Degradation Mechanisms of Concrete Due to Water Flow in Cracks of Prestressed Railroad Sleepers under Cyclic Loading

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Abstract: Visual inspection and field experience from concrete railroad sleepers (crossties) provide evidence that cyclic loading of train axles accelerates their degradation in areas of high precipitation. Because prestressing forces close flexural cracks after every load application, this repetitive motion generates water flow within cracks. In this study, multiple mechanisms are systematically investigated through laboratory experimentation to understand the deterioration of concrete in cracked prestressed beams exposed to moisture and under cyclic loading. Results identified abrasion as the leading degradation mechanism. High hydraulic pressures, cavitation, and leaching damage are also investigated but seem less likely to govern this problem. **DOI: 10.1061/(ASCE)MT.1943-5533.0004144.**

Introduction

Water flow in cracks may be an important factor in accelerating flexural distress in pretensioned concrete beams subjected to loading conditions similar to railroad sleepers (crossties). Field observations indicate that cracked sleeper deterioration is accelerated in locations with high precipitation (Fig. 1).

Concrete sleepers crack at the top when center-binding support conditions induce sufficiently high negative bending moments. These cracks repeatedly open and shut as wheels pass over the sleeper, a consequence of cyclic application and removal of wheel loads combined with the effect of the prestressing loads in the sleeper. If water is present, such as during or after precipitation events, it will enter the open cracks and then be expelled from or trapped in them when the cracks close. We have observed that the water flow in and out of cracks may cause concrete damage and affect the structural integrity of sleepers and other prestressed concrete beams subjected to similar loading conditions. In this novel investigation, we wanted to identify the mechanism of concrete degradation observed when water is present in flexural cracks of cyclically loaded prestressed beams. Based on relevant literature and experience, various hypotheses were proposed and tested experimentally.

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Note. This manuscript was submitted on September 19, 2020; approved on August 13, 2021; published online on January 22, 2022. Discussion period open until June 22, 2022; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, © ASCE, ISSN 0899-1561.

Investigation Approach and Results

In the following sections, the question of what is the leading degradation mechanism of concrete is addressed with multiple hypothetical answers that are evaluated experimentally and analytically. This method of study is referred to as the *method of multiple working hypotheses*, as described by Chamberlin (1965). Its primary advantage is the reduction in bias to prove a theory true due to *parental affection*, which would be greater if only one hypothesis was investigated. In our investigation, we followed the traditional approach of hypothesis rejection (Popper 2005), by which the phenomenon being evaluated is suppressed. This suppressed phenomenon represents the null hypothesis, which is expected to be rejected.

The laboratory experiments described next were carried out with common designs of concrete sleepers, scaled beams (prisms), or both. The concrete sleepers used are typical of North American heavy axle load (HAL) freight railroad applications, which are prestressed beams made with high-strength concrete (Bastos et al. 2017). The sleepers were 2,591 mm (102 in.) long and had a ratio of steel in the center cross section of 0.0114. Their concrete strength was 56.8 MPa (8.2 ksi) and they were constructed with 20 wires pretensioned to 31.1 kN (7 kips) each. The prisms are scaled pretensioned beams intended to represent sleepers (Momeni et al. 2018). They were used to better control variability in laboratory tests, increase experimental practicality, and provide generalized results (Fig. 2). Four pretensioned steel wires of the same type adopted by one of the crosstie designs were used, and the ratio of steel to concrete in the cross-sectional area was like those of real concrete crossties at their center section. The wires were made of Grade 250, low-relaxation steel, with a chevron indent pattern of 0.119 mm (0.0047 in.) depth, and had a diameter of 5.32 mm (0.21 in.). Each wire was pretensioned to 31.1 kN (7 kips), and the wires were released 5 days after the concrete pour [concrete release strength over 55 MPa (8 ksi)]. The prisms were 1,067 mm (42 in.) long to ensure that the development length did not reach the test span, which was 267 mm (10.5 in.) long. This allowed for a development length of 400 mm (15.75 in.). Based on the experiments presented by Momeni et al. (2018), the transfer length should be less than 274 mm (10.4 in.) because the concrete release strength was higher than that in the cited experiments (cf. wire type

Fig. 1. Center-cracked pretensioned concrete sleeper after precipitation event.

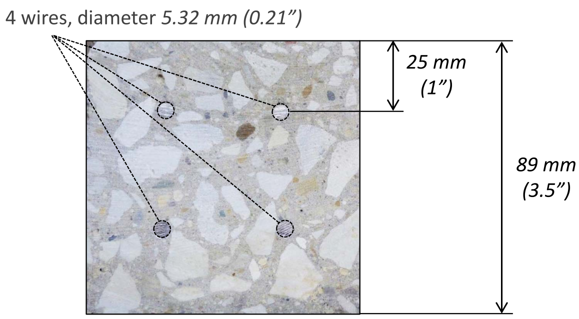

Fig. 2. Cross section of pretensioned concrete prisms.

WI). The chosen cross-sectional dimensions are shown in Fig. 2. Two prism batches were cast, one with a concrete strength of 66.9 MPa (9.7 ksi) and the other with a strength of 90.3 MPa (13.1 ksi).

When prestressed concrete beams crack in flexure, the cracks formed are narrow and are sometimes referred to as hairline cracks. This type of cracking is typical in standard laboratory tests and is only visible when loads are applied because of the resistance exerted by internal prestressing forces. Nevertheless, concrete sleepers in the field develop cracks that are significantly more severe than those in the laboratory environment, sometimes leading to a loss of concrete cover (Fig. 3).

Concrete degradation is accelerated under field conditions, but the cause of this degradation is not obvious. In the following sections, we investigate how the presence of water contributes to this degradation. When addressing hydraulic structures, the American Concrete Institute (ACI) identifies three common causes for concrete erosion: cavitation, abrasion, and chemical attack [American Concrete Institute Committee 210 (ACI 1998)]. One additional possibility is the presence of high hydraulic pressures in confined spaces, such as inside flexural cracks. One relevant application is that of hydraulic fracturing (fracking), a common method used to extract shale gas. Fracking uses pressures of 25 MPa (3.6 ksi) at the bore hole surface, with higher pressures generated at the end of bore holes (Bažant et al. 2014).

Fig. 3. Observation of severe expansion of flexural cracks.

Therefore, we considered four hypotheses (Fig. 4):
1. Concrete fails due to bursting pressures caused by pressurized water in cracks.
2. Concrete is damaged by cavitation within cracks.
3. Concrete is weakened from increased porosity due to leaching of its constituents.
4. Concrete erodes due to action of abrasive fluid (water and fines) in cracks.

In the following sections, we further describe each of these hypotheses and the related tests.

Concrete Fails Due to Bursting Pressures Caused by Pressurized Water in Cracks (M1)

When hypothesizing that concrete fails due to high hydraulic pressure in cracks, we assumed that water was trapped when the prestress forces closed them, causing internal pressures that were higher than the concrete tensile strength. To test this hypothesis, we designed laboratory experiments in which the internal hydraulic pressures could be measured in cracks within pretensioned concrete prisms.

The effects of water pressure inside cracks in concrete structures, such as gravity concrete dams, have been the subject of a great deal of research. Bruhwiler and Saouma (1995a, b) investigated the consequences of high hydraulic pressure from the water head within a dam. By experimenting with a wedge splitting device and pressurized water, they concluded that plain concrete experiences a reduction of fracture toughness and fracture energy in the presence of water-pressurized cracks for pressures higher than 0.1 MPa (14.5 psi). They also suggested that hydraulic pressure within cracks is a function of crack displacements. Chen et al. (2017) also experimented with a wedge splitting device that was combined with a novel sealing apparatus to pressurize the water around a concrete specimen. They applied two static loading rates, one being 100 times greater than the other, and concluded that the pressure distribution and crack propagation rate was different for each case (Chen et al. 2017). Wang et al. (2019) added to this research and found that unstable fracture toughness and cohesive fracture toughness decrease with increasing water pressure. Beyond the study of single loading events, Javanmardi et al. (2005) developed a laboratory test setup to simulate seismic water pressure in cracked concrete gravity dams (Fig. 5). They also developed a theoretical model for the problem based on the theory of rock hydraulics developed by Louis (1969, 1972).

In concrete sleeper research, hydraulic pressure has been associated with rail seat deterioration (RSD). Bakharev and Struble (1997) hypothesized that hydraulic pressure damage was a contributing mechanism to RSD. Zeman et al. (2012) tested this hypothesis and demonstrated that, for certain conditions, surface water pressure can be sufficiently high to cause cracking of the rail seat surface. Other than RSD, there has been no research published on the effects of water flow and hydraulic pressures on concrete sleeper degradation.

In our experiments, the prisms were completely submerged in water and cyclically loaded in three-point bending with pressure transducers inserted into the flexural cracks (Fig. 6). To ensure this connection, special features were added. Two holes with diameters of 3.2 mm (0.125 in.) crossed the prisms, front to back, at a 45° angle (Fig. 7). The holes were placed in horizontal planes at 12.7 and 38.1 mm (0.5 and 1.5 in.) from the bottom surface, thereby ensuring their placement in the tensile region under flexure (i.e., below the neutral axis). One end of each hole was closed while the

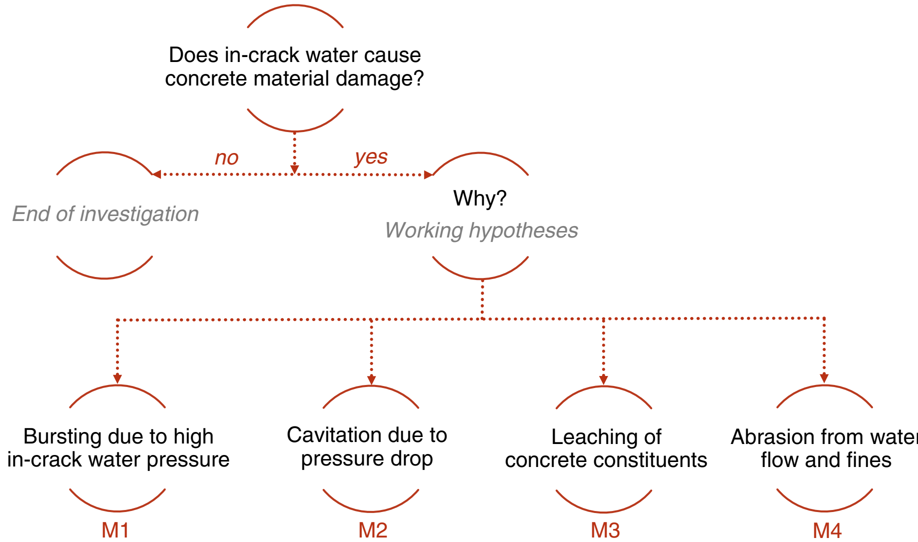

Fig. 4. Hypotheses for accelerated deterioration of concrete material (numbered M1-M4).

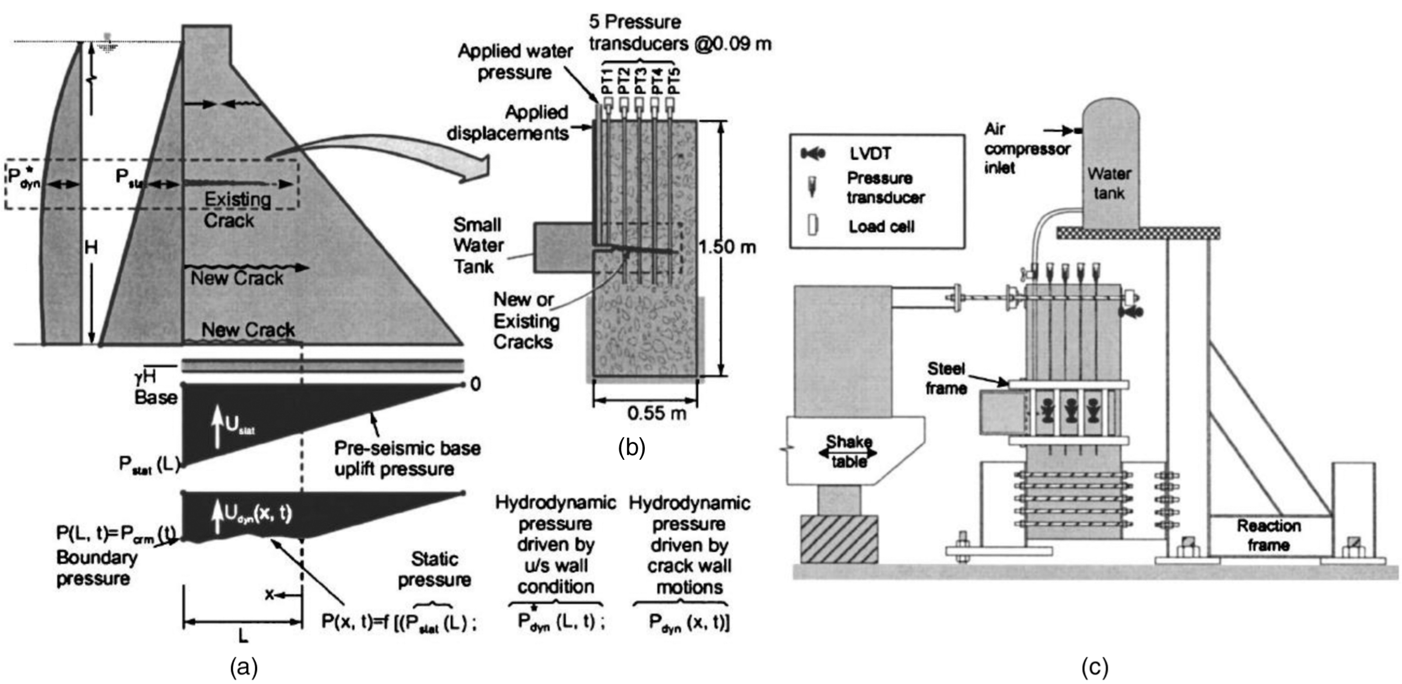

Fig. 5. Laboratory setup for measuring water pressures inside cracks subjected to seismic motions in concrete gravity dam. (Reprinted from Javanmardi et al. 2005, © ASCE.)

other was attached to a pressure transducer with a connector. Each connector was made with a compression fitting adapter linked to a 3.18 mm (1/8 in.) outside diameter copper tube glued and soldered to a 1.59 mm (1/16 in.) outside diameter brass tube. The connectors were attached to the prisms with the brass tube fitting inside the precast holes and attached to the concrete specimen with glue and epoxy (Fig. 8). A notch was placed on the prisms to control the location of crack initiation. When subjecting notched prisms to three-point bending, only one crack is generated. The crack grows under load, crossing the precast holes, and allowing water to fill them and interface with the pressure transducers.

We tested a total of seven prisms equipped with pressure transducers. For each test, load was applied at 70% or 80% of the ultimate load (i.e., flexural capacity in air), and the frequency of loading varied between 1, 2, and 6 Hz (Table 1). Higher loads create deeper cracks and shorten testing time (specimens fail after approximately 8,000 cycles). The tests were conducted at different frequencies to identify the effect of crack closing speed on hydraulic pressure (the faster the load is removed, the faster the cracks close), with the selected frequency roughly reflecting the loading pattern sleepers experience with common freight train speeds.

All experiments showed hydraulic pressures below 0.034 MPa (5 psi), which is negligible when compared to the concrete tensile strength of 4.8 MPa (700 psi). Typical pressure measurements indicate that high loads correspond to low pressures (Fig. 9).

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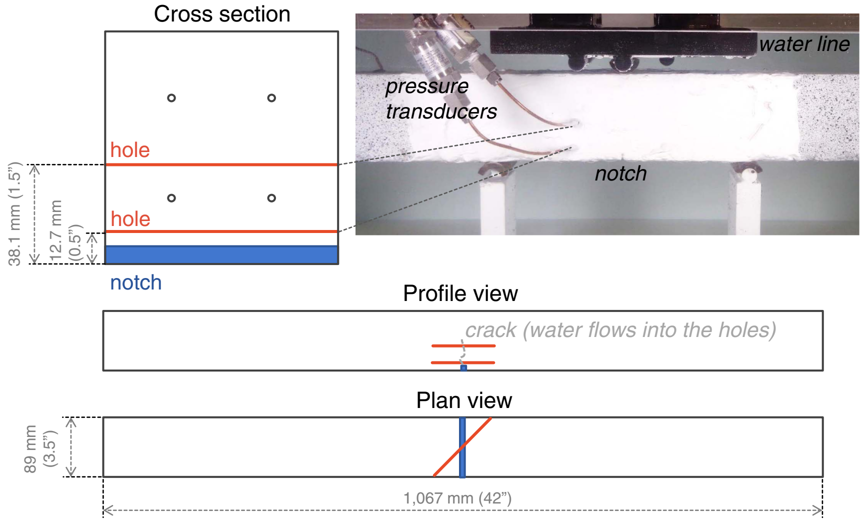

Fig. 6. Schematic of prism with pressure transducers and submerged three-point bending configuration photograph.

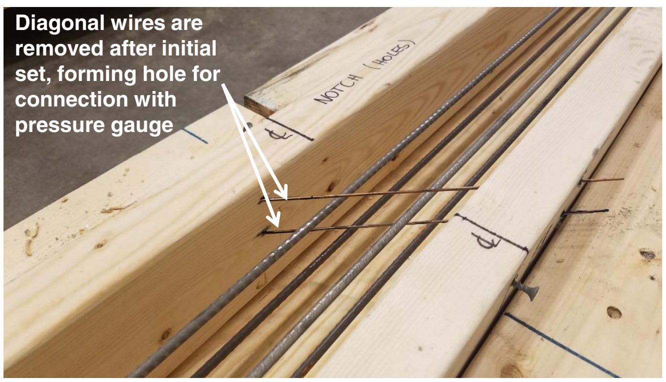

Fig. 7. Form detail showing method for precasting 1.59 mm (1/16 in.) holes (diagonal wires removed after initial set of concrete).

This is reasonable given that water flows into an open crack when load is applied. Decreasing loads correspond to high pressures because that is when the crack closes and the prestressing force pressurizes water in the crack. The low pressure values were not due to the formation of multiple cracks because the experimental design was successful in inducing only one flexural crack. This was confirmed with digital image correlation (DIC) results (Fig. 10).

The DIC variable shown in Fig. 10 is principal strain, but no scale is provided given the objective of presenting this figure is for visualization of a singular crack location. Even through water and with some concrete spalling, the crack opening displacements are much greater than the concrete deformation strains, making them clearly identifiable. For regions where the speckled pattern was not present, the rough concrete surface was sufficient for the DIC strain computation needed to identify concrete cracks. In addition, recorded videos and the inspection of the region of expelled


(a) (b)

Fig. 8. (a) Pressure transducer connector; and (b) attachment to prism.

Table 1. Test conditions for prisms equipped with pressure transducers

Specimens tested	Load level (fraction of ultimate in air)	Loading frequency (Hz)
3	0.8	1
2	0.8	6
1	0.8	2
1	0.7	1

debris, which will be discussed in the section "Concrete Erodes due to Action of Abrasive Fluid (Water and Fines) in Cracks (M4)," confirm the formation of a single crack. Moreover, the pressure results also agreed in magnitude with the hydrodynamic pressures driven by crack wall motions reported by Javanmardi et al. (2005) in their experiments with plain concrete (Fig. 5). As such, because the maximum pressures were considerably lower than the concrete tensile strength, hydraulic pressure is unlikely to be the sole cause of accelerated concrete deterioration.

There are, however, limitations to the presented approach. The magnitude of hydraulic pressure at the crack tip may differ from that measured in our experiment. Moreover, concrete tensile strength may not be the best metric to define a pressure threshold for failure since it is a bulk material property that represents an average behavior of a rapid sequence of micro failures of a material. For a localized investigation of a crack tip, it may be useful to use concrete fracture mechanics concepts. These include consideration of stress concentration factors at the crack tip, modes of fracture, and strain energy dissipation (Hashtroodi 2015). Research has demonstrated the feasibility of using numerical simulations to model crack propagation in concrete sleepers using parameters such as fracture toughness (critical stress intensity factor), crack length, and crack mouth opening displacement (Farnam and Rezaie 2019; Rezaie et al. 2012; Rezaie and Farnam 2015). Despite these considerations, it is expected that a fracture at the crack tip will only be affected by hydraulic pressures greater than 14.5 psi (0.1 MPa) (Bruhwiler and Saouma 1995a, b), as mentioned earlier.

Concrete Is Damaged by Cavitation within Cracks (M2)

Under this hypothesis, water flow velocity is high enough to cause cavitation in the presence of surface irregularities within cracks. We assumed that there was water suction during the opening movement of cracks, leading to pressures as low as the water vapor pressure and, thus, forming bubbles. The bubbles then collapse due to the sudden increase of pressure caused by the crack closing. We tested this hypothesis experimentally with prisms being cyclically loaded at different frequencies.

If cavitation happens, then the deterioration rate should be higher for greater water flow velocities (the more rapidly the crack opens and closes, the more bubbles form and collapse). Cyclically loading prisms under water at different frequencies should lead to different water flow velocities and, thus, different cycles to failure. Therefore, the cavitation hypothesis should be rejected if the number of cycles to failure is not correlated with loading frequency.

We subjected prisms to four-point bending in a configuration based on the ASTM standard C78/C78M–16 (ASTM 2016, p. 78) (Fig. 11). Unlike the specimen typically used for plain concrete, the prestressed test prism is longer than the test span to ensure prestressing forces are fully developed in the region of testing. Loading frequencies included 1, 2, 2.5, and 6 Hz, while the load level varied from 0.5 to 0.8 of the reference ultimate load. We carried out 17 additional tests (Table 2), generating 24 total data points including

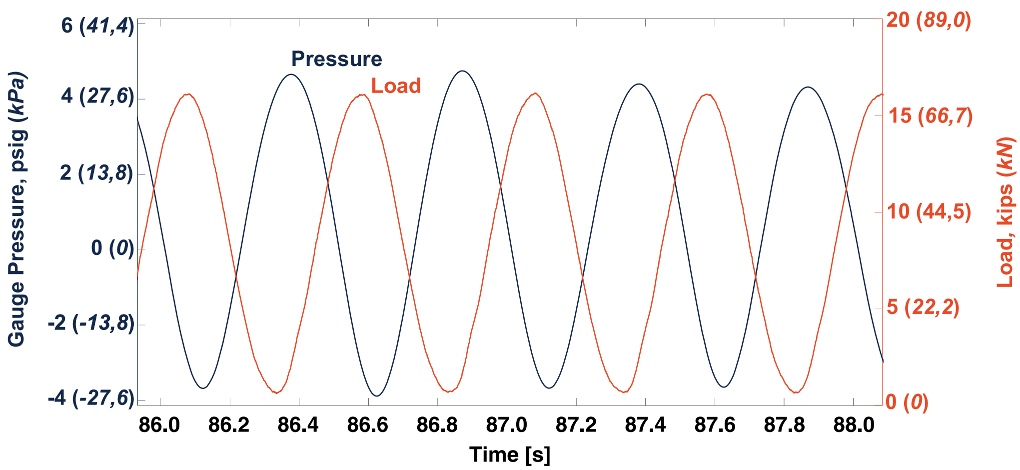

Fig. 9. In-crack water pressure in submerged cyclic loading test. (Note: 1 psi = 6.9 kPa; 1 kip = 4.4 kN.)

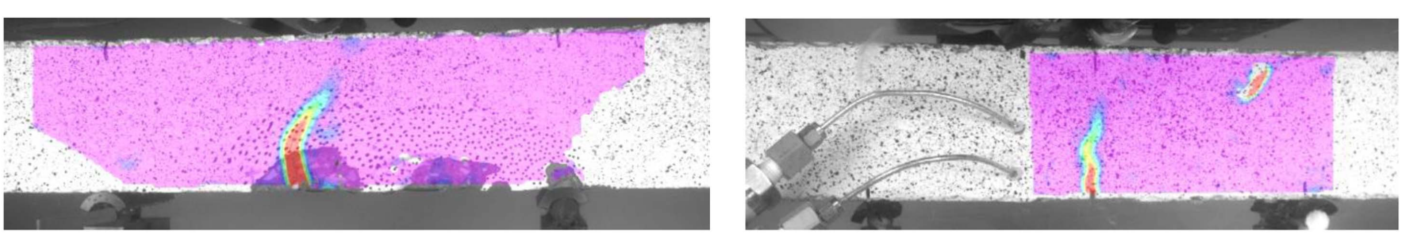

Fig. 10. Strain maps of submerged prisms generated with DIC showing that only one flexural crack was generated in three-point bending.

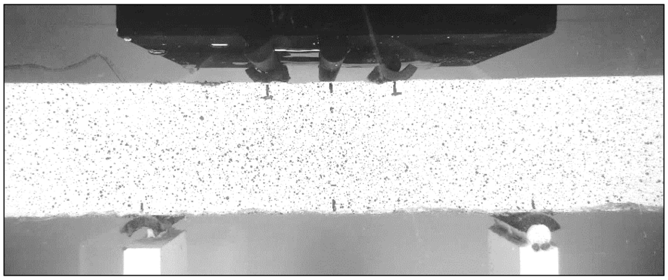

Fig. 11. Underwater prism in four-point bending configuration.

Table 2. Experimental conditions for prisms tested in four-point bending under water

Specimens tested	Load level (fraction of ultimate in air)	Loading frequency (Hz)	Prism batch
1	0.80	2	1
3	0.80	1	1
3	0.70	1	1
3	0.60	2.5	2
5	0.57	2.5	2
2	0.49	2.5	2

Table 3. Test results used in ANOVA procedure

Test run	Batch	Load	Frequency (Hz)	Cycles
1	1	0.80	2	644
2	1	0.80	1	586
3	1	0.80	1	498
4	1	0.80	1	631
5	1	0.80	2	11,353
6	1	0.80	6	2,129
7	1	0.80	6	10,438
8	1	0.80	1	10,420
9	1	0.80	1	4,914
10	1	0.80	1	7,450
11	1	0.70	1	443
12	1	0.70	1	1,175
13	1	0.70	1	2,912
14	1	0.70	1	5,209
15	2	0.60	2.5	28,992
16	2	0.60	2.5	627
17	2	0.60	2.5	24,956
18	2	0.49	2.5	5,000,000
19	2	0.49	2.5	790,218
20	2	0.57	2.5	38,211
21	2	0.57	2.5	855,914
22	2	0.57	2.5	1,851
23	2	0.57	2.5	1,217
24	2	0.57	2.5	769,241

the three-point bending results from the water pressure investigation (Table 3).

We used a statistical model to investigate the effect of frequency on number of cycles to failure (in logarithmic scale) through ANOVA. The model accounted for load level, loading frequency, support condition, and prism batch. The latter two are classification variables, because support condition can be three- or four-point bending (also a proxy for number of cracks), and prism batch accounts for the fact two batches of prisms were cast. When carrying

Table 4. Significance of loading frequency and other variables on cycles to failure

Variable	t-statistic	p-value
Intercept	2.34	0.03
Load level	−2.11	0.05
Prism batch	0.01	1.00
Support condition	2.24	0.04
Loading frequency	0.11	0.91

out this analysis, the residuals were verified to be uniformly distributed (Shapiro and Wilk 1965) with homogeneous variance (Brown and Forsythe 1974). The ANOVA results showed that the effect of loading frequency on cycles to failure is not statistically significant ($p = 0.91$) (Table 4).

The statistical analysis was not the only evidence favoring rejection of the cavitation hypothesis. The previous hydraulic pressure results (Fig. 9) indicated intake pressures around −20 kPa gauge pressure (−3 psig), which is equivalent to about 80 kPa absolute pressure. These are not low enough to reach water vapor pressure, which is about 3 kPa absolute pressure (0.4 psi) (Lide 2004). Without reaching water vapor pressure, vapor bubbles will not form, preventing cavitation from happening.

Concrete Is Weakened from Increased Porosity Due to Leaching of Its Constituents (M3)

The third hypothesis is that leaching of concrete constituents plays a role in the degradation of concrete. We assumed that such leaching weakened the concrete by lowering its resistance to abrasion. To test this, we subjected prisms and sleepers to cyclic four-point bending while exposing them to a solution similar to concrete pore water to suppress leaching. We then compared their cyclic life with those in plain water.

Before describing the hypothesis and experiments, it is necessary to provide background on leaching and its consequences. Calcium hydroxide (CH in cement chemistry notation) is the primary component that leaches out of the concrete matrix, which can correspond to approximately 20% of a mature cement paste by volume (Mehta and Monteiro 2014). In pure water, CH dissociation follows the reaction

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$$

The kinetics of this reaction are governed by Fick's law of diffusivity [Eq. (6)], in which J represents the mass transport rate, D is the diffusion coefficient, and dC/dx is the concentration gradient. Low values of pH and Ca^{2+} concentration, therefore, contribute to a faster rate of reaction

$$J = D\left(\frac{dC}{dx}\right) \quad (1)$$

Although CH is not considered a primary contributor to concrete strength, previous research has shown that CH leaching can affect the mechanical properties of concrete. Carde and François (1997) investigated the effect of calcium hydroxide leaching from cement paste on the compressive strength and porosity of cement paste samples, which were 20 × 40-mm cylinders. They reported that samples with 100% "deteriorated area" (where the residual calcium content in the solid phase was less than a threshold) showed a 75% decrease in compressive strength and a 20% increase in porosity. Despite the study limitations (e.g., small sample size and lack of control of C–S–H decalcification), these experiments

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demonstrated the consequences of leaching. In an extensive literature review, Duchesne and Bertron (2013) provided "a description of the media, and the degradation mechanisms of cementitious materials by pure water and strong acids," alluding to reaction kinetics and concrete durability. They summarize the results of several studies showing evidence that CH leaching increases concrete porosity and permeability. The increase in porosity is commonly associated with reduction in abrasion resistance (Atiş 2003; Dhir et al. 1991; Liu et al. 2006). It has also been shown that porosity-decreasing cementitious materials (such as silica fume) in concrete increases its abrasion resistance (Liu 2007; Shurpali et al. 2013). There is, therefore, a potential correlation between leaching and lowering of abrasion resistance. Rosenqvist et al. (2017) considered the synergistic effects between leaching, frost action, and abrasion on the surface deterioration of concrete. Through laboratory experimentation, they showed that the total deterioration caused by these mechanisms happening simultaneously is greater than the sum of the deterioration caused by each mechanism separately. In addition, when freeze-thaw or abrasion damage takes place, it also increases the leaching rate because the removal of the deteriorated concrete surface increases the diffusion coefficient in accordance with Fick's law.

For cracked concrete sleepers, our hypothesis of leaching damage is based on the following sequence of events. First, porosity increases once CH leaches out of open cracks due to the presence of water (e.g., from rain, snow). Second, cracks close and an abrasive flush of water and fines remove the weakened, leached surface, keeping the diffusion coefficient high because the leached surface is not present to pose a physical barrier. Then, fresh water again enters the crack when it reopens, restarting the cycle. Thus, leaching may not reduce over time as it would in other structures when the leached surface is not removed, or the outside water solution reaches equilibrium with the concrete pore water (i.e., rainwater pH does not increase).

To test this hypothesis, we compared the number of cycles to failure of prisms and sleepers subjected to leaching to those with negligible leaching. If the cyclic life with and without leaching is similar, then it follows that leaching is not a mechanism governing deterioration; however, if the specimens subjected to leaching have a significantly shorter cyclic life, then the hypothesis cannot be rejected.

We fully submerged the prisms while applying load in four-point bending at 2.5 Hz up to 60% of the ultimate capacity obtained from dry static tests. We submerged them in either plain water to represent regular leaching conditions or in a solution like the concrete pore water to suppress leaching (Table 5). The latter was a solution of sodium hydroxide and calcium chloride, with pH 12 at a temperature ranging between 20°C and 25°C and a Ca^{2+} concentration of approximately 3 mmol/L. This value for pH is comparable to what is typically found in concrete pore water, while the Ca^{2+} concentration is sufficiently high to prevent C–S–H decalcification (Berner 1992; Page and Vennesland 1983; Rosenqvist et al. 2017). By increasing the relevant concentration gradients, leaching of concrete constituents is drastically reduced in comparison with the control case (plain water).

Table 5. Conditions of prisms tested in four-point bending for leaching investigation

Specimens tested	Load level (fraction of ultimate in air)	Loading frequency (Hz)	Alkaline solution
3	0.6	2.5	No
1	0.6	2.5	Yes

Table 6. Conditions of sleepers tested in four-point bending for leaching investigation

Specimens tested	Load level (fraction of ultimate in air)	Loading frequency (Hz)	Alkaline spray
4	0.7	2.5	No
1	0.7	2.5	Yes

Fig. 12. Setup of water spray for cyclic loading of sleepers.

The cyclic lives for three prisms in plain water were 28,992, 627, and 24,956 cycles (mean of 18,192 cycles). One prism was loaded in the alkaline solution representing concrete pore water and lasted 9,557 cycles. This is an indication that leaching may not be a governing mechanism in this investigation because it was expected that the prism with suppressed leaching would have a much longer life than the others. Although broad differences were observed between data points, this is not unprecedent—cycles to failure are known to have exceedingly high scatter (Shi et al. 1993; Wirsching 1995).

For additional evidence, we also experimented with full-size sleepers in a manner more representative of track conditions (Table 6). Sleepers were not submerged but were subjected to a water spray representing precipitation events (Fig. 12). We arranged them in a four-point bending configuration and loaded at 2.5 Hz up to 70% of the ultimate capacity of dry static tests.

Four sleepers were tested under a plain water spray and failed at 1.01, 1.68, 1.56, and 0.57 million cycles (mean of 1,205,039 cycles). One sleeper was tested under a constant spray of the same alkaline solution used for testing prisms (pH 12 and Ca^{2+} at 3 mmol/L) and failed at 892,500 cycles. Once again, the results suggest that leaching is not a governing deterioration mechanism. The cyclic life of the specimen with negligible leaching was lower than the mean life with normal leaching, which is the opposite of what would be expected if leaching governed deterioration.

It could be argued that there were too few data points to determine the cyclic life of prisms and sleepers. In fact, fatigue experiments are known for having great variability of results (Shi et al. 1993; Wirsching 1995). Nevertheless, our objective was not to precisely determine cyclic life but to observe the effects of leaching. For both sets of experiments (prisms and sleepers), the expected expressive increase in cyclic life was not observed. Future research should consider conducting a chemical analysis of constituent materials in the expelled debris to provide insight into which phases of the concrete matrix are degrading.

Concrete Erodes Due to Action of Abrasive Fluid (Water and Fines) in Cracks (M4)

This abrasion-related hypothesis states that the flow of water and fines abrades internal crack surfaces in prestressed concrete beams. We assumed that the movement of water due to the opening and closing of cracks, combined with the presence of debris (from outside contamination or inside deterioration), could lead to concrete erosion (Fig. 13). We used supporting evidence from

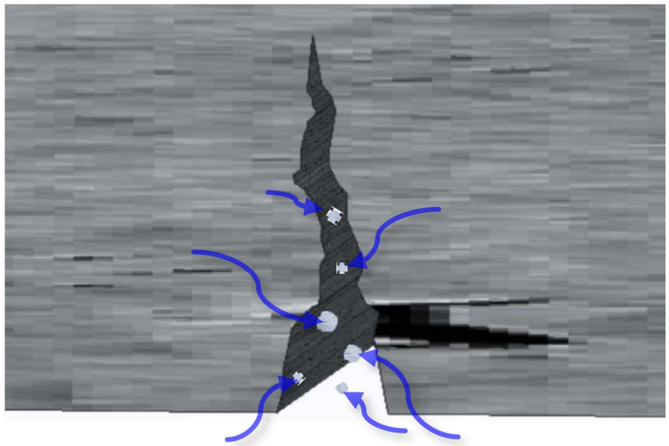

Fig. 13. Schematic showing flow of water and fines to cause hydro-abrasion.

prior experiments, and no additional tests were conducted for the explicit purpose of investigating this hypothesis.

Abrasion is a common concrete sleeper degradation mechanism. It has been identified as a major contributor to RSD and section loss in concrete sleepers, and research has shown that the presence of water contributes to greater damage in both of these cases (Kernes et al. 2014; Riding et al. 2018; Zeman 2010). Hydro-abrasion has also been identified in other concrete applications, such as spillways, culverts, and dams (Kryžanowski et al. 2009; Liu et al. 2006). To prevent confusion, we avoid use of the term *scour* despite its occasional, casual use in reference to abrasion. Scour is defined as the removal of sediment around the foundation of a structure surrounded by a hydraulic flow (Hoffmans and Verheij 1997; Melville and Coleman 2000).

In principle, eliminating water flow is a possible way to test the hydro-abrasion hypothesis. If a sleeper that is not exposed to a water spray fails at the same number of cycles as a sleeper with the spray, then the hypothesis could be rejected. By eliminating water flow, however, the other degradation mechanisms that we investigated are also suppressed (i.e., hydraulic pressure, cavitation, and leaching), and the results would be ambiguous. We needed to develop an experiment that would allow us to differentiate between these alternatives.

A possible experiment consists of cyclically loading a sleeper using the same support and loading configuration previously described, except that the sleeper is kept "wet" but without water flow in cracks. Keeping a sleeper wet is an attempt to eliminate hydro-abrasion while minimizing the suppression of other mechanisms that may happen in a moist condition. Ideally, a wet sleeper would be one saturated with water, but this is not practical. It could take years for a sleeper submerged in water to reach saturation (i.e., capillary pores completely filled with free water) given the low permeability coefficient associated with high-quality concrete having a water-binder ratio less than 0.3 (assuming minor cracking) (Mindess et al. 2003). We envisioned placing the sleeper (or prism) in a moist environment (over 90% relative humidity) without water flow. These, however, are not ideal conditions, because the specific crack surface saturation is uncertain, which could lead to inconclusive tests. In light of these considerations and due to practical challenges, this hypothesis was not evaluated experimentally.

Despite the lack of additional tests, evidence of abrasion damage was found in previous experiments designed to address other hypotheses. For example, when experimenting with prisms, debris were observed being expelled from cracks in an abrasive slurry (Fig. 14). Therefore, there is insufficient evidence to reject hydro-abrasion as a potential mechanism governing concrete deterioration.

After considering abrasion from water flow and fines, a different type of abrasion mechanism was identified as a possible alternative hypothesis. We refer to this mechanism as *wedging abrasion*.

Wedging Abrasion (A Candidate for Hypothesis M5)

Wedging abrasion refers to degradation caused by entrapped abrasive particles that may increase the stresses at the crack tip. This hypothesis emerged late into our research process and has not been tested. Nevertheless, wedging abrasion can be described by the following sequence of events:

1. A hard particle (e.g., grain of sand) is displaced from the concrete matrix inside a crack.

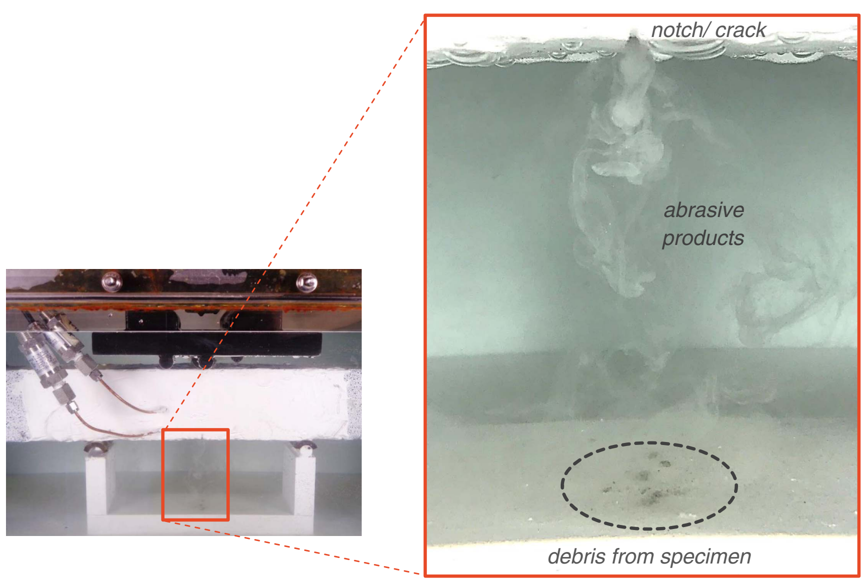

Fig. 14. Evidence of abrasion in prism crack.

2. As the crack closes during the unloading phase, the hard particle behaves as a fulcrum, inducing a lever effect and increasing the stresses at the crack tip.
3. As the crack opens in the next loading cycle, the negative pressures (suction) may prevent the hard particle from exiting the crack and the incoming flow may move it further toward the crack tip.
4. As cycles continue, the hard particle may continue to wedge itself deeper into the crack, increasing stresses at the crack tip and facilitating crack growth.

Future research should consider this candidate hypothesis for concrete material damage.

Discussion and Conclusions

It is evident that water flow in cracks is an important factor in accelerating the flexural distress of pretensioned concrete beams. It leads to both material deterioration and structural failure. To minimize this type of deterioration, we suggest several mitigating measures and some possible future research topics. Because concrete abrasion is likely a governing problem, it is useful to design a concrete mix to increase abrasion resistance, such as by adding steel fibers (Horszczaruk 2009), rubber granules (Grdić et al. 2014), or silica fume (Liu 2007). Moreover, our research did not account for the interaction between the investigated mechanisms for either material damage or structural failure. Further investigation may show that damage caused by interactions is greater than the combined damage caused by these mechanisms individually, as documented by Rosenqvist et al. (2017).

In conclusion, we presented a discussion of how water flow in cracks can deteriorate pretensioned concrete beams. We studied four working hypotheses regarding material damage. The following Hypotheses M1, M2, and M3 were rejected, leaving concrete erosion due to the flow of abrasive liquids as a likely explanation for concrete deterioration. Due to practical challenges, Hypothesis M4 was not experimentally tested. Wedging abrasion is also a possible degradation mechanism, and it is closely related to Hypothesis M4. Being identified later in our research, this hypothesis is not stated here but should be considered in future work as a fifth hypothesis. A summarized list of hypotheses and our conclusions is presented next.

M1. Concrete fails due to bursting pressures caused by pressurized water in cracks—*rejected*.

M2. Concrete is damaged by cavitation within cracks—*rejected*.

M3. Concrete is weakened from porosity increase due to leaching of its constituents—*rejected*.

M4. Concrete erodes due to action of abrasive fluid (water and fines) in cracks—*pending experimental testing (future research)*.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

This research effort is funded by the Federal Railroad Administration (FRA), part of the USDOT. This work was also supported by the National University Rail Center, a US Department of Transportation Office of the Assistant Secretary for Research and Technology Tier 1 University Transportation Center. The material in this paper represents the position of the authors and not necessarily that of the sponsors. The authors are grateful for the comments of Prof. Willian Gamble and his contribution to the derivation of an empirical equation for the stress-strain behavior of prestressing tendons. The authors also would like to acknowledge the following industry partners: Union Pacific Railroad; BNSF Railway; National Railway Passenger Corporation (Amtrak); Progress Rail Services, Inc.; Gutanna Technologies; Hanson Professional Services, Inc.; and CXT Concrete Ties, Inc., an LB Foster Company. J. Riley Edwards was supported in part by grants to the University of Illinois Rail Transportation and Engineering Center (RailTEC) from CN and Hanson Professional Services, Inc.

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