (RSD)

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Reference

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ABSTRACT

Rail seat deterioration (RSD) refers to the degradation of concrete material at the contact interface between the concrete crosstie rail seat and the rail pad that protects the bearing area of the crosstie, which supports the rail. Abrasion is a viable mechanism that causes RSD. The objective of this study is to investigate the abrasion resistance of several approaches, such as the addition of mineral admixtures, fibers, and varying curing conditions, to mitigate abrasion of the rail seat. In order to achieve this objective, the abrasion mechanism of RSD was simulated using the small-scale test for abrasion resistance, which was designed by researchers at University of Illinois at Urbana-Champaign. The results of this study show that the addition of optimal amounts of silica fume, fly ash, steel fibers, as well as increased moisture availability while curing improves the abrasion resistance of concrete.

Keywords

crosstie, rail seat, sleeper, mixture design, admixture, silica fume, fly ash, fiber-reinforced concrete, curing, abrasion resistance, abrasion test

Introduction

The purpose of a railroad track structure is to support the loads of cars and locomotives and guide their movement [1]. Fig. 1 depicts the components of a typical railroad track [2]. The function of concrete crossties (or sleepers) is to maintain gage (i.e., the distance between the rails of the track), uniformly distribute loads to acceptable levels for ballast, and provide support and restraint for the rail [3]. The rail seats are locations on the crosstie that support the rails [4]. The assembly that fastens the rail to the crosstie commonly consists of an elastic pad or pad assembly between the concrete rail seat and the base of the rail (referred to as a "rail pad"), cast-in steel shoulder inserts, spring clips attached to the shoulder inserts that hold the rail, and plastic insulators between the clips and shoulders and the rail. The design and manufacture of various track components, including concrete crossties in North America, is primarily guided by Part 4 of Chapter 30 of the American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering [5].

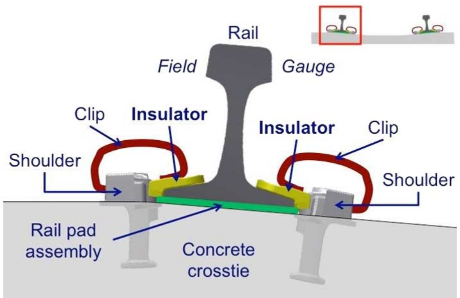
Rail seat deterioration (RSD) refers to the degradation of material at the contact interface between the concrete rail seat and the rail pad [6]. RSD has been identified as one of the primary factors limiting concrete crosstie service life in North American heavy-haul freight infrastructure [7,8]. RSD can lead to problems with track geometry and can lead to unstable rail conditions and/or derailments [9]. RSD is difficult to detect and repair without lifting the rail and removing the rail pad through a labor-intensive and costly repair process that results in track outages, traffic disruptions, and increased operating costs.

Previously, concrete crosstie research and industry design practices have focused on mitigating the wear of concrete through various fastening system design modifications and pad design improvements with little focus on concrete mix design enhancements [6,10]. Going forward, additional RSD research should focus on improving the performance of concrete materials used in rail seats. One of the most viable areas of research focuses on the development of stronger, more durable materials in the concrete crosstie and concrete rail seat to prevent or delay the onset of RSD and increase the service life of the rail seat [11].

Background

Through previous research on RSD, the University of Illinois at Urbana-Champaign (UIUC) has identified five possible mechanisms that potentially contribute to RSD. These feasible mechanisms are abrasion, crushing, freeze-thaw cracking, hydraulic-pressure

FIG. 1
Components of a railroad track.



cracking, and hydroabrasive erosion [6,12]. Of these mechanisms, abrasion, hydraulic-pressure cracking, and hydroabrasive erosion were investigated at UIUC and found to be feasible mechanisms resulting in RSD [6,12,13]. According to another study, RSD resembled damage that is typically caused by abrasion, with hydraulic-pressure cracking and freeze-thaw cracking also being identified as possible contributors [14]. The work described in this paper seeks to build on previous research by evaluating methods to resist abrasion.

Abrasion is defined as the wear of a material as two or more surfaces in contact move relative to each another [11]. Abrasion is a progressive failure mechanism and occurs when shear forces in the rail pad overcome static friction, causing slip relative to the concrete surface and imparting strain on the concrete surface [11]. The abrasion mechanism of RSD is accelerated due to the occurrence of three-body wear. Three-body wear occurs as a result of an abrasive slurry (e.g., abrasive fines and water) that often exists in addition to the two interacting surfaces (i.e., rail seat and rail pad) [15]. The abrasive fine particles are harder than the rail seat surface and so cut or plough into the concrete matrix.

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 cause wear [11]. Increasing the abrasion resistance of the rail seat should be strongly considered as a way of improving the durability and performance of concrete crossties [6].

METHODOLOGY

A prioritized list of abrasion mitigation approaches was developed based on the opinions of industry experts and literature in the domain of abrasion resistance of concrete materials [16]. For experiments presented in this paper, all the test specimens were prepared in the concrete materials laboratory at UIUC. Subsequently, we conducted another experiment to evaluate the effect of additional abrasion mitigation approaches for specimens that were prepared in concrete crosstie manufacturing facilities [17].

ABRASION MITIGATION APPROACHES

Effect of Mineral Admixtures

The effect of mineral admixtures such as silica fume (SF) and fly ash (FA) on the abrasion resistance of concrete has been extensively investigated based on the understanding that mineral admixtures improve the workability and strength properties of concrete. Literature suggests that there is a correlation between compressive strength and the abrasion resistance of concrete [18–22].

The smaller particle size of mineral admixtures (like SF) allows them to fill the voids between larger cement particles, which would otherwise have been occupied by water. Although the nominal size of SF particles is around 0.5 μm, the size of cement particles is 45 μm [23]. Hence, the water demand decreases and a denser matrix is obtained. Moreover, pozzolonic reactions between mineral admixtures and calcium hydroxide (a major hydration product of hydrated cement paste) can produce more calcium-silicate-hydrate gel, which leads to significant reduction in porosity of both the matrix and the interfacial transition zone [24].

The introduction of SF has been found to significantly improve the abrasion resistance of concrete [25,26]. A mixture with 4 % SF and slag had a significantly higher abrasion resistance as compared with the control mixture, and increasing the SF content beyond 4 % had no further beneficial effect on the abrasion resistance based on the modified ASTM C779/C779M, *Standard Test Method for Abrasion Resistance of Horizontal*

Concrete Surfaces [27,28]. Turk and Karatas examined the abrasion resistance of self-compacting concrete in which cement was replaced by SF at four levels (5 %, 10 %, 15 %, and 20 %) and concluded that increasing SF content up to 15 % continuously improves the abrasion resistance of concrete [21].

Workability is a property of fresh concrete and has a profound effect on the compressive strength of concrete, which in turn is correlated to abrasion resistance of concrete [22]. This is because high workability helps to achieve proper consolidation of concrete resulting in a denser, compact microstructure. The size of FA particles is similar to that of cement particles. FA particles are spherical in shape, which allows FA to lubricate the concrete mix by acting as billions of tiny ball bearings, thereby improving the workability.

In addition, the specific densities of mineral admixtures are less than those of cement, resulting in the formation of a larger volume of paste compared to an equal weight of cement. Also, the rate of hydration of FA is negligible during the initial hydration period. This results in a greater availability of free moisture in the FA mix when compared with a control mix with the same water/cementitious (w/c) ratio and consists of pure cement paste.

These improvements to the workability and density of FA concrete have been shown to improve the abrasion resistance. Some studies found that at a specific FA replacement level, the abrasion resistance is comparable to the control concrete [29,30]. In this study, the replacement level of mineral admixtures was defined as the percentage of cement replaced (by weight) by mineral admixture. Siddique reported an improved abrasion resistance of FA concrete when FA was used to partially replace sand [31]. Gebler and Klieger concluded that Class C FA concrete generally showed superior abrasion resistance over Class F FA concretes [32]. Turk and Karatas, Naik, Singh, and Hossain, Siddique, and Çavdar and Yetgin revealed that partial replacement of cement by FA decreases the abrasion resistance due to a loss of compressive strength [21,33–35]. Given the variability in the results obtained by previous studies, researchers at UIUC decided to conduct a study to evaluate the effect that the addition of FA has on the abrasion resistance of concrete.

Effect of Fiber-Reinforced Concrete

The abrasion resistance of fiber-reinforced concrete (FRC) was evaluated based on the understanding that FRC has the ability to mitigate crack growth. Microcracking is suspected to occur in the rail seat due to freeze-thaw cycles and hydraulic pressure [14,22,36]. Because FRC may have the potential to mitigate microcracking, we tested FRC in order to investigate its ability to resist abrasion. Vassou, Short, and Kettle found that including 0.5 % steel fiber and 0.1 % polyurethane fiber in concrete improved the abrasion resistance of concrete floors [37]. Horszczaruk reported that steel fiber with an aspect ratio above 50 and polyurethane fiber increased the abrasion resistance of high-performance concrete (HPC) [38]. However, Nanni, Atis et al., and Sonebi and Khayat found that fibers had no effect on the abrasion resistance of concrete [39–41]. Given the inconclusive nature of past studies, the effect of FRC on the abrasion resistance of concrete was evaluated using the small-scale test for abrasion resistance (SSTAR).

Effect of Curing Conditions

Curing conditions were varied to evaluate the effect of availability of moisture for curing on the abrasion resistance of concrete. An ample amount of moisture is required for the cement to fully hydrate and the concrete to gain the desired strength. Moisture availability becomes even more important in the current study due to low w/c ratios (0.32) used in the concrete mix design. The w/c ratio of 0.32 used in this study was selected because it is representative of current concrete sleeper manufacturing practices in North America. The authors understand the importance of w/c ratios as an experimental variable that should be considered in future experimentation related to abrasion resistance of concrete.

Curing techniques used in concrete crosstie manufacturing vary throughout the world. Concrete crossties in North America are allowed to cure while stacked in open air after the prestress force is transferred and they are removed from the forms. In India and in some European nations, concrete crossties are submerged in pools of water while they cure [42].

Curing conditions are increasingly important when introducing mineral admixtures. Admixtures like finely divided SF require ample moisture availability due to potential problems like self-desiccation and microscopic lumping that are caused by SF. Self-desiccation of concrete is defined as the consumption of water by the constituents of the concrete for reacting with various other constituents as a part of the hydration reactions. Also, the presence of SF in the form of numerous microscopic lumps is referred to as microscopic lumping. Due to the fine particle size of SF, any increase of SF content in the mix tends to increase the water demand or super plasticizer to maintain the same workability. Wong and Razak studied the effect of SF (0, 5, 10, and 15 % replacement) on the workability of concrete for w/c ratios of 0.27 and 0.33. The slump values significantly decrease with increased SF proportion when the w/c and super plasticizer were kept constant [43].

The following four curing conditions were varied in order to study the effect of varying moisture availability on the abrasion resistance of concrete:

1. Moist curing: after de-molding, the specimens were placed in a room with 100 % humidity for 28 days.
2. Submerged curing: after de-molding, specimens were completely submerged in a pool of water for 28 days.
3. Air curing: after de-molding, specimens were exposed to air in the atmosphere for 28 days.
4. Oven curing: after de-molding, specimens were placed in a hot oven at 200°F (94°C) for 28 days.

Concrete Mix Designs

Table 1 and Table 2 show the concrete mix designs used in this study for mineral admixtures and FRC, respectively.

Evaluating Abrasion Resistance

EXISTING 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 AREMA developed a Wear and Abrasion Resistance Test (AREMA Test 6) designed specifically for concrete crossties and fastening systems [5]. This test allows tie and fastener designers to gather data on individual components' wear as the components and materials interact as a system. Although AREMA Test 6 is a representative test for full-scale concrete crosstie and fastening systems, it does not generate quantifiable abrasion on the concrete rail seat

TABLE 1
Concrete mix designs for specimens with mineral admixtures.

Mix Constituent / Information	Units	Control	15 % FA	30 % FA	5 % SF	10 % SF
Batch Volume	M^3	0.06	0.06	0.06	0.06	0.06
Cement	kg	21.47	18.25	15.03	20.40	19.32
SF	kg	0.00	0.00	0.00	1.07	2.15
FA	kg	0.00	3.22	6.44	0.00	0.00
Coarse Aggregate	kg	60.70	60.70	60.70	60.70	60.70
Fine Aggregate	kg	40.86	40.86	40.86	40.86	40.86
Metal Fiber	kg	0.00	0.00	0.00	0.00	0.00
Polymer Fiber	kg	0.00	0.00	0.00	0.00	0.00
Actual Water	kg	8.73	8.73	8.73	8.73	8.73
Theoretical Water	kg	6.88	6.88	6.88	6.88	6.88
Air Entrainment	mL	10.00	10.00	8.00	10.00	7.00
HRWR[a]	mL	160.00	130.00	55.00	130.00	170.00

[a] High Range Water Reducer.

TABLE 2
Concrete mix designs for FRC.

Mix Constituent / Information	Units	FRC 0.3 % Poly	FRC 0.5 % Poly	FRC 0.5 % Steel	FRC 1 % Steel
Batch Volume	M^3	0.06	0.06	0.06	0.06
Cement	kg	21.47	21.47	21.47	21.47
SF	kg	0.00	0.00	0.00	0.00
FA	kg	0.00	0.00	0.00	0.00
Coarse Aggregate	kg	60.70	60.70	60.70	60.70
Fine Aggregate	kg	40.86	40.86	40.86	40.86
Metal Fiber	kg	0.00	0.00	2.21	4.41
Polymer Fiber	kg	0.16	0.26	0.00	0.00
Actual Water	kg	8.73	8.73	8.73	8.73
Theoretical Water	kg	6.88	6.88	6.88	6.88
Air Entrainment	mL	10.00	10.00	7.00	7.00
HRWR[a]	mL	180.00	180.00	170.00	170.00

[a] High Range Water Reducer.

within a reasonable amount of time. In fact, the test typically focuses on the wear performance of other components of the fastening system such as the rail pad, insulator, etc. Although RSD has been initiated with Test 6, most tests have resulted in insignificant amounts of wear of the concrete rail seat.

In addition to AREMA Test 6, there are other tests used to evaluate the abrasion resistance of concrete that are prescribed by the concrete materials industry. ASTM C779/C779M contains three submethods for testing. Method A is the revolving disks method, in which three revolving steel disks—each rotating about their own axis and an axis central to all three—are placed on the concrete while an abrasive slurry is added. Method B has three sets of steel dressing wheels that continuously roll over the concrete specimen while an abrasive slurry is added. Method C is the ball bearings method, in which 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 and require complicated test setups that are not easily obtained or constructed. Also, the results from Methods B and C have high coefficients of variation [44].

The fourth test to evaluate the abrasion resistance of concrete is found in ASTM C944/C944M, *Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method*, and subjects concrete specimens to small abrasive wheels that are attached to a drill press [44]. The fifth test is ASTM C627-10, *Standard Test Method for Evaluating Ceramic Floor Tile Installation Systems Using the Robinson-Type Floor Tester* [45]. This test was adapted to abrade concrete by allowing three hardened steel wheels to traverse the concrete surface in a circular path.

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, *Methods of Testing for Natural Building Stones*, and British Standard BS 812-113:1990, *Testing Aggregates. Method for Determination of Aggregate Abrasion Value (AAV)*, are similar and involve a concrete specimen being applied to a rotating steel wheel [46,47]. An abrasive slurry can also be applied to the wheel, and the depth of wear is recorded after a set amount of time.

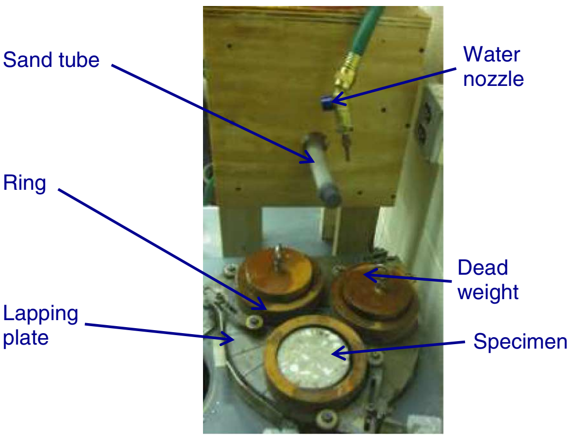
Limitations and lessons learned from the design of previous tests led UIUC researchers to develop the SSTAR. The relative simplicity of the test apparatus and procedure combined with lower equipment costs make SSTAR an ideal alternative to the abovementioned tests.

SSTAR

TEST SETUP

The SSTAR was constructed by modifying a lapping machine that is typically used to sharpen tools or create flat, smooth surfaces on machined metal parts (**Fig. 2**) [16]. The lapping machine is composed of a revolving steel plate with concrete specimens loaded in three counter-rotational rings that rest on top of the plate. The three rings are held in place by small rubber wheels attached to the main frame. This allows the circular specimens to revolve around their center while still maintaining the same position relative to the revolving lapping plate. A dead weight that weighs 4.5 lbs (2 kg) is placed on top of each specimen to provide a normal load. To represent the influence of three-body

FIG. 2
SSTAR setup.



wear, an abrasive slurry of water and sand is applied to the lapping plate throughout the test at a uniform rate to abrade the concrete surface that mates against the lapping plate. Water is delivered to the lapping plate through a plastic tube that has a valve to control the flow rate.

SSTAR TEST PROTOCOL

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 mix design (i.e., specimens without any admixture or fiber and are cured in 100 % humidity) will hereafter be referred to as "control specimens." Any change in abrasion resistance is measured relative to the control specimens. Six specimens (or replicates) were tested for each abrasion mitigation approach. Each specimen was cured for 28 days before the abrasion resistance tests were conducted. Next, the concrete specimens were marked to identify the wearing surface (the as-cast surface). The as-cast surface is defined as the surface that is in contact with the closed end of the cylindrical mold. Also, we marked the locations where thickness readings were to be taken. Vernier calipers were used to measure the initial thicknesses at the four marked locations. We placed three specimens in the lapping machine rings and applied dead weights. At the same time, an abrasive slurry of water and manufactured sand was introduced into the specimen-lapping plate interface. The manufactured sand used in this research is Ottawa sand and has a gradation of 20–30, which indicates that the sand particles pass through a nominal sieve opening size of 841 μm and are retained on a nominal sieve opening size of 596 μm. The total test duration was 100 minutes, with thickness measurements taken at 20-minute time intervals.

After testing, the wear depth (i.e., the difference between initial and final thicknesses taken at every time step using vernier calipers) was plotted with respect to testing duration to represent the progression of abrasion with time (wear rate curves). The wear rate is used as a metric to quantify abrasion resistance of concrete instead of weight or volume loss, or both. This is done to counter the variability induced by the weight and volume loss measurements due to absorption of water by the concrete specimens during testing.

Experimental Results and Discussion

Figs. 3, **4**, and **5** show the wear rate curves for specimens, in which each data point represents the average wear depth value obtained from the six specimens at a specific time step. Error bars representing two standard errors (both positive and negative) in wear depth are shown on all data points. As the wear curves shift downward on the graph, it can be understood that the corresponding abrasion mitigation approach shows higher abrasion resistance based on SSTAR testing. **Table 3** summarizes the percentage change in abrasion resistance of various specimen types relative to control specimens. **Fig. 6** summarizes the compressive strength data obtained for all the concrete mix designs tested in this study.

EFFECT OF MINERAL ADMIXTURES

The addition of 15 % FA improved the abrasion resistance by 30 %, whereas increasing the FA content to 30 % reduced the abrasion resistance by 3 %. Although concrete with a higher percentage of FA typically takes longer to gain full strength, the compressive strength (at 28 days) of the 30 % FA was found to be higher than that of the 15 % FA [22]. Therefore, the slow pozzolonic reactions that typically characterize FA concrete

FIG. 3

Wear rate curves of specimens with admixtures.

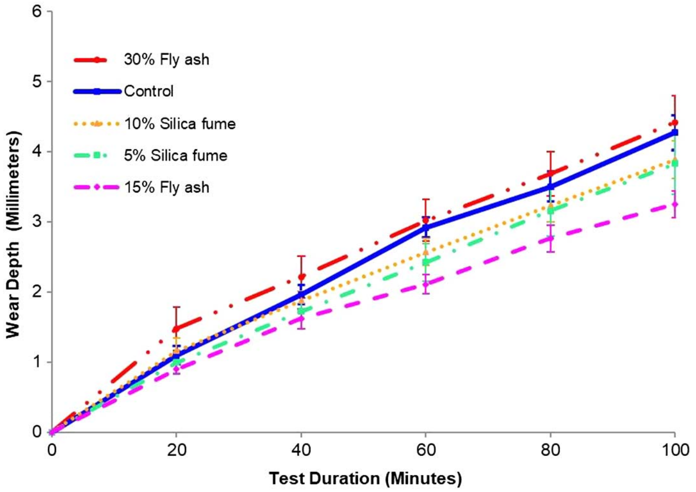
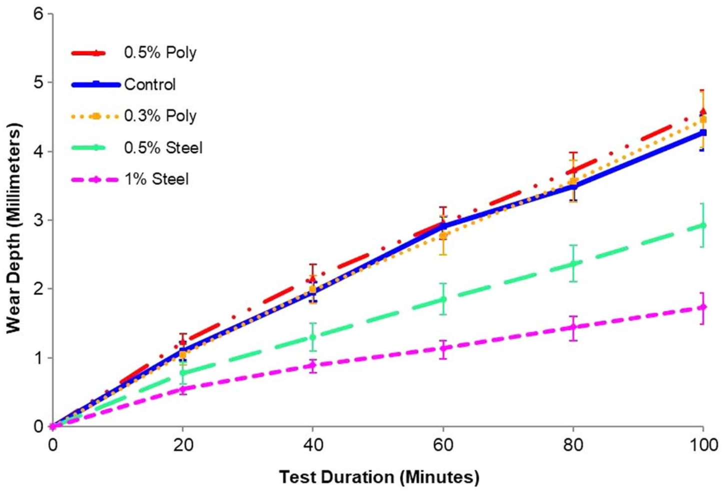


FIG. 4

Wear rate curves of various specimens with FRC.



cannot explain the difference between 15 % FA and 30 % FA. When proportioning the concrete mixtures, the amount of water should have been adjusted for these mixes because the water demand decreases as the amount of FA increases. Excess water in the fresh concrete likely increased the permeability, especially at 30 % replacement, thus reducing the abrasion resistance.

Data from SSTAR showed that the addition of small amounts of SF, 5 % and 10 %, improved the abrasion resistance by 10 % and 12 %, respectively (Fig. 3). The improvement in SF specimens is lower than that of 15 % FA specimens, possibly because of the presence of microlumps in the SF, which results in a nonuniform dispersion of SF particles while mixing the concrete. Also, excess water may have been present because the amount of water was not adjusted, and the increased permeability could have reduced the abrasion resistance.

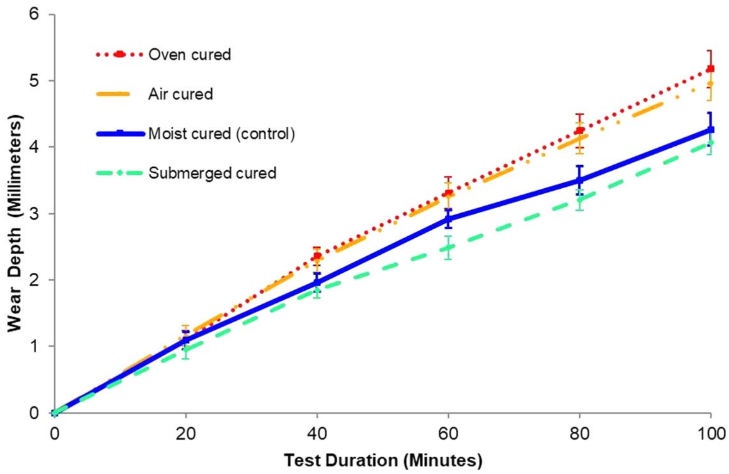


FIG. 5
Wear rate curves of specimens prepared under alternative curing conditions.

TABLE 3
Change in abrasion resistance relative to control specimens.

Specimen Type	Change in Abrasion Resistance (%)
Control	*
15 % FA	20
30 % FA	−3
5 % SF	10
10 % SF	12
Oven Cured	−16
Air Cured	−16
Submerged Cured	5
0.3 % Poly	10
0.5 % Poly	8
0.5 % Steel	41
1 % Steel	65

FRC

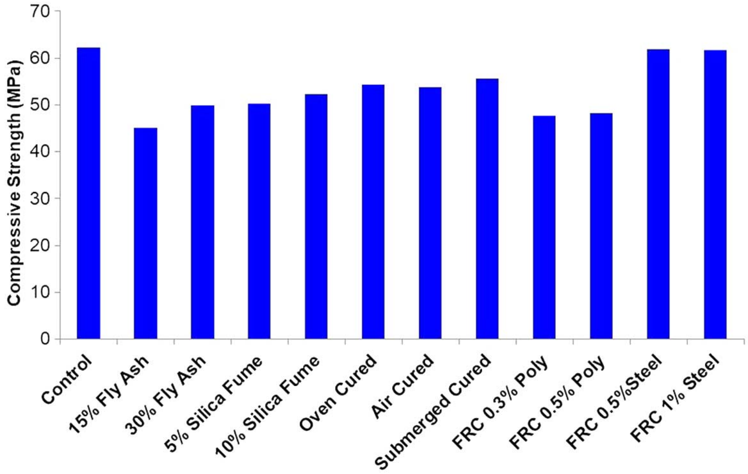
Steel fibers were found to significantly improve the abrasion resistance of concrete by 41 % (0.5 % steel) and 61 % (1 % steel) (Fig. 4). Poly fibers were less effective than steel fibers because they improved the abrasion resistance of concrete by 10 % (0.3 % poly) and 8 % (0.5 % poly) (Fig. 4). It was observed that fibers protected the concrete from abrasion by acting as a protective layer between the concrete and the abrasive lapping plate. Also, the corrugations in the steel fibers seemed to act as an anchor for the surrounding concrete, thereby not allowing particles to dislodge from the surface.

EFFECT OF CURING CONDITION

Curing conditions seem to have a slight impact on the abrasion resistance of concrete. Submerged specimens cured in a pool of water showed an improvement of approximately 7 % relative to the abrasion resistance of the control specimens (Fig. 5). The rest of the curing conditions tested such as air curing and oven curing resulted in a reduction in

FIG. 6

Compressive strength data.



abrasion resistance of concrete relative to control specimens, which was likely due to the lack of adequate moisture content at the surface of the concrete.

Conclusions

SSTAR is capable of producing quantifiable abrasion of concrete specimens in an accelerated manner. Also, based on the results obtained from SSTAR, the experimental test setup proved to be a reliable and representative alternative to existing abrasion resistance tests and provided repeatable data. This is illustrated in Figs. 3, 4, and 5, where the error bars representing two standard errors do not indicate a wide scatter of data. Through experimental testing using the SSTAR, researchers at UIUC have successfully compared 21 abrasion mitigation approaches involving material improvements.

Replacing cement with SF or FA appears to be a feasible method of improving the abrasion resistance of concrete. Each concrete mixture should be optimized based on local materials because the relationship between the quantity of added mineral admixtures and increased abrasion resistance is not a direct relationship. Steel fibers were found to significantly improve the abrasion resistance, but the effect of steel fibers on the fastening system components must be evaluated before steel fibers are included in concrete crosstie design. Finally, the curing conditions had a noticeable impact on the abrasion resistance of concrete. The surface of the concrete must have significant moisture available during curing in order to maximize the performance of the concrete in an abrasive environment.

Future Research

As part of an effort to develop a simplified industry-standard abrasion resistance test for concrete crossties, data obtained from SSTAR will be correlated with the data from AREMA Test 6 (Wear and Abrasion) on the Pulsating Load Testing Machine at UIUC. Ultimately, this research will help in formulating design recommendations for the industry to mitigate RSD from a materials standpoint.

Another research project is underway at UIUC, which aims to evaluate the performance of HPC mix designs in concrete crossties. This will be done by conducting a comprehensive array of tests to evaluate the durability of concrete crossties. Results from this project will supplement the conclusions from the current study related to the abrasion resistance of various rail seat materials.

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