Original Article

Institution of MECHANICAL ENGINEERS

Journal of RAIL AND RAPID TRANSIT

Proc IMechE Part F:
J Rail and Rapid Transit
0(0) 1–8

DOI: 10.1177/0954409718795920
journals.sagepub.com/home/pif
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Laboratory fatigue performance of under-ballast mats under varying loads and support conditions

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Abstract

Primarily being employed in ballasted bridge decks and tunnels, under-ballast mat applications have seen growth in the North American market as a solution to reduce the stress state of the ballast by lowering the track stiffness and reducing ground-borne vibrations. However, the German DIN 45673 standard is currently the sole reference procedure for quantifying under-ballast mat's mechanical fatigue performance by using real ballast particles as a loading contact interface and is tailored to European loading characteristics. This presents challenges for testing materials intended for North American heavy haul freight lines implementing such procedures. Moreover, large intrinsic variability is present when employing the real ballast material as a loading contact interface. This work presents findings from laboratory mechanical fatigue experiments conducted on under-ballast mat samples based on DIN-recommended procedures. Two loading contact interfaces—ballast box and geometric ballast plate—and two load magnitudes—representing European mainline and North American heavy haul freight loading environments—were applied to the samples in this study. For all tests, no significant physical sample damage was observed after testing. Further, although significant immediate change in bedding modulus was observed for the North American-loaded samples, modulus changes in both test cases were similar when evaluated one week after the completion of the tests. In addition, gradation analysis of the ballast material revealed little impact other than particle surface wear. Finally, results from this work demonstrate that geometric ballast plate is an effective alternative for investigating under-ballast mat's performance and should be useful for the future development of North American-recommended practices for testing under-ballast mats subjected to heavy haul loads.

Keywords

Under-ballast mats, fatigue, geometric ballast plate

Date received: 10 May 2018; accepted: 28 July 2018

Introduction

Railroad companies continually look for ways to extend the life of their track infrastructure, given that poor track performance can lead to reduced transportation efficiencies, as good track performance is vital to the success of rail transport.[1] 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.[2] Excessive degradation of the ballast can contribute to fouling and settlement, which consequently may increase impact loading due to the uneven track surface.[3,4] 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).[5] 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

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UBMs and USPs.[2,6–12] Nimbalkar et al.[10] 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.

To date, the German Deutsches Institut für Normung (DIN) 45673-5, titled "Mechanical vibration – Resilient elements used in railway tracks – Part 5: Laboratory test procedures for under-ballast mats,"[13] (hereafter referred to as DIN), is the only standardized testing procedure available for the determination of UBM mechanical properties. Further, limited research has been conducted to date to evaluate the mechanical fatigue performance of UBMs. Finally, the limited number of reports available is based on measurements obtained from samples of a single supplier recovered from field installations.[14,15] Additionally, through conversations with many in the industry, most laboratory studies conducted have been performed for product development purposes and have not been widely made available to the industry. Moreover, the limited literature on this topic is constrained to European applications and testing procedures. Yet, even though installations in countries such as the United States, Canada, and Brazil are known, no reports are available providing insight into the component's fatigue performance under heavy axle loads (HALs).

Selig and Waters[16] describe traditional characteristics of ballast as "[...] angular, crushed hard stones and rocks, uniformly graded, [...]." However, there exists no thorough agreement on the specific characteristics to which ballast should conform. Various organizations (International Union of Railways (UIC), American Railway Engineering and Maintenance-of-way Association (AREMA), etc.) provide desirable ballast material characteristics within their published documents, most focusing on particle sizes leading to a wide range of possible combinations of ballast material characteristics. Material variations become even more pronounced as parameters given in the AREMA Manual for Railway Engineering[17] require only particle elongation features be measured—to mitigate particle breakage under load—but do not specify ballast particle angularity features.

Stemming from these considerations, large intrinsic variability is present in testing procedures employing actual ballast particles as a contact interface. Such is the case for current standardized assessments of UBM fatigue performance.[13] To avoid these influences, the European standardized geometric ballast plate (GBP) was adopted for the development of fatigue tests in this work.[18] The GBP is currently utilized for testing of fatigue performance of USPs intended for vibration attenuation.[18] In conjunction with the rationale presented, the use of the GBP also provides a greater ability for monitoring gradual changes in UBM performance allowing for partial measurements of material characteristics without the need of a complete deconstruction of the test setup as is the case for all ballast box tests.

Objective and scope

Given the increase in interest from North American (N.A.) railroads and the lack of N.A. HAL fatigue performance results, this paper presents results from laboratory mechanical fatigue tests conducted with two main objectives:

- Compare UBM performance when subjected to European mainline axle loads and N.A. HALs while also exploring the impact on ballast degradation;
- Investigate the feasibility and effectiveness of employing the GBP as an alternative to the ballast box for fatigue performance evaluations.

Results and methods described here follow related work previously completed by the authors[19,20] and are part of a larger scope research initiative at the University of Illinois at Urbana-Champaign (UIUC) evaluating and quantifying the overall performance of UBMs and USPs, and their benefits to the track structure while exploring testing procedures for the N.A. environment.

As part of this study, laboratory mechanical fatigue tests were performed on UBM samples that originated from the same lot (i.e. roll). Two load ranges representing nominal European loads and N.A. HAL, respectively, were employed. The fatigue performance of all samples was assessed using four criteria: (1) a qualitative visual assessment of the sample's physical damage; (2) a comparison of bedding modulus values measured prior to and after repeated load cycles; (3) monitoring of sample temperature buildup; and lastly, (4) the impacts to ballast degradation.

Materials

Under-ballast mat

Under-ballast mat samples designed for freight traffic loading conditions, labeled "Type A," were used in this investigation (Figure 1). The samples consist of a profiled mat with thickness between 5 mm (0.197 in.) and 10 mm (0.394 in.) bonded to a flat protective layer with a synthetic fiber grid between, same as that studied in prior published research.[19–21] Samples were cut into different size squares to fit each test setup. Ballast box fatigue samples sported 699 mm (27.5 in.) sides while GBP fatigue samples sported 254 mm (10 in.) sides.

Ballast

Ballast material employed consisted of the same uniformly graded crushed granite compliant with the

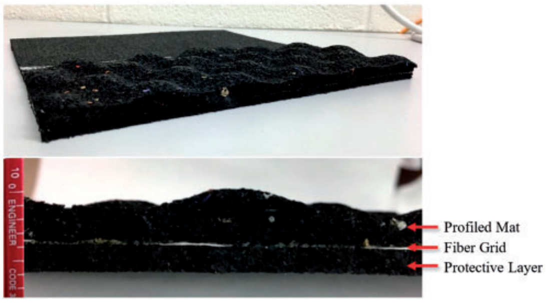

Figure 1. Type A UBM sample used for fatigue tests.

AREMA No. 4A gradation recommendations[17] employed by Lima et al.[19,20] In the same manner as Lima et al.[19,20] all ballast was washed, oven dried, and sieved to remove all fines from its initial state. Throughout this research study, fines were considered as any particle passing the ⅜ in. sieve or smaller than 9.5 mm.[22] After sieving, the ballast material 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.[23]

Laboratory experimentation

Laboratory experiments performed as part of this study followed modified recommendations from the DIN standard for the determination of the mechanical fatigue resistance of UBM samples.[13]

Test setup

Testing was conducted using the pulsating load testing machine (PLTM) frame at the Research and Innovation Laboratory in the Harry Schnabel Jr. Geotechnical Laboratory at UIUC. The PLTM setup includes a 250 kN (55,000 lb) vertical actuator for load application. In the test setup, four potentiometers quantified loading plate vertical displacements. These potentiometers were located on each quadrant of the loading plate, which was attached to the actuator (Figure 2). This arrangement exceeds the recommended number of displacement gauges (three) specified by the DIN.[13]

Ballast box fatigue. Due to space constraints of the test frame available for testing, the standard ballast box and loading plate had to be scaled down as described by Lima et al.[19] 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 capable of supporting a full 30.5 cm (12 in.) thick ballast layer section. The UIUC ballast box and loading plate are shown in Figure 2.

The UBM sample was placed on the bottom of the box over the flat steel bottom. To better simulate particle confinement experienced in the field, 6.35 mm (¼ in.) thick neoprene sheets were placed along the sidewalls. Clean ballast—obtained from the washed gradation process—was compacted for 90 s 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.

Figure 2. UIUC ballast box design and loading plate with potentiometer arrangement.

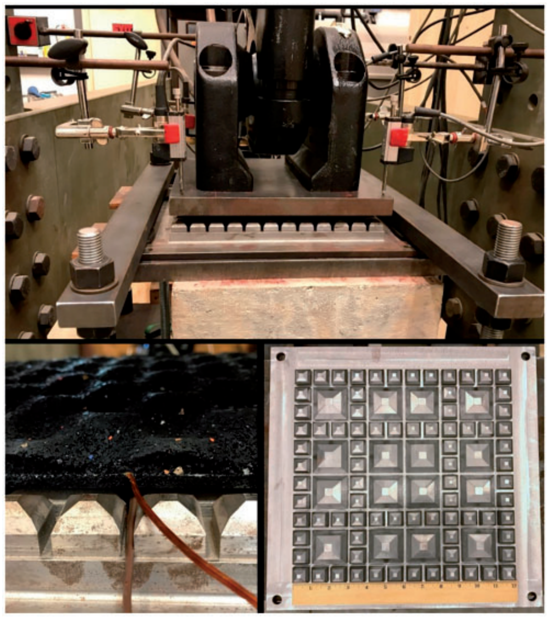

Figure 3. GBP fatigue test setup (top), detail of thermocouple placement (bottom left), and GBP manufactured and used at UIUC (bottom right).

GBP fatigue. The GBP has a complex surface representing various ballast particles yet has symmetric geometry providing a uniform contact surface independent of specimen orientation (Figure 3). As previously discussed, the most relevant objective of the GBP with respect to this research is to remove the intrinsic variability due to the heterogeneous nature of ballast particles.

The GBP was placed over the support concrete block inside the PLTM's frame and fixed to the frame's floor by braces to ensure no movement of the plate during the repeated load tests (Figure 3). Thermocouples, attached to each sample at both the center and edge locations, were deployed to monitor temperature changes in the UBM sample during tests and assure no heat buildup occurred. Additionally, ambient temperatures were monitored to provide added context to sample temperature variations.

Test procedures

Mechanical fatigue testing procedures in the DIN comprise of two stages of cyclic loading at incremental load levels (i.e. load levels 1 and 2) and constant frequency in the range of 3–5 Hz. Due to the substantial amount of time required to perform the complete test procedure, as well as the fact that the second stage loading produces the greatest amount of damage, it has become common practice to restrict testing to second stage loading (i.e. 2,500,000 cycles), which reduces the testing time by 80%.[19] Hence, this work presents results of tests performed using only the second stage loading in the DIN.[13]

A visual assessment was conducted on each sample to investigate physical damage incurred as a result of the repeated load cycles to ensure UBM samples could withstand high contact stresses and friction against either loading interface. In general, significant damage is considered to be tearing or rupturing of the component that may hinder its ability to provide stable resiliency to the track structure. Although potentially not as relevant to the reduction of the ballast stress state in heavy haul environments, bedding modulus changes were quantified to assess the UBM's ability to retain its noise and vibration mitigation performance. For tests conducted using the DIN-recommended ballast box setup, values were obtained at three different instances: immediately before, within 12 h after, and one week after the repeated loading. On the other hand, for tests conducted with the GBP, bedding modulus values were obtained immediately before and within 12 h after only.

Bedding modulus values were determined as per Lima et al.[19] while considering specific loading scenarios for which each studied component is intended. Table 1 presents the evaluation ranges corresponding to the two loading scenarios investigated. From previous studies, it is known that sample conditioning has a significant influence on the determination of bedding modulus.[21] Therefore, to ensure consistency in sample conditioning, all samples were loaded to the full load range of the N.A. scenario while bedding modulus values were calculated using each specific evaluation range in Table 1.

Moreover, after the conclusion of each ballast box test (i.e. 2,500,000 cycles) ballast material was collected and a sieve analysis, as per ASTM C136,[24] was conducted to quantify the effects of the increased loads to the degradation of the ballast aggregate. Based on the literature available, it is believed that this material could contribute further to ballast degradation.[16,25,26]

Loading conditions. To quantify the effects of European and N.A. loads on the fatigue performance of the component, both load scenarios were simulated as shown in Table 2. Detailed descriptions of assumptions and considerations in the determination of loading conditions employed during ballast box test are presented by Lima et al.[19]

For tests conducted using the GBP, new load magnitudes were determined based on the estimated pressures acting on the UBM samples during both ballast box test cases. Talbot's pressure distribution equation (equation (1))[27] was used to estimate these pressures based on the corresponding ballast box applied loads. Maximum stresses—and corresponding loads—to be applied to the UBM samples during GBP fatigue tests were determined as described and are presented in Table 2

$$p_c = \frac{16.8 p_a}{h^{1.25}} \tag{1}$$

where p_c = pressure at given point at depth "h" (psi)
p_a = average pressure on bottom of tie (assumed equal to pressure at ballast box loading plate) (psi)
h = depth of ballast (in.)

Table 1. Bedding modulus evaluation ranges.

Loading scenario	Evaluation range Minimum kN (kips)	Evaluation range Maximum kN (kips)	Loading rate MPa/s (psi/s)	No. of cycles Applied/Recorded
European	0.9 (0.2)	12.9 (2.9)	0.01 (1.45)	3/1
North American[a]	0.9 (0.2)	16.9 (3.8)	0.01 (1.45)	3/1

[a]Load range employed for all tests.

Table 2. Fatigue loading conditions for all test types.

Test type	Loading scenario	Loading range Minimum kN (kips)	Maximum kN (kips)	Sinusoidal frequency Hz	No. of cycles
Ballast box fatigue	European	1.8 (0.4)	25.8 (5.8)	5	2.5×10^6
	North American	1.8 (0.4)	41.6 (9.4)	5	2.5×10^6
GBP fatigue	European	1.8 (0.4)	17.2 (3.9)	5	2.5×10^6
	North American	1.8 (0.4)	27.8 (6.3)	5	2.5×10^6

GBP: geometric ballast plate.

Results and discussion

Physical damages

After each test the ballast box was deconstructed, ballast material was collected, and the UBM samples were thoroughly evaluated for physical damage. Minor surface wear and compression spots were observed immediately after testing in the sample tested to European loads. However, all areas initially displaying wear and/or 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 a similar manner to the European sample, most compression marks observed were able to recover. However, even after a few days of rest, there were still visible ballast particle imprints and minor superficial tears/cracks present around existing compression marks. These were accompanied by signs of wear attributed to particle attrition against the UBM surface (Figure 4). Yet, ballast particles did not puncture through the protective layer, with damages being smaller than 0.5 in. (12.7 mm) long, 0.1 in. (2.5 mm) wide, and 0.08 in. (2 mm) deep. No damage incurred to either sample was considered to be detrimental to the performance of the component.

Similar to results obtained in the ballast box tests, a visual assessment on the UBM samples tested in the GBP fatigue setup found imprints from the GBP contact points (Figure 5). Recovery of these deformations was also observed to be similar to ballast box samples with imprints fully recovering for the European samples but only partially for the N.A. samples. Moreover, samples subjected to N.A. loading conditions showed the formation of shallow tears/cracks of the protective layer around the edges of the contact points between sample and GBP, as evidenced in Figure 5. Again, these effects could not be observed in samples tested under European loading conditions. This may be correlated to the same damages caused by the contact between the UBM and the edge of ballast particles. It is believed that the developed cracks are formed by tearing of the specimen as the sample is compressed and material in contact with the profile of the GBP is held by frictional forces while free material tries to deform into the grooves of the GBP.

Figure 4. Superficial damage incurred to N.A. sample (ruler scale in inches).

Figure 5. Superficial imprints and cracks at edges of contact points for GBP sample #3.

Bedding modulus changes

As mentioned previously, bedding modulus values were calculated for each UBM prior to and after

Table 3. Ballast box fatigue bedding modulus results.

Loading scenario	Stage	C_{stat}	%Δ
European	Initial	0.084 (309)	
	After	0.092 (340)	10
	One-week	0.082 (301)	−3
North American	Initial	0.100 (370)	
	After	0.167 (617)	67
	One-week	0.108 (398)	8

Note: Units in N/mm^3 (lb/in.^{3}).

Table 4. GBP fatigue bedding modulus results.

Loading Scenario	Sample	$C_{stat,Initial}$	$C_{stat,After}$	%Δ
European	#1	0.071 (262.4)	0.079 (290.3)	11
	#2	0.087 (321.7)	0.091 (336.8)	5
North American	#3	0.093 (343.6)	0.101 (372.9)	9
	#4	0.091 (337.0)	0.099 (366.4)	9

GBP: geometric ballast plate.
Note: Units in N/mm^3 (lb/in.^{3}).

fatigue testing. Results obtained for ballast box fatigue tests are presented in Table 3. As previously explained, values shown in Table 3 correspond to compatible evaluation ranges (e.g. European loading scenario results use N.A. loading range but European evaluation range, etc.).

As is demonstrated in Table 3, there exists 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 higher variation in bedding modulus observed for the N.A. loading scenario compared to the DIN-recommended European loading scenario. It is hypothesized that larger amounts of elastoplastic deformation with lower rate of recovery develop due to the higher loads, which in turn stiffens the component as attested by an increase in bedding modulus results immediately after the test.

However, results obtained after a one-week rest period depict bedding modulus values much smaller than those obtained immediately after the completion of the fatigue loading—8 and −3% for N.A. and European samples, respectively—indicating elastic recovery. This value is important considering a rest period naturally exists in revenue service with train headways, which tend to be larger the higher the axle loads. Hence, these should to be taken into consideration in situations where UBMs are sought to achieve a desired vibration attenuation in heavy haul railway lines. The observed negative percentage change in final static bedding modulus value for the European sample may point to the precision of the testing procedures in place (i.e. margin of error).

Static bedding modulus values were also obtained before and after each GBP fatigue test in accordance with the procedures presented previously and are presented in Table 4. Note that static bedding modulus values are calculated for each respective evaluation range as discussed previously.

In the above results, samples #3 and #4 (tested under N.A. HAL) display identical percent changes in performance after the end of the tests. Meanwhile, a larger spread in results is seen for samples tested under European loads with percent change results larger than the N.A. tests. Overall, all samples displayed small changes in static bedding modulus

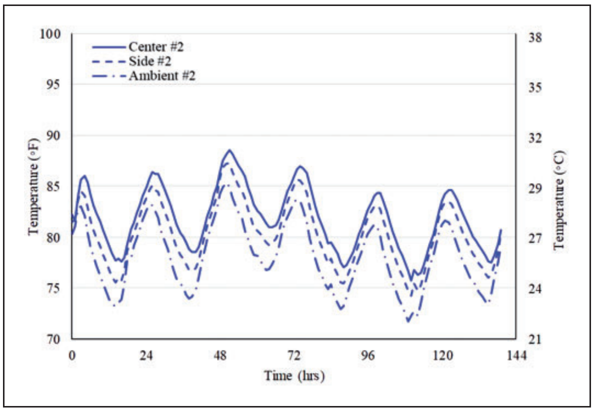

Figure 6. Temperature variation time-history plot for sample #2.

(Table 4) when compared to values obtained from the DIN-recommended ballast box test procedures (Table 3). Results obtained are comparable to ballast box one-week static bedding modulus values which further provide evidence that ballast box tests might represent harsher conditions to the samples compared to the GBP fatigue setup.

Temperature monitoring

Thermal aging—due to exposure to increased temperatures—can also result in degrading conditions for elastomer materials,[28] so temperature monitoring was of importance to ensure no heat buildup occurred during tests. Monitoring was only possible during GBP fatigue tests. A time-history plot of temperature variation for GBP fatigue test of sample #2 is presented in Figure 6. Similar to what is observed in Figure 6, temperature monitoring of all samples during testing showed normal daily fluctuations of sample temperature parallel to variations in ambient temperature readings. The maximum temperature value recorded during testing was of 92.5°F (33.6°C)—sample #3—which was below the DIN-specified limit of 104°F (40°C).

Ballast degradation

To provide researchers with additional insight into the effects of the higher loads on track deterioration, ballast gradation was monitored in all ballast box fatigue tests. Comparative results indicated no significant damage to the ballast particles from cyclic loading. Qualitative visual assessment of the particles showed little to no signs of particle breakage. However, fines were present within the ballast material after both load levels. This is believed to be associated with aggregate particle surface wear due to the relative movement between particles during loading cycles.

As previously mentioned, material passing the ⅜ in. (9.5 mm) sieve was defined as fines within this study and discarded prior to the construction of the ballast box tests. Accordingly, an estimate of generated fines can be obtained from the difference in weight between initial and final conditions. 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%.

Conclusion

As part of this study, UBM samples were subjected to repeated fatigue loading in a ballast box simulating a section of track and over a standardized GBP. Two loading scenarios were used to represent N.A. HALs and European mainline axle loads. The main objectives were to: (i) quantify the effect of increased loads and (ii) quantify effects of different test setups on the UBM physical health assessment and the change in bedding modulus of the samples. Additionally, degradation trends of the ballast material used during ballast box testing were monitored.

Comparison of effects obtained from both test setups demonstrated similar results in terms of physical damage incurred. Samples tested under N.A. loading conditions displayed superficial tears around edges of contact points—either ballast particle or profile edge—but none capable of penetrating further than the superficial protective layer of the UBM. Tears caused by ballast particles did appear to be accompanied by minor wear, most likely due to rubbing actions from the moving particle with loading. In a similar manner, sample deformation at the contact points was noticeable on all samples after testing, but only N.A. samples partially retained these after resting unloaded for approximately seven days. Meanwhile, samples tested under European loading conditions showed marginal signs of physical damages independent of the test setup employed.

Overall, the minimal amount of physical damage observed on all samples tested is not believed to negatively influence the performance of the component in revenue service especially since the simulated loading conditions represent much harsher circumstances than in-service conditions UBMs are subjected to. These results demonstrate the GBP to be an effective alternative to the ballast box in assessing the physical fatigue behavior of UBM samples at different load levels while also providing considerable simplification of test execution.

Static bedding modulus assessments showed more intriguing results in terms of comparison between the two employed test setups. The GBP test samples presented bedding modulus changes much smaller than the corresponding samples tested using the ballast box setup for the conditions directly after the end of the loading cycles. Results are more comparable to ballast box results after rest, indicating that the GBP setup may provide a lesser degrading environment for the sample when considering bedding modulus changes. However, it is believed that the after-rest condition is a more realistic approximation of the revenue service conditions to which samples are subject to, due to component rest during train intervals. Further, based on the experience obtained throughout this study, the variations in percent changes between N.A. and European results—8% versus −3% and 9% versus 5%/11%—may be most associated with test and sample variability than differences in the effects of each simulated scenario. This understanding further supports the effectiveness of the GBP setup to serve as an alternative method for quantifying the fatigue performance of UBM components.

Lastly, the monitored conditions of the ballast material throughout the ballast box tests demonstrated the setup—and/or procedure—to be unable to generate enough degradation of the ballast material to simulate the service conditions and provide insight as to the ballast degradation behavior under such loading conditions. As demonstrated by Lima et al.,[20] tests developed as part of this research showed that under rigid conditions (i.e. no UBM installed) the ballast box test is unable to simulate degradation conditions seen in revenue service.

All the same, it is important to consider that any attempted comparison between the effectiveness of each one of the employed test setups must consider the differences in test constructability, with the GBP setup providing an extreme ease of assembly and condition monitoring during testing while also providing comparable results to the ballast box test. In addition, the use of the simplified GBP setup may provide additional benefits in allowing for assessments of partial development of sample degradation based on bedding modulus—or other metric—obtained at smaller intervals during tests without the need for disturbing the setup.

Acknowledgements

The authors would like to thank the UIUC Machine Shop, the students and staff from RailTEC for their assistance and advice, as well as Brendan Schmit, Brevel Holder, and Kaila Simpson for their assistance with laboratory testing.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by research funds from Progress Rail Services Corporation and the National University Rail (NURail) Center, a USDOT-OST Tier 1 University Transportation Center. J Riley Edwards has been supported in part by the grants to the UIUC RailTEC from Canadian National Railway and Hanson Professional Services.

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