Draft Paper
Proceedings of the 2018 Joint Rail Conference
JRC2018
April 18-20, 2017, Pittsburgh, PA, USA

JRC2018-6166

ENVIRONMENTAL AND TRACK FACTORS THAT CONTRIBUTE TO ABRASION DAMAGE

Kyle A. Riding
University of Florida
Gainesville, Florida, USA

Robert J. Peterman
Kansas State University
Manhattan, Kansas, USA

Spencer Guthrie
Brigham Young University
Provo, Utah, USA

Matthew Brueseke
Kansas State University
Manhattan, Kansas, USA

Hossein Mosavi
University of Florida
Gainesville, Florida, USA

Koby Daily
Kansas State University
Manhattan, Kansas, USA

Wyatt Risovi-Hendrickson
Kansas State University
Manhattan, Kansas, USA

ABSTRACT

Sites with known occurrences of mud pumping or other track concerns were investigated to determine the prevalence of concrete bottom tie abrasion and environmental and track conditions that could contribute to its occurrence. Field investigations showed that it occurs in diverse geographic locations around the U.S. and is a source of continued maintenance concern for railroads. Water appeared to be a significant factor involved in concrete bottom tie abrasion. Ballast fouling, center-binding cracking, rail surface profile variations, and large track movement during loading was seen in locations with concrete bottom tie abrasion. Bumps or track stiffness changes were often found at locations of abrasion damage. Specifically, some locations with known stiff track conditions exhibited significant abrasion damage.

INTRODUCTION

Concrete railroad ties are being more frequently used in the railroad industry. Railroad ties are used to transmit loads from the train and rail to the subgrade and also to hold rail gage. Concrete ties are used in heavy-haul rail lines and high-speed rail lines because of their ability to carry large, repeated loads for a very long time. Concrete ties can last 50 years or longer when fabricated properly and the track is properly designed, built, and maintained. In order to achieve this life span, prestressed concrete tie thickness and prestressing forces are fabricated to resist design positive and negative bending moments. These design criteria are meant to prevent excessive deflections and gage widening during train loading and prevent ties from failing through breakage. If the tie section properties change during use, there is a potential for a loss in moment capacity, gage widening, tie breakage, and ultimately derailment [1]. Abrasion loss on the concrete tie sides and bottom could provide such a moment capacity reduction.

On July 18, 2013, 10 cars on a northbound train on the Metro-North Hudson Line in the Bronx, NY containing municipal solid waste derailed, causing $827,700 in damage [2] [3] [4]. At the location of derailment, the ballast was severely fouled with gray mud. The gray mud was mostly from ground up concrete fines from concrete ties that had lost section on the bottom. The ties also had center-binding cracking from high negative moments in the tie center that occurred or were worsened because of loss of ballast support near the ends and reduced section thickness. The investigation faulted the combination of ballast fouling, concrete tie side and bottom abrasion, center-binding cracking, rail seat abrasion, and rail surface profile issues for loss of gage and causing the accident [2].

Concrete tie section loss on the tie bottom or sides from abrasion is a newly identified track failure risk. Concrete railroad tie section loss could result from one mechanism or a combination of mechanisms. Mechanisms that could be responsible for this section loss include classic concrete abrasion [5], hydro-abrasive action [6], ice abrasion [7], concrete crushing, cavitation erosion, and freeze-thaw cycling [8]. No studies have been performed to date to identify the extent of this risk in track or the relative contribution and importance of potential section-loss mechanisms.

The research objectives of this study were to determine the extent of concrete railroad tie abrasion wear at the interface between the tie and ballast in service and determine the track and environmental conditions present at locations with this type of concrete deterioration. In order to accomplish the project objectives, field visits were made to concrete tie storage areas, also known as boneyards, and track locations with known mud spots. The research team worked with the Federal Railroad Administration (FRA), Class I and II railroads, and concrete railroad tie producers to identify track locations to visit that could have bottom tie abrasion damage. Track sites with concrete railroad ties that had mud spots present, locations that require constant maintenance, and previous known occurrences of tie wear were targeted for field site visits. Used concrete tie boneyards were visited to document the frequency of tie abrasion wear and wear patterns on the bottom and sides of ties. Table 1 summarizes the types and distributions of track and boneyard sites visited. Although sites were classified as only one type in the table, some sites exhibited characteristics common to several categories, such as a railroad crossing in tangent track or a crossing immediately after a switch. A total of 36 track sites were visited in eight different U.S. states to ensure diverse geography and exposure climate.

Table 1: Summary of Sites Visited

Site Type	# Sites Visited
Bridges	3
Bridge and Tunnel Approaches	4
Switches and Signals	4
Railroad Crossings	9
Curves	5
Tangent Track	11
Concrete Tie Storage Areas or Boneyards	6

Track sites with potential concrete tie abrasion damage were identified by the railroads and visited by the research team to document track and environmental conditions present. Track access and project objectives led the team to focus the research approach on rapid, qualitative visual inspections in this track scanning study. The research team documented the extent of ballast fouling present on the ballast surface, track drainage and moisture availability, weather conditions, tie deterioration or defects, and rail condition. Ballast samples were taken when possible to determine the source of ballast fouling and ballast condition. Discussions with roadmasters and maintenance personnel provided valuable information about track deterioration timelines and potential causes of damage. Digital image correlation can used to estimate track displacements [9]. When possible, videos of train passes were recorded to document track movement and support conditions. Also, accelerometer readings of tie movement during selected train passes were taken to gauge support conditions [10] and to inform future laboratory studies focused on determining the mechanism of abrasion.

Results of the site visits and surveys reveal trends about the prevalence of abrasion, and common environmental and track conditions observed across the visited locations.

ENVIRONMENT

Two environmental factors were identified before the project began as being potential contributing factors to concrete railroad tie abrasion wear: poor drainage and freezing conditions. Site visits paid special attention to these environmental factors.

Drainage

The presence of water or poor drainage was an issue at all sites with significant abrasion damage. Poor drainage was seen in 95 percent of the sites with measured abrasion damage greater than 0.5 in. The cause of the poor drainage was in many cases inadequate grading, such as that shown in Figure 1. In other cases it could have been caused by ballast breakdown. Sites visited with center-binding cracking but without significant abrasion were in locations with excellent drainage and often in arid climates. In a tunnel location, water was seen in the ditches on both sides of the road, as shown in Figure 2. After the water in the south-side ditch traveled a few dozen yards from the tunnel entrance, it turned and went through the track structure to empty out into the north-side ditch. Concrete ties near the location where the water went under the track were recently replaced in part because of abrasion damage.

Figure 1: Location with concrete tie abrasion damage had grading issues at signal controls

Figure 2: Water emanating from tunnel portal

Mud pumping was seen in sites both with and without severe abrasion damage but was seen in 89 percent of the sites with measured abrasion damage greater than 0.5 in. The sites that did not have evidence of pumping had maintenance performed recently, making it inconclusive on those sites whether pumping was a factor or not. Ponding was also seen in track locations with pumping and abrasion damage, as shown in Figure 3. Pumping occurs when ties are loaded and apply pressure on the ballast below. When this occurs, water in the pores is pressurized. High pressure causes the water to move to areas of lower pressure, forcing water around the tie. When the loading is removed from the tie, the water pressure in the ballast pores decreases, sucking the water back in to the ballast [11]. Hydro-abrasion damage from the mud pumping could contribute to the tie bottom rounding observed.

Figure 3: Water ponding in track, contributing to mud pumping

Pumping evidence was seen in four locations in two different states with low amounts of abrasion damage. These sites included an asphalt intersection, a curve, and two tangent track locations. These sites did not contain gray mud and had low amounts of ballast underneath, giving much different support conditions. This indicates that pumping by itself is not sufficient to cause bottom tie abrasion.

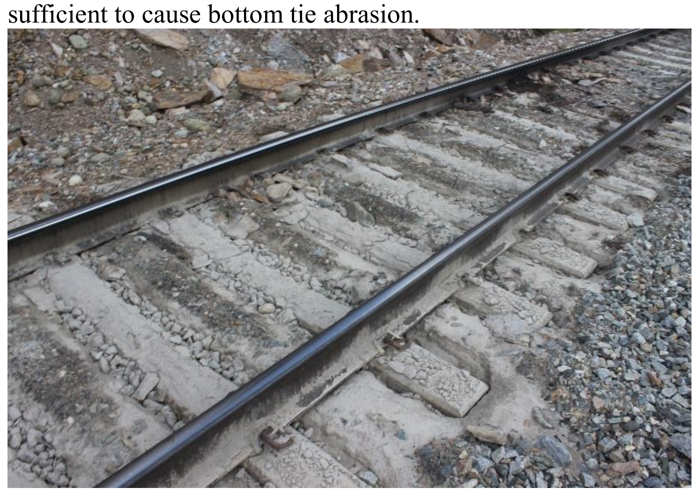

Figure 4: Pumping with very little ballast under ties and only minor abrasion damage

Freezing

Freezing was hypothesized to be a contributing factor to abrasion damage in ties. Abrasion damage of concrete railroad ties was seen in geographic locations with and without freezing conditions as determined by annual snowfall. This included a site in subarctic conditions with 75.5 in. of annual snowfall, and a site with no snowfall and an average low temperature in January of 42°F in the US South-Central region. This means that ice abrasion is not the primary mechanism causing concrete tie bottom abrasion. It is possible that ice formation in track could stiffen the track and slightly accelerate the rate of deterioration, but it is not a primary factor required for abrasion damage.

TRACK CONDITIONS

Track conditions that correlate with abrasion damage were identified. These factors include train dynamic effects, concrete tie materials, track stiffness, track maintenance, and center-binding cracking.

Train Dynamic Effects

Sudden changes in track stiffness or discontinuities in rail or support conditions cause vertical movement in the trains during travel. This phenomenon is well known in the highway industry. Bumps at bridge approaches cause vertical vehicle movement and increase impact loads on the bridge. Bumps can cause an increase in train wheel loads during the downward motion of the train. Once the train experiences significant vertical acceleration from the bump, the train can experience harmonics that may create a few locations of increased wheel loads after the original bump before the train vertical acceleration is damped and returns to normal conditions. The repeated increased wheel loads could cause increased ballast stress and breakdown. This can exacerbate drainage issues, cause mud pumping, and contribute to concrete tie wear. Sites with multiple mud spots near each other in track were found in 13 of the 36 sites visited. It is likely that, as damage progresses with time on the other sites, this number will grow. Locations commonly seen to provide train dynamics that could contribute to concrete bottom tie abrasion included bridge abutments and transition areas, insulated joints, transitions from wood-to-concrete ties, and railroad crossings. Figure 5 shows examples of this phenomenon in track. The roadmaster over the site shown in Figure 5a indicated that the number of locations with mud pumping adjacent to each other grew with time. The size of each spot with gray mud also grew with time as damage accumulated. He also indicated that the damage was spread wider under the surface. Fouling under the surface is like a cancer; it causes additional ballast and tie breakdown, causing mud spots to grow and spread.

Figure 5: Locations of concrete tie abrasion found that show train vertical harmonics in the a) U.S. Southeast, b) U.S. South-Central, and c) U.S. Mountain West region

Bumps or track stiffness changes were not a requirement for abrasion to occur but were found on 9 out of 19 sites with more than 0.5 in. of measured abrasion loss. Abrasion damage was found at some locations in curves and tangent track without these features. Track bumps could be a trigger for ballast breakdown and changes in track conditions that could cause abrasion damage.

Where permitted, a three-dimensional accelerometer was fixed to the top surface of a concrete tie that showed evidence of abrasion damage to measure the tie movement during a train pass. Tie movement is necessary to cause frictional rubbing and grinding according to classical abrasion mechanisms [8]. Significant tie acceleration under train loading was measured in the vertical, rail, and tie directions in locations with abrasion damage, as shown in the acceleration envelope for a tie near an asphalt crossing in Figure 6. All of the sites where tie acceleration was measured showed vertical accelerations higher than 5 g, indicating significant tie movement. The acceleration in the direction of the tie and rail was shown to exceed 10 g in the acceleration measurements shown in Figure 6 and one additional site near an insulated joint in the U.S. Southeast region with 2 in. of measured abrasion wear.

There was a gap between the tie and ballast underneath many ties that showed abrasion damage. This was felt after removing the ballast from the side, or in other cases when mud pumping removed the ballast surrounding the sides of the tie, and the research team was able to feel the gap underneath. Accelerations in the rail or tie direction could create frictional rubbing given sufficiently high tie normal forces to cause significant abrasion. Gaps between the ties and ballast were also seen in video footage to allow ballast to move or vibrate. Vibrational motion of abrasive material on a surface is known to cause wear. Besides translational motion, ties are known to have a slight rocking as the train load is applied to the tie. This rolling could also create frictional forces. The role of acceleration in the rail or tie directions in causing abrasion damage warrants further examination.

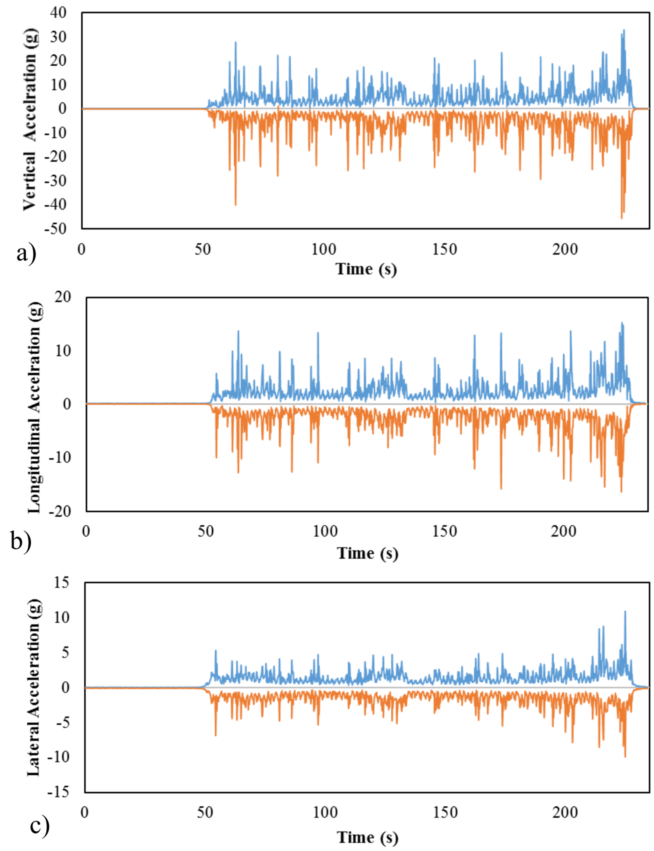

Figure 6: Concrete tie acceleration in the a) vertical direction, b) longitudinal (rail) direction, and c) laterial (tie) direction

Concrete Material

Track sites visited contained ties from at least five different concrete tie plants. Each plant uses a different concrete mixture design with different locally-available aggregates. Concrete abrasion damage was seen in ties made from four of the plants. Concrete mixture proportioning and material selection cannot alone prevent abrasion damage. Definitive conclusions about the abrasion resistance of the concrete materials cannot be made based on track inspections alone because the track location had very different environments, loading conditions, and maintenance. Some conclusions about wear patterns can nonetheless be drawn based on visual tie observations.

Concrete abrasion resistance is primarily a function of the aggregate hardness and cement paste hardness [5]. The cement paste hardness is primarily a function of the concrete compressive strength [8]. Limestone and dolomitic limestone typically have a Mohs hardness under 4. Gravel and granite aggregates have a Mohs hardness above 6. Siliceous gravel and granite aggregates are known to provide more abrasion resistance. Aggregate hardness was reflected in Schmidt hammer readings obtained by the research team. The average Schmidt hammer readings of ties made with limestone aggregates was 4.8 lower than that of the ties made with siliceous gravel or granite. Ties made with limestone aggregates showed more even wear across the tie bottom and sides, with tie bottom corner rounding being more pronounced as shown in Figure 7. Compared to siliceous gravel, the hardness of limestone aggregates is more similar to that of cement paste, giving a more even wear. Abrasion on concrete ties with siliceous aggregates was much more varied, as shown in Figure 8, with the cement paste wearing at a much faster rate than the aggregates. This gave the ties with siliceous aggregates more topology on the bottom. The more even wear seen on ties with limestone aggregates is indicative of faster abrasion rate; however, a more in-depth, controlled study is needed.

Figure 7: Abrasion damage found on concrete made with limestone aggregate

Figure 8: Abrasion damage found on concrete made with siliceous coarse aggregates

Rail Surface Profile and Alignment

Rail surface profile variations were seen on track in locations with concrete abrasion damage. Profile variations change continuously through track use, deterioration, and maintenance activities. Rail surface profile variations are not a cause of concrete tie wear, but they are a symptom. The observed variations likely occurred because ballast fouling and mud pumping caused excessive deflections in track.

Large amounts of tie deflection was measured on a site near an insulated joint during a train pass as shown in Figure 9. Deviations in the alignment occurred just from one train pass because of poor horizontal ballast restraint from mud pumping around the ties, ballast fouling, and tie wear, as shown in the before and after pictures in Figure 10 and Figure 11, respectively. After the train passed, maintenance crews removed a tie from service, allowing the team to measure the bottom wear. Figure 12 shows the concrete wear measured in the tie removed from track.

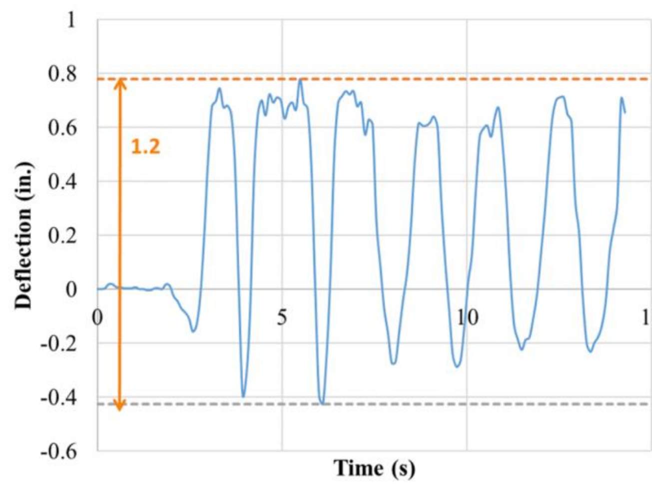

Figure 9: Rail vertical deflection on site near insulated joint

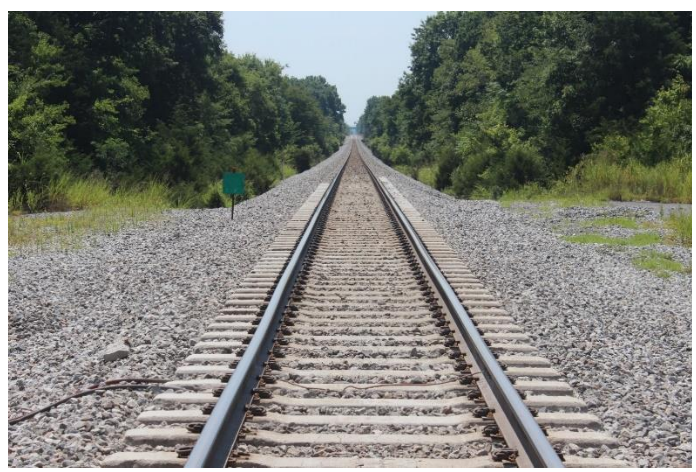

Figure 10: Track near insulated joint before train pass

Figure 11: Track near joint after train pass, showing alignment issues

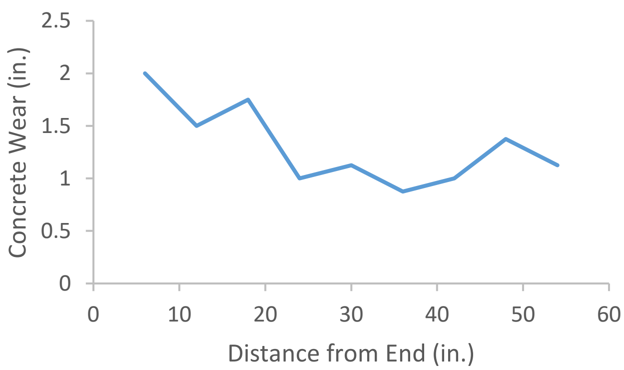

Figure 12: Bottom wear on tie removed from track shown in Figures 10 and 11

A track site in the U.S. South-Central region was visited that was built on top of an old concrete highway. At one location, a large rail surface profile variation was seen at the location of a mudspot and concrete tie bottom wear, as shown in Figure 13. This level of rail and tie deflections during loading could fatigue the rail or contribute to rail breaks. Rail welds were commonly found at locations with abrasion damage. Worn out rail sections were also occasionally found discarded on the side of the track, indicating a lower rail life than the rest of the track – a potential side effect of concrete tie wear.

It did not take much abrasion wear to cause alignment issues in ties made without scallops, as seen in a curve in a canyon in the U.S. West region in Figure 14. Ties in the curve had only minor abrasion damage but had problems with track wander, causing the ties to be replaced. Scallops would prevent minor wear from causing track wander.

Figure 13: Rail surface profile variations seen in a track site constructed over an old concrete highway. Red lines drawn to highlight the more than 1.3 in. of surface profile variation measured by Automated Track Inspection Program (ATIP) geometry car about 2 years before the research team visited the site

Figure 14: Canyon site with ties that after only minor abrasion started to cause alignment wander

Track Stiffness

Track stiffness is likely one of the most important contributing factors to concrete abrasion damage. Track stiffness conditions were not measured directly as part of this study. Locations with known high stiffness were seen to have large amounts of abrasion. These locations included three bridges visited and the track built over an old concrete highway shown in Figure 5b and Figure 13. In these locations, given that the infiltration of subgrade fines was restricted, the occurrence of fouling was clearly caused by ballast and concrete tie breakdown. For the track over the old concrete highway, mudspots and abrasion damage were seen at locations with lower amounts of ballast between the ties and concrete pavement. The concrete ties and ballast at these locations would experience much higher stresses and consequently more breakdown.

Another location that was especially illustrative of the effects of increased track stiffness was a curve visited in the U.S. Pacific Northwest region. Two ties were found with severe abrasion on the sides facing towards each other. Part of an old tie was left between the two ties with severe side abrasion damage, as shown in Figure 15. The low amount of ballast between the old tie and damaged in-use ties created stiff track conditions between the ties as well as fouled ballast to retain moisture. Other locations with fines and insufficient ballast underneath ties showed mud pumping, but only minor amounts of abrasion damage. Track with fouled ballast is known to have varying stiffness depending on the track moisture content. During dry conditions, the fines greatly increase the track stiffness, while during wet conditions they greatly decrease the track stiffness.

Figure 15: Ties with old tie in between and side abrasion

Track Maintenance

Track maintenance personnel were consistently aware of the locations that had concrete abrasion damage. The presence of a fine gray mud was a good sign that concrete wear was occurring. The gray color is indicative that the fines are from concrete instead of ballast or other material. As long as limestone ballast is not used, confirmation of the presence of concrete fines in the ballast can be performed with a simple acid test. The calcium-based material in the concrete fines will react with a few drops of hydrochloric acid to produce fizzing gas bubbles.

Some locations had low amounts of gray mud and abrasion damage. Track maintenance was emphasized at these locations, such as the canyon site shown in Figure 14, with significant resources being continually used to ensure good track conditions. The locations were well graded, ballast was undercut periodically, and ballast tamping was regularly performed. All of these factors ensure good drainage. The concrete ties at these locations showed far less abrasion wear than other locations with the ties made at approximately the same time but without the same level of maintenance.

At many locations with concrete wear, ballast tamping was performed regularly. This was done to restore track profile and improve track support conditions. Tamping, however, does nothing to address the underlying conditions that contribute to tie abrasion. Tamping does not remove fouling, significantly improve drainage, or change track stiffness. Mud pumping and variable track support conditions returned after tamping. Local cribbing out of ballast was tried on a concrete bridge visited by the research team. After only eight months after the ballast cribbing, fouling was present, as shown in Figure 16. Ballast replacement does not change track stiffness and only removes part of the fouled ballast. Mud spots have a tendency to spread and grow in size. It is also difficult to remove all of the fouled ballast since it is often present in a larger area under the surface. Track undercutting is more helpful but does not change underlying stiffness issues in track. Although pumping could eventually return, performance after undercutting was much better than that achieved with tamping alone and also provided improvement over a longer period of time.

Figure 16: Track at concrete bridge eight months after ballast was replaced

Center-Binding Cracks

Center-binding cracks were regularly found at track locations with mud pumping and abrasion damage. The presence of center-binding cracks did not necessarily mean that the ties had also experienced abrasion damage; however, sections of track with center-binding cracking that had issues with ballast support on the shoulders but did not have fouling or drainage issues did show problems with abrasion damage. Track with severe abrasion damage often had severe center-binding cracks, sometimes with shattered tie tops.

ABRASION PREVALENCE

Abrasion damage is very dependent on location. One Class I railroad engineer estimated that abrasion damage occurs in 1% or more of ties. It occurs in isolated track sections with poor track conditions and plenty of moisture. Ties with abrasion damage tend to cluster together. While 15 ties in a couple of miles of track may constitute only a small percentage of the overall number of ties, they can have a disproportionally large impact on maintenance needs and safety, as track safety is only as good as the weakest link in the system. Locations with mud pumping and abrasion damage, which lead to rail replacement, surfacing issues, track wander, and slow orders, are much larger in number than the percentage of damaged ties may suggest. Issues with mud pumping and concrete tie abrasion do not appear overnight, but, once they reach a critical point, they can cause track conditions to deteriorate rapidly over the course of just a few weeks.

Concrete railroad ties make up a minority of ties in track. While the overall number of ties with concrete bottom abrasion damage may be a small percentage of all ties in track, the number of ties with abrasion damage is expected to increase as the number of concrete ties in track increases. The same conditions that cause concrete railroad ties to experience abrasion damage could also contribute to wood tie thinning. Additional study of the mechanism behind concrete tie wear could help find methods to reduce wear on both types of ties.

CONCLUSIONS

Thirty-six track sites with known occurrences of mud pumping or other track concerns were investigated to determine the prevalence of concrete bottom tie abrasion and environmental and track conditions that could contribute to its occurrence. Field investigations showed that concrete bottom tie abrasion, while not the largest source of concrete tie safety issues present in track, does occur in diverse geographic locations around the U.S. and is a source of continued maintenance concern for railroads. Concrete bottom tie abrasion occurs in discrete locations, but its occurrence is not unusual.

Water appeared to be a significant factor involved in concrete bottom tie abrasion. Visual evidence of grading or drainage issues were found in 95% of the sites with significant abrasion damage. Freezing conditions were not required for bottom tie abrasion to occur.

Significant tie acceleration and displacement during train loading, rail surface profile variations, and center-binding cracking were often seen at locations with abrasion damage. These features were likely symptoms of track condition issues rather than causes of the concrete wear. Bumps or track stiffness changes were often found at locations of abrasion damage, but not always. Track stiffness appeared to be a contributing factor to concrete tie bottom abrasion. Although the research team was not able to measure in-situ track stiffness in this study, significant abrasion damage was observed at some locations with known stiff track.

The severity of bottom tie abrasion can increase with time if railroads do not take corrective maintenance action. Ballast fouling was seen in locations with concrete bottom tie abrasion. Tamping, localized ballast removal, or individual tie replacement helped temporarily mitigate track defects, but these methods did not adequately stop abrasion damage from progressing or recurring. Ballast undercutting was a more effective method for delaying or slowing down concrete bottom tie abrasion but was not generally observed to address the root causes of the problem.

ACKNOWLEDGEMENTS

The funding to perform this project was provided by the Federal Railroad Administration and is gratefully acknowledged. This project was performed with the cooperation of industry partners BNSF, CSX, Kansas City Southern, Alaska Railroad, Amtrak, and Rocla Concrete Ties. The assistance of Erik Frohberg, Chris Upward, Damon Smith, Mark Austin, Chris Moale, Shawn Vecellio, Garrett Cross, Brian Lindamood, Steve Melniczuk, and Rusty Croley in arranging the site visits is greatly appreciated.

REFERENCES

[1] H. Yu, B. P. Marquis and D. Y. Jeong, "Failure Analysis of Railroad Concrete Crossties in the Center Negative Flexural Mode Using Finite Element Method," Proceedings of the

Institution of Mechanical Engineering, Part F: Journal of Rail and Rapid Transit, vol 231, no. 5, pp. 610-619, 2017.

[2] NTSB, "Metro-North Derailment, Accident ID DCA13FR009," National Transportation Safety Board, 2014.

[3] M. Flegenheimer and W. Hu, Metro-North Line is Tied Up After a Freight Train Derails, New York: New York Times, 2013.

[4] B. Marquis, J. LeBlanc, H. Yu and D. Jeong, "CSX Derailment on Metro-North Tracks in Bronx, NY, July 18, 2013," 2014.

[5] E. Van Dam, "Abrasion resistance of concrete and the use of high performance concrete for concrete railway crossties," University of Illinois, Urbana-Champaign, 2014.

[6] A. Kryzanowski, M. Mikos, J. Sustersic and I. Planinc, "Abrasion Resistance of Concrete in Hydraulic Structures," ACI Materials Journal, vol. 106, no. 4, pp. 349-356, 2009.

[7] S. Jacobsen, "A Norwegian Concrete-Ice Abrasion Laboratory," in Proceedings of the XXII Nordic Concrete Research Symposium, Reykjavik, Iceland, 2014.

[8] ACI 201.2R-08, "Guide to Durable Concrete," American Concrete Institute, Farmington Hills, MI, 2008.

[9] C. A. Murray, A. W. Take and N. A. Hoult, "Measurement of Vertical and Longtidinal Rail Displacements Using Digital Image Correlation," Canadian Geotechnical Journal, vol. 52, no. 2, pp. 141-155, 2015.

[10] S. T. Wilk, T. D. Stark and J. G. Rose, "Evaluating Tie Support At Railway Bridge Transitions," Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, vol. 230, no. 4, pp. 1336-1350, 2015.

[11] H. Huang, E. Tutumluer and W. Dombrow, "Laboratory Characterization of Fouled Railroad Ballast Behavior," Transportation Research Record, vol. 2117, pp. 93-101, 2009.

