Laboratory mechanical fatigue performance of under-ballast mats subjected to North American loading conditions

A. de O. Lima, M. S. Dersch, Y. Qian, E. Tutumluer & J.R. Edwards
University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

ABSTRACT: Under-ballast mat applications have seen growth in the North American freight market, primarily being employed in ballasted concrete bridge decks and tunnels as a solution to lower the track stiffness while reducing the stress state of the ballast and reducing ground-borne vibrations. However, current standard procedures quantifying the under-ballast mat mechanical fatigue performance are provided solely by the German DIN 45673 standard which is tailored to European Mainline freight and passenger service. This in-turn provides challenges in implementing such test procedures to test materials intended for North American heavy haul freight lines, where the under-ballast mats will be exposed to higher axle loads. As part of this research, laboratory mechanical fatigue experiments were conducted on under-ballast mat samples based on recommended procedures from the DIN standard. Two load magnitudes were applied to the under-ballast mats in this study: loads representing the European mainline loading environment and loads representing the North American heavy haul freight loading environment. The fatigue performance was assessed using three criteria: a qualitative visual assessment of the sample's physical damage, a comparison of bedding modulus values measured prior-to and after repeated load cycles, and lastly, the impacts to the life cycle of the ballast. Samples tested showed no significant physical damage after testing. Further, although there was a significant change in the bedding modulus of the North American loaded sample immediately after the completion of the repeated loading cycles, the bedding modulus change in both the European and North American samples was practically the same when tested one week after the completion of the tests. Further, a gradation analysis revealed little impact to the ballast material other than particle surface wear. Therefore, the results from this work should provide information for future North American recommended testing of ballast mats subjected to heavy haul loads.

1 INTRODUCTION

Railroads continually look for ways to extend the life of their track infrastructure given poor track performance can lead to reduced transportation efficiencies which are vital to the success of rail transport (Sawadisavi 2010). North American (N.A.) heavy haul freight corridors are subject to both an increase in axle loads and higher expectations for reliability between service failures. To address these challenges and further increase the service-life of track components, it is important to reduce the stress state of the entire track structure, including the ballast (Indraratna et al. 2014). Maintenance and renewal expenses related to track ballast add up to 2% of the total annual spending across N.A. Class I railroads (Association of American Railroads 2016). Excessive degradation of the ballast can contribute to fouling and settlement, which consequently may increase impact loading due to the uneven track surface (Giannakos 2010, Le Pen & Powrie 2011). Hence, increasing the life of the ballast is of great interest.

An extension in ballast life may be accomplished through a variety of methods, and one emerging solution is the use of energy absorbing resilient materials in the track structure, primarily under-sleeper pads (USPs) and under-ballast mats (UBMs) (Esveld 2001). The former is an elastic pad bonded to the bottom surface of the sleeper while the latter is the focus of this study and is an elastic mat inserted below the ballast layer or concrete slab. Various researchers have already reported the benefits of introducing resilient pads in the track structure, including both UBMs and USPs (Sasaoka & Davis 2005, Auersch 2006, Dahlberg 2010, Marschnig & Veit 2011, Nimbalkar et al. 2012, Schilder 2013, Indraratna et al. 2014, Li & Maal 2015).

Marschnig & Veit (2011) reported in an assessment conducted for the Austrian Federal Railways that the implementation of USPs increased the time between tamping cycles by at least 100%. Further, Nimbalkar et al. (2012) concluded that the benefits of introducing resilient pads to the track structure were twofold: (i) attenuation of the impact forces and (ii) reduced magnitude and duration for the impact force. Additionally, Nimbalkar et al. (2012) demonstrated a higher efficiency of UBMs in reducing impact magnitudes and ballast damage when installed over stiff supports (e.g. stiff subgrade or structure). Similarly, Indraratna et al. (2014) quantified the impacts of the component on the ballast material degradation under drop-hammer impact loads, reporting reduction values between 46.5% and 65.0% for hard and weak support conditions respectively. Indraratna et al. (2014) also concluded that the use of resilient pads provided more benefits in hard support conditions as the hard support promotes higher particle breakage and the weak support acts as an additional energy absorption medium.

Nevertheless, studies concerning the evaluation of the mechanical fatigue performance of UBMs are limited. The few published reports available are based on measurements obtained from samples from a single supplier recovered from field installations after many years of service (Wettschureck et al. 2002, Dold & Potocan 2013). Furthermore, through conversations with many in the industry, the majority of laboratory studies conducted have solely been performed for product development purposes, and have not been widely made available to the industry. Finally, the limited literature on this topic is constrained to European applications and testing procedures, with no reports providing insight into the component's performance under higher loading conditions (i.e. N.A. freight heavy axle loads or HAL).

Application cases of UBMs in N.A. freight lines have grown over the last two decades. The UBM growth has primarily been driven through the installation on ballasted bridge decks and tunnels, though there have been cases where the UBM was chosen due to its capabilities for mitigating ground borne noise and vibration. In fact, multiple Class I railroads have employed the component for new ballast deck bridge and/or tunnel construction or retrofit (Nunez 2014, Hanson et al. 2006).

Given this increase in installation frequency and lack of N.A. performance evaluation, this paper presents results from laboratory mechanical fatigue tests conducted to compare component performances under European mainline axle loads and N.A. HALs.

2 OBJECTIVE AND SCOPE

The primary objective of this study is to quantify the effects of increased load (i.e. N.A. HAL) on the mechanical fatigue performance of UBMs relative to European testing specifications. The results presented are only a portion of a larger research effort at the University of Illinois at Urbana-Champaign (UIUC) aimed at evaluating and quantifying the overall performance of UBMs and their benefits to the track structure, while exploring testing procedures for the N.A. environment.

During this study, laboratory mechanical fatigue tests were performed on three UBM samples that originated from the same lot. Each sample was subjected to a different load range representing European and N.A. loads, respectively. A visual assessment of the sample was performed to assess the physical damage incurred as a result of the repeated load cycles. Although potentially not as critical in reducing the ballast stress state in the heavy haul environment, the changes in the UBM bedding modulus were quantified to assess the UBMs ability to mitigate noise and vibration. Values were obtained directly prior-to, within 12-hours after, and 7 days after the repeated loading under a 30-cm (12-inch) ballast layer. Bedding modulus results were used to determine the relative performance of the component. Finally, ballast material characteristics were measured before and after the tests to quantify material degradation incurred due to the increased loading.

3 MATERIALS

3.1 *Under-ballast mat*

UBM samples intended for freight traffic loading conditions, "Type A", were used in this study (Figure 1). The samples comprised of a profiled mat bonded to a flat protective rubber layer with a synthetic fibre grid between. Table 1 provides details of the sample geometry, including its dimensions and thickness.

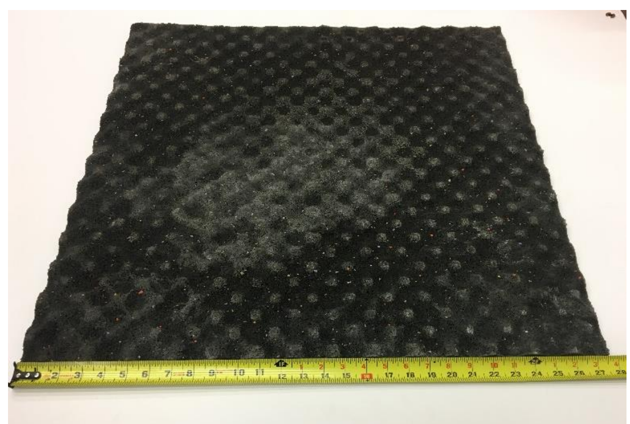

Figure 1. Type A under-ballast mat designed for freight traffic loading

Table 1. Under-ballast mat sample properties.

Label	Mat Thickness Minimum	Mat Thickness Maximum	Sample Size	Construction
	mm (in.)		mm (in.)	
Type A	5 (0.197)	10 (0.394)	699x699 (27.5x27.5)	Profiled mat bonded to flat protective layer

3.2 *Ballast*

Ballast material used for this investigation originated from a quarry commonly used by a N.A. Class I railroad and was stored in a stockpile at the laboratory facility. The coarse aggregate material consisted of crushed granite with uniformly graded particle size distribution compliant with the American Railway Engineering and Maintenance-of-way Association (AREMA) No. 4A gradation recommendations (AREMA 2016). Figure 2 shows the original gradation for the ballast material employed along with the AREMA specified gradation limits for No. 4A ballast. To ensure the quality and uniformity of the ballast used for each test, all ballast was washed, oven dried, and sieved to remove all fines from its initial state. For the purpose of this research study, fines were considered as all particles smaller than 9.5 mm or passing the ⅜-in. sieve (Qian et al. 2014). Ballast material separated during the sieving process was recombined and mixed using the recommended practices from AASHTO T 248, mixing and quartering procedures from Method B were employed due to the large size of the sample (AASHTO 2011).

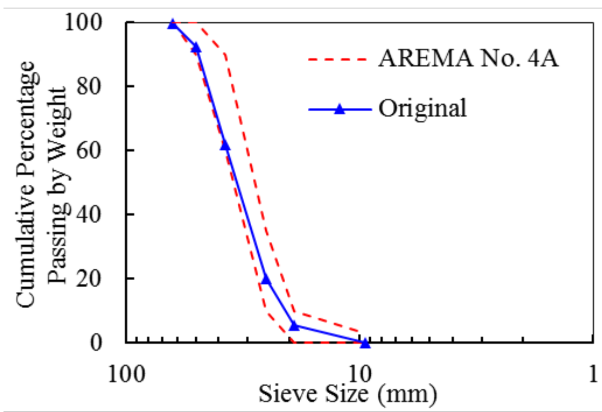

Figure 2. Ballast gradation curve

4 LABORATORY EXPERIMENTATION

Laboratory tests performed as part of this study followed modified recommendations from the German Deutsches Institut für Normung (DIN) 45673-5 standard (hereinafter referred to as DIN) for the determination of the mechanical fatigue resistance of under-ballast mat samples (DIN 2010).

4.1 *Test setup*

Due to space constraints of the test frame available for testing, the ballast box and loading plate had to be scaled down. Hence, a new design was conceived with the intent to maintain most of the considerations of the original design, notably ballast depth, and pressures at the tie/ballast and ballast/UBM interfaces. The newly designed apparatus consisted of a 30.5-cm (12-in.) diameter loading plate and a ballast box of 71 cm (28 in.) sides and 35.6 cm (14 in.) depth supporting a full 30.5-cm (12-in.) thick ballast layer section and capable of accommodating the thickest UBM sample available to the researchers at this time. Figure 3 shows the newly designed ballast box - named as the UIUC ballast box - and loading plate.

Figure 3. UIUC ballast box design and loading plate

The UBM sample was placed on the bottom of the box over the flat steel bottom. Neoprene sheets, 6.35 mm (¼ in.) thick, were placed on the sidewalls, as specified by the DIN 45673-5, to provide elasticity to the ballast layer and better simulate particle confinement experienced in the field. Clean ballast was added and compacted for 90 seconds in three 10.2-cm (4-in.) lifts; an adjustable formwork vibrator attached to a steel plate provided a 4.4-kN (1000-lbf) compaction force at 60 Hz.

4.2 *Test procedures*

Mechanical fatigue testing procedures in the DIN standard comprise of two stages of cyclic loading at incremental load levels and constant frequency in the range of 3 to 5 Hz. The two test stages apply 10,000,000 and 2,500,000 cycles, respectively, on the top-of-ballast in the setup. This leads to continuous testing lasting between 29 and 48 days depending on the loading frequency employed.

Consequently, due to the substantial amount of time required to perform the complete test procedure it has become common practice to restrict testing to the second stage loading (i.e. 2.500,000 cycles), which reduces the testing time to ⅕ of the original. This protocol is still considered to provide an appropriate indication of component performance, especially in cases of relative comparison such as the one presented in this paper; further, a similar number of cycles is used elsewhere in fatigue testing of resilient components (BS EN 16730 2016). Therefore, this work presents results of tests performed using only the second stage of testing recommended in the DIN standard.

Both qualitative and quantitative assessments of the UBM performance were performed during the tests conducted. Primarily, a qualitative assessment of physical damages incurred to the specimens tested was performed after each of the tests. Additionally, in order to quantify the relative change in the component's vibration mitigation performance, static bedding modulus values for each sample were determined prior-to and subsequent the applied fatigue loading as specified in the DIN standard.

Throughout this research, bedding modulus is determined as the secant modulus of the stress-displacement curves within the specified load ranges for which the component is intended. Table 2 presents the evaluation ranges considered for each of the two scenarios investigated. It is worth noting that even though the evaluation ranges employed are individual to each scenario, both tested samples were loaded to the full load range of the N.A. scenario to maintain consistency of testing and enabling researchers to later evaluate bedding modulus values in additional load scenarios.

Table 2. Bedding modulus evaluation ranges employed

Loading Scenario	Evaluation Range Minimum	Evaluation Range Maximum	Loading Rate	No. of Cycles
	kN (kips)	kN (kips)	psi/s (MPa/s)	Applied/ Recorded
European	0.9 (0.2)	12.9 (2.9)	1.45 (0.01)	3/1
N. American*	0.9 (0.2)	16.9 (3.8)	1.45 (0.01)	3/1

*Load range employed for all tests.

Additionally, after the completion of each test (i.e. 2,500,000 cycles), the ballast was collected and the effects of the increased loads to the degradation of the ballast aggregate were quantified by sieve analysis as per ASTM C136. It is believed that this material could contribute further to ballast degradation (Selig et al. 1988, Selig & Waters 1994, Qian et al. 2014).

4.2.1 *Loading conditions*

To provide a means for quantifying the effects of European and N.A. loads on the fatigue performance of the component, both load scenarios were simulated. For the first scenario, the maximum load was of 100kN (22.5 kips) which was obtained from the DIN standard. To maintain the same stress level of the DIN recommendations (i.e., 354 kPa or 51.3 psi) with the reduced-size loading plate of the UIUC ballast box, the DIN recommended load was scaled based on the loading plate areas. The resulting load value to be employed during testing was determined as 25.8 kN (5.8 kips).

Next, the equivalent N.A. scenario load was determined based on the assumption of the 95th percentile nominal N. A. HAL of 356 kN (80 kips) (AREMA 2016) and a back-calculation of the DIN-employed impact factor. The main considerations used by the DIN 45673-5 standard procedure and applied in the impact factor backcalculation are listed below:

- 22.5 tonnes (49.6 kips) European mainline axle load, and
- Loading plate area which corresponds to the support area under one rail seat of the German B70 sleeper.

Given these assumptions, and the assumption that the sleeper directly below the loading axle supports 50% of the axle load, a dynamic impact factor of 1.8 was calculated and used in the determination of the equivalent load of 161 kN (36.3 kips) for the N.A. scenario. Subsequently, the applied test load was scaled based on the same considerations previously described for the European load scenario due to the reduced loading plate size resulting in an applied load of 41.6 kN (9.4 kips). Table 3 presents additional details of both loading scenarios used.

Table 3. Fatigue loading procedures employed.

Loading Scenario	Loading Range Minimum	Loading Range Maximum	Sinusoidal Frequency	No. of Cycles
	kN (kips)	kN (kips)	Hz	
European	1.8 (0.4)	25.8 (5.8)	5	2.5×10^6
N. American	1.8 (0.4)	41.6 (9.4)	5	2.5×10^6

5 RESULTS AND DISCUSSION

After the deconstruction of the ballast box setup of each test, ballast materials were collected and the UBM samples were thoroughly evaluated for physical damage. The sample tested to European loads displayed minor surface wear and compression spots immediately after testing. However, all areas initially displaying wear and compression were able to recover after just a few days of rest (i.e. no loading). Likewise, little signs of physical damage could be assessed on the sample tested to N.A. loads. In like manner to the European sample, most compression marks observed in the N.A. sample were able to recover, however, even after a few days of rest, there

Figure 4. Superficial damage incurred to N.A. sample

were still clear ballast particle imprints and minor superficial tears present around some of the existing compression marks (Figure 4). However, even the initial damages were found to be smaller than 12.7 mm (0.5 in.) long, 2.5 mm (0.1 in.) wide and 2 mm (0.08 in.) deep, and so not able to puncture through even the protective layer. Nevertheless, all observed damage incurred to either sample is not seen as degrading to the performance of the component.

As mentioned previously, bedding modulus values were calculated for both evaluation ranges of each mat prior to and after fatigue testing. Furthermore, in order to explore the effects of sample rest period on bedding modulus, two values were obtained for each loading scenario. First, immediately after the completion of the fatigue testing (i.e. test to be completed within 12 hours of the completion of the test) and second after approximately one week of test completion. Due to schedule constraints during the testing, the acquisition of immediate results from the first European sample tested was not possible, hence, a second sample had to be tested separately to provide the immediate results for the European loading scenario. All obtained results are presented in Table 4. It is worth mentioning that even though all samples were evaluated for both ranges, the percent change in bedding modulus is most relevant within the range compatible to the fatigue loading scenario of each particular sample (e.g. European Evaluation Range is most applicable to the European Loading Scenario, etc.).

Table 4. Bedding modulus results

Loading Scenario	Stage	Evaluation Range: European C_{stat} N/mm³ (lbs/in³)	%Δ	Evaluation Range: N. American C_{stat} N/mm³ (lbs/in³)	%Δ
European*	Initial	0.084 (309)		0.098 (360)	
	After	0.092 (340)	10%	0.107 (395)	10%
European	Initial	0.080 (295)		0.095 (349)	
	1-week	0.086 (315)	7%	0.099 (365)	5%
N. American	Initial	0.086 (316)		0.100 (370)	
	After	0.147 (540)	71%	0.167 (617)	67%
	1-week	0.093 (342)	8%	0.108 (398)	8%

*Additional sample necessary to provide results for the immediately after case of the European loading scenario.

From the presented results, there is a clear difference in the bedding modulus performance metric immediately after the completion of the fatigue loading. This can be observed across the two tests with variation in bedding modulus being higher for the N.A loading scenario than the DIN recommended European loading condition. It is hypothesized that larger amounts of elastic deformation with lower rate of recovery develop due to the higher loads, which in turn temporarily stiffens the component as is attested by an increase in bedding modulus results immediately after the test.

Conversely, results obtained after a one week rest period of the samples depict very similar percent changes of bedding modulus values – 8% and 7% for N.A and European samples respectively – values much smaller than the obtained immediately after the completion of the fatigue loading. Hence, elastic recovery of the deformations occur during the sample's rest period as supported by the bedding modulus results obtained after one week of test completion.

To provide researchers with additional insight into the effects of the higher loads, ballast gradation results were obtained in both tests. These results are presented in Figure 5 indicating no significant damage to the ballast particles had occurred due to the repeated loading. A qualitative visual assessment conducted during the collection of the particles after testing showed no signs of particle breakage. However, the presence of fines within the ballast material was noted after both load levels. This assessment, together with small shifts in the gradation curve, are thought to be related to particle surface wear of the aggregates caused by the relative movement between particles during loading and unloading cycles.

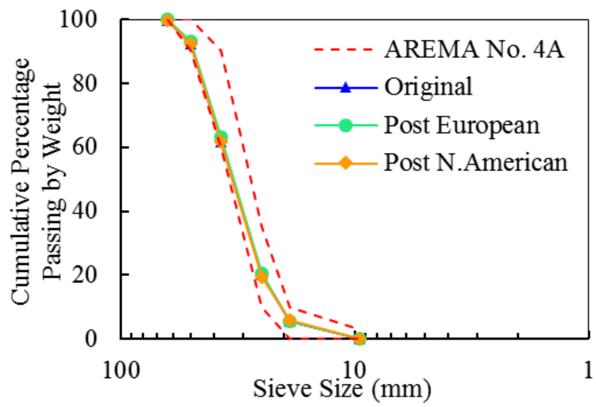

Figure 5. Ballast gradation curves from all tests conducted

As previously mentioned, material passing the 9.5-mm (⅜-in.) sieve was considered to be fines and discarded prior to construction of the box. Accordingly, an estimate measure of fine material produced can be drawn from the difference in weight between the initial and final conditions of the material. Such conclusion can only be drawn based on the assumption that loss of material was due to the generation of particles finer than the employed sieve threshold. Unfortunately, due to issues during the laboratory procedures, an exact loss amount cannot be provided for each individual case. Yet, for both tests the loss in weight of the original material employed was below 1.5%.

6 CONCLUSION

As part of this study, UBM samples were subjected to repeated loading in a ballast box simulating a section of track. Two load scenarios were employed representing North American freight heavy axle loads and the standard procedure (i.e. DIN 45673-5) representing European mainline axle loads. The objective was to quantify the effect of increased loads on the UBM physical health and the change in bedding modulus of the samples. Additionally, degradation trends of the ballast material employed during testing were also monitored.

Although there were slightly more areas of damage as a result of the North American loading, both samples displayed negligible physical damage as a result of the load through a qualitative visual assessment. Therefore, given the fact that the samples showed no significant damage this particular UBM could withstand both North American and European loading environments.

The UBM subjected to North American loading did display a larger reduction in vibration mitigation performance when quantified immediately after the completion of the fatigue testing when compared to the UBM subjected to European loading (67% change vs 7%, respectively). However, this differences became negligible for the test case after approximately one week. Undoubtedly, these results are important when considering that a rest period exists between revenue service load applications and can allow the recuperation of the component. Further, given vibration attenuation is not typically the primary function of UBMs on heavy haul lines, this UBM should be able to serve the primary purpose of reducing the stress state on ballasted bridge decks or in tunnels. Finally, the gradation analysis results demonstrated that no significant ballast breakage occurred during either test further supporting the effectiveness of the UBM in surviving the loading environments.

This testing has provided researchers and practitioners with information into the importance of case-specific testing procedures for proper assessment of the fatigue performance of UBMs. Additionally, the compelling effects of sample rest period to the determination of changes in the bedding modulus parameter were also demonstrated and should be carefully considered when developing recommended practices.

7 REFERENCES

American Association of State Highway and Transportation Officials (AASHTO) T 248. 2011. Reducing samples of aggregate to testing size. Washington, D.C., USA.

American Railway Engineering and Maintenance-of-Way Association (AREMA). 2016. *Manual for Railway Engineering*. The American Railway Engineering and Maintenance-of-Way Association, Lanham, MD, USA.

American Society for Testing and Materials (ASTM) C136. 2014. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. *Annual Book of ASTM Standards* 4 (2). West Conshohocken, PA, USA.

Association of American Railroads (AAR). 2016. *Total Annual Spending - 2015 Data*. Washington DC, USA.

Auersch, L. 2006. Dynamic Axle Loads on Tracks With and Without Ballast Mats: Numerical Results of Three-Dimensional Vehicle-Track-Soil Models. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 220 (2): 169–183.

British Standards Institution. BS EN 16730: Concrete sleepers and bearers with under sleeper pads, 2016.

Dahlberg, T. 2010. Railway Track Stiffness Variations – Consequences and Countermeasures. *International Journal of Civil Engineering* 8 (1): 1–12.

Deutsches Institut für Normung (DIN) 45673-5. 2013. Mechanical vibration - resilient elements used in railway tracks - Part 5: Laboratory test procedures for under-ballast mats. Berlin, Germany.

Dold, M. & Potocan, S. 2013. Long-term Behaviour of Sylomer Ballast Mats. *Rail Technology Review* 53.

Esveld, C. 2001. *Modern Railway Track*, 2. ed. MRT-Productions, Zaltbommel.

Giannakos, K. 2010. Stress on Ballast-Bed and Deterioration of Geometry in a Railway Track. *Journal of Civil Engineering and Architecture* 4 (6): 31.

Hanson, C., Towers, D.A. & Meister, L.D. 2006. *Transit Noise and Vibration Impact Assessment*.

Indraratna, B., Nimbalkar, S., Navaratnarajah, S. K., Rujikiatkamjorn, C. & Neville, T. 2014. Use of Shock Mats for Mitigating Degradation of Railroad Ballast. In: *Sri Lankan Geotechnical Journal - Special Issue on Ground Improvement*, 6 (1): 32–41.

Le Pen, L.M. & Powrie, W. 2011. Contribution of base, crib, and shoulder ballast to the lateral sliding resistance of railway track: a geotechnical perspective. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 225 (2): 113–128.

Li, D. & Maal, L. 2015. Heavy Axle Load Revenue Service Bridge Approach Problems and Remedies. In: *Proceedings of the 2015 Joint Rail Conference*, American Society of Mechanical Engineers.

Marschnig, S. & Veit, P. 2011. Making a case for under-sleeper pads. *International Railway Journal* 51 (1): 27–29.

Nimbalkar, S., Indraratna, B., Dash, S.K. & Christie, D. 2012. Improved Performance of Railway Ballast under Impact Loads Using Shock Mats. *Journal of Geotechnical and Geoenvironmental Engineering* 138 (3): 281–294.

Nunez, J. 2014. Gripping Fastening Systems. *Railway Track and Structures* (July 2014): 14–18.

Qian, Y., Boler, H., Moaveni, M., Tutumluer, E., Hashash, Y. & Ghaboussi, J. 2014. Characterizing Ballast Degradation through Los Angeles Abrasion Test and Image Analysis. *Transportation Research Record: Journal of the Transportation Research Board* 2448: 142–151.

Sasaoka, C.D. & Davis, D. 2005. Implementing Track Transition Solutions for Heavy Axle Load Service. In: *Proceedings, AREMA 2005 Annual Conference,* Chicago, IL, USA.

Sawadisavi, S.V. 2010. *Development of Machine-Vision Technology for Inspection of Railroad Track.* Master's Thesis. University of Illinois at Urbana-Champaign, Urbana, IL, USA.

Schilder, R. 2013. USP (Under Sleeper Pads) - A Contribution To Save Money In Track Maintenance. In: *AusRAIL PLUS 2013 – Driving cost out of rail*, Sydney, Australia.

Selig, E. T. & Waters, J. M. 1994. *Track Geotechnology and Substructure Management*. London: Thomas Telford Publications.

Selig, E. T., Collingwood, B. I. & Field, S. W. 1988. Causes of fouling in track. *AREA Bulletin* 717.

Wettschureck, R. G., Heim, M. & Tecklenburg, M. 2002. Long-term properties of Sylomer® ballast mats installed in the rapid transit railway tunnel near the Philharmonic Hall of Munich, Germany. *Rail engineering international* 31 (4): 6–11.