

Settlement behaviour of hybrid asphalt-ballast railway tracks

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Abstract

The use of structural asphalt layers inside ballasted railway tracks is attractive because it can increase track bending stiffness. Therefore, for the first time, this paper investigates the long-term settlement characteristics of asphaltic track in the presence of a subgrade stiffness transition zone. Phased load cyclic compression laboratory tests are performed on a large-scale hybrid asphalt-ballast track, supported by subgrade with varying stiffness. It is found that an asphaltic layer acts as a bridge to shield the subgrade from high stresses. It is also found that the asphalt reduces track settlement, and is particularly effective when subgrade stiffness is low.

Key words (10): Railway track settlement; Laboratory railroad testing; Asphalt-bitumen railway; Railway track stiffness; Subgrade transition zone; Railroad asphalt; Railway engineering; Railway track design; Permanent way construction; Asphaltic-bituminous track design

1 Introduction

Ballasted railway track foundations are composed of superstructure and substructure components [1]. The superstructure consists of rails, fastening systems and sleepers, while the substructure typically consists of the ballast, the sub-ballast and the subgrade. The nature of ballast means it is typically experiences degradation due to particle breakage and fouling [2], thus requiring frequent maintenance.

To reduce maintenance cost, geogrids can be used to decrease both vertical and lateral deformation, leading to reduced track maintenance ([3], [4], [5],[6], [7]). Alternatively, [8] and [9] proposed elastomer polyurethane ballast coatings to increase shear strength. Further, [10] and [11] suggested using random fibre reinforcement of ballast to increase shear strength. Alternatively, [12] investigated injecting bitumen into ballast to improve stiffness, while [13] and [14] inserted rubber crumbs into it to reduce particle abrasion.

Instead of directly modifying the ballast however, it is possible to modify alternative track components using under sleeper pads and/or asphaltic layers. Considering the use of under sleeper pads, both numerical and experimental investigations have shown improved track behaviour ([15], [16], [17], [18] and [19]). For the use of asphalt layers, early work included ([20], [21], [22], [23], [24], [25] and [26]) and focused on the field application of asphalt. Throughout these works it was concluded that asphaltic layers served to increase the longevity of ballasted track, however quantitative measurement data was sparse.

Therefore, to better understand the underlying behaviour of asphalt tracks, [27] used a numerical model ([28]). Similarly, [29] developed an analytical approach to compare the performance of ballasted track with and without asphalt. The results confirmed that asphalt layer reduced dynamic forces and ground vibration. Also, [30] and [31] used the finite element method

to analyse asphalt railway substructures. It was found that the asphalt improved resilient performance and stress distribution, while also lowering vibration levels.

Although numerical modelling is useful for assessing dynamic response, laboratory testing is often preferred when investigating longer-term settlement response. Therefore, using physical tests, [32] and [33] also showed that asphalt reduced residual settlement and that thicker asphalt improved performance. Further, [34] used bituminous sub-ballast on a high-speed line and proposed a theoretical asphalt design to protect the subgrade and reduce maintenance costs. Similarly, [35] placed warm-mix asphalt within the track and found lower permanent deformation and higher static and dynamic moduli compared with traditional granular subballast. To investigate the performance of asphalt in cold regions, [36] used mastic asphalt as a waterproofing layer and performed both laboratory and field tests. Further, [37] and [38] performed full-scale static tests to evaluate the performance of an asphalt track-bed system. Results showed that it could support a railway track without incurring major cracking.

When investigating the long-term behaviour of railway track settlement, it is important that the excitation is representative of the loading experienced in the field [39]. To achieve this, test samples should be of similar scale to real tracks and load cycles can be accelerated to allow for a large number of train passages to be simulated in a reasonable time. Therefore, large scale testing apparatus often requires development.

To achieve this, [40] used a one-third scale testing facility to study the dynamic behaviour of railway tracks. It was found that global stiffness is variable in terms of the number of load cycles. It was also observed that the settlement depended strongly on the moving train speed due to increased levels of ballast acceleration. Further, [41] used a full-scale, single sleeper testing facility to study the performance of the railway track substructure during flooding. It was found that subgrade behaviour was significantly affected by water content changes.

Alternatively, to include the effect of multiple sleepers on track response, [42] used a full-scale test facility with 4 sleepers to study the characteristics of ballasted track under cyclic longitudinal loading. It was found that the ballasted track was subject to cyclic softening with increased load cycles, resulting in reduced longitudinal bearing capacity. This cyclic softening was found to be dependent upon displacement magnitude. Expanding upon this approach, [43] developed a test facility with 8 sleepers to investigate dynamic performance and long-term durability of railway track. Ballastless track was tested and it was found that the roadbed shielded the underlying subgrade from slab vibrations.

This work builds upon previous research and investigates the settlement performance of hybrid asphalt railway tracks. First, the performance of asphalt-ballast track over a low stiffness transition zone is evaluated and compared to a conventional ballasted track with the same support conditions. Next, the long-term settlement behaviour of asphalt-ballast track is investigated to quantify the benefit of using an asphalt layer within railway track to reduced track deflections and subgrade pressures.

The work presents several key novelties:

- It is the only large-scale laboratory study where asphalt behaviour is investigated in the presence of a soil stiffness transition zone
- It is one of the few, large-scale laboratory asphalt track studies that directly compares asphalt track settlement to ballasted track settlement. Therefore it provides much-needed qualitative data related to asphalt track performance.
- It provides substantial long-term settlement data (345MGT) for asphaltic track which is lacking in currently published research

2 Laboratory testing

To assess settlement response, a bespoke railway fatigue testing facility, 'Geo-pavement and Railways Accelerated Fatigue Testing facility' (hereafter called GRAFTII - [44]), was developed (Figure 1). It is the largest of its kind in the UK (as of 2018) and purpose-built to test and characterise the long-term performance (i.e. settlement) of railway track components and infrastructure. It is 6.2m long, 3.4m wide and 3.8m high, with ability to house test samples 6m long, 2m wide and 2m high (Figure 2). GRAFTII is capable of operating using 6 independent hydraulic actuators, across 3 sleepers to simulate the passage of a moving train. Each actuator is connected to a load cell and a linear variable displacement transducer for control purposes. The use of multiple actuators means that each sleeper can be loaded in phase to represent a moving train wheel. Therefore, GRAFTII is capable of approximating the rolling loading conditions encountered within railway tracks during train passage.



Figure 1. Geo-pavement and Railways Accelerated Fatigue Testing facility (GRAFT II) Photograph

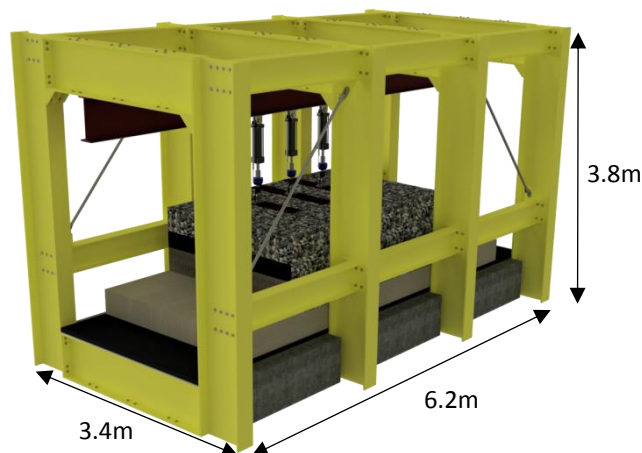


Figure 2. GRAFTII with asphalt track setup

2.1 Test overview

To investigate the effect of an asphaltic layer within the railway track structure, two tests setups were considered:

1. A standard ballast track (Figure 3)
2. A hybrid asphalt-ballast track (Figure 4).

The setups consisted of 3 half sleepers of 200mm depth, laid at 600mm centres. They were fully embedded in 400mm of ballast as shown in Figure 3. In the case of the hybrid track, a 200mm thick asphalt layer supported the ballast. Then, either the ballast or asphalt (depending on track type) was supported by a homogenous 100mm deep granular layer. This granular layer also extended to a further depth of 300mm, however at its horizontal centre was a low-stiffness rubber layer. This rubber volume was intended to represent a 'wet-spot' type defect, commonly found on ballasted rail lines.

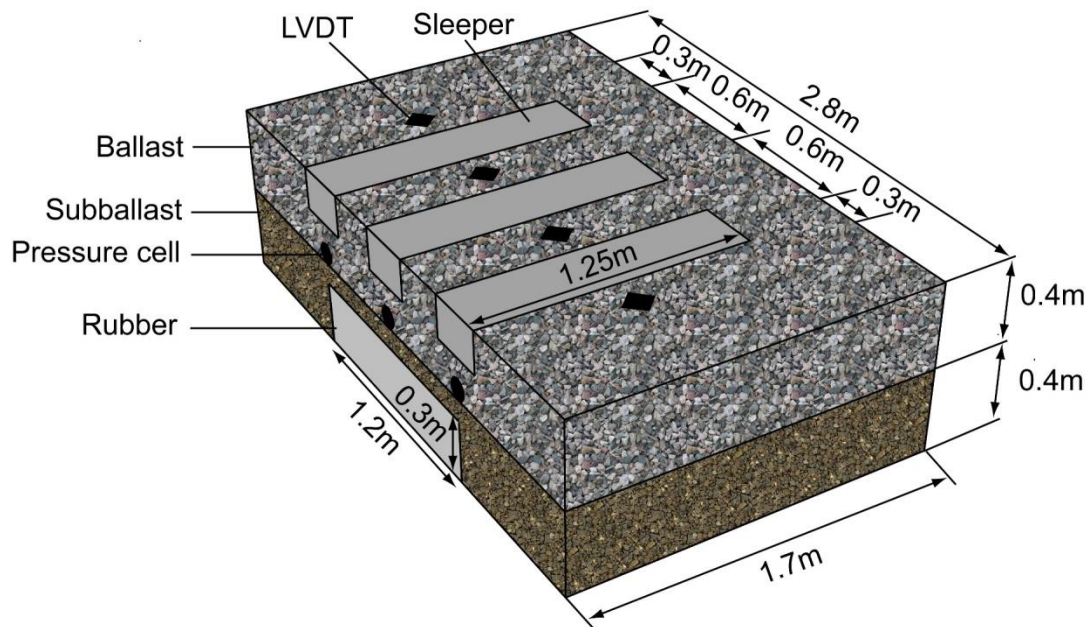


Figure 3. Layout of ballasted track sample

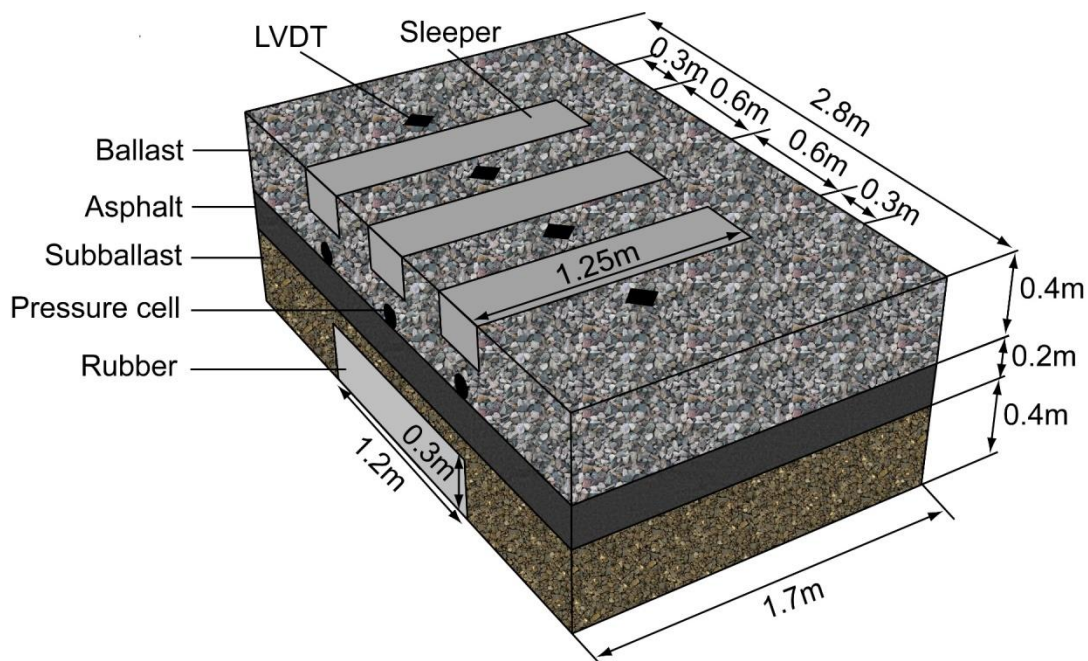


Figure 4. Layout of asphalt-ballast track sample

2.2 Instrumentation

The following sensors were used to monitor track behaviour:

- Temperature gauges: Used to monitor the cooling of the asphalt after laying, and both the ambient and asphalt temperature during loading. Gauges were placed inside the asphalt and elsewhere in the lab to monitor ambient temperature.
- Displacement transducers: Linear variable displacement transducers (LVDTs) were used to record vertical displacements during testing. Four 25mm LVDT's (RDP Model DCTH400AG) were used to record asphalt surface displacements and three 300mm LVDT's (RDP model ACT6000C) were used to record sleeper displacements. The asphalt surface LVDT's were located above the test sample and connected to the asphalt layer via sheathed rods (Figure 11)
- Pressure plates: Used to record the vertical pressures at the asphalt-ballast interface. Three were used during testing, and each was placed directly below a single sleeper (Geokon model 3510).

2.3 Subgrade preparation

Due to physical space limitations inside GRAFTII, the test sample layers located below the ballast were constructed inside a bespoke steel box out-with GRAFTII. Then the box was craned inside, before finalising track construction and performing cyclic loading. The first layer to be constructed was the subgrade. Rubber mats (shown in blue in Figure 5) were placed in the centre of the test box and the outer areas filled with a compacted granular sub-ballast (shown in dark grey in Figure 5) to the same height as the rubber (300mm). The bedding modulus/subgrade reaction C_{stat} of the rubber mats was 30MPa/m. Typically railway base layer stiffness is greater than 130 MPa/m ([46]), meaning this soft zone was approximately a quarter of the value typically used on railway lines. The stiffness of all layers was determined using light weight deflectometer (LWD) measurements. The results are presented in Figure 8 and Table 1, where 'section 1' is the exit of transition and 'section 3' is the entry of transition (note that the LWD was unusable for the rubber sections 2L and 2R due to their very low stiffness). The rubber was designed to represent a typical soft subgrade found on UK railway lines, whereas the areas consisting of sub-ballast were designed to represent a typical stiff subgrade.

After LWD testing, an additional 100mm layer of sub-ballast was placed on top of the lower sub-ballast-rubber layer. Once complete, another series of LWD tests were performed.



Figure 5. Compaction of sub-ballast (left) and Dynamic Plate Load testing using the LWD

2.4 Asphalt preparation in asphalt-ballast track sample

Asphalt was only laid inside the hybrid track samples (i.e. was absent for the ballast-only samples). The asphalt was poured and compacted to a depth of 100mm as shown in Figure 7 (left). A thermometer was placed at the centre and the third set of dynamic plate load tests were undertaken. Finally, while the asphalt was still hot, another 100mm thick layer of asphalt was poured and compacted as shown in Figure 7 (right). This total thickness of asphalt was chosen in accordance with [45] which concluded that increasing asphalt thickness from 100mm to 200mm significantly extended its fatigue life and decreased subgrade stress. At the upper surface of the asphalt, dynamic plate load tests were performed: once while the asphalt was still hot and once after it had cooled.



Figure 6. 400mm height of subballast



Figure 7. 100mm depth of asphalt with thermometer (left) and 200 mm depth of asphalt (right)

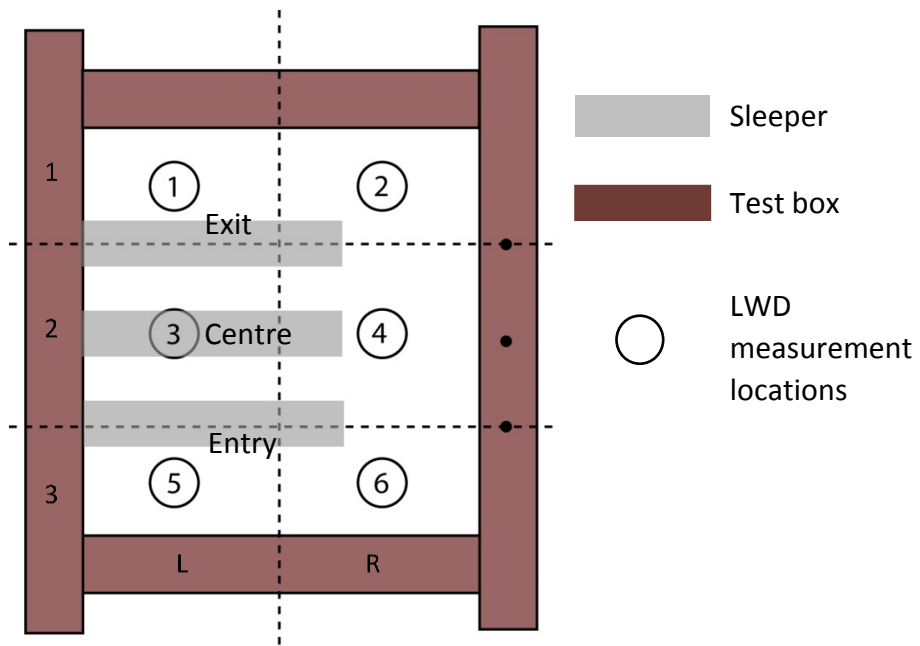


Figure 8. Layout of LWD test locations

Location	Depth from box base				
	300mm	400mm	500mm	600mm (hot)	600mm (cold)
①(1L)	53	54	88	100	352
②(1R)	54	72	67	81	300
③(2L)	N/A	4	11	17	210
④(2R)	N/A	4	11	14	185
⑤(3L)	53	50	82	87	400
⑥(3R)	45	67	80	83	183

Table 1. Results of LWD tests in unit of MPa (hot = 10 mins after laying, cold = 24 hours after laying)

2.5 Ballast preparation

The test box was craned into GRAFTII. For the ballast-only track sample, pressure cells were placed on the subgrade surface, while for the asphalt track sample, they were placed on the asphalt surface. They were placed directly below the location of the sleepers.



Figure 9. Placement of pressure cell plate in asphalt-ballast track (left) and ballasted track (right)

Ballast was hand-packed around the pressure cells and then further ballast was poured to a depth of 200mm. At the same time, 400mm long hollow plastic tubes were placed vertically within the ballast to connect the lower asphalt and upper ballast surfaces. Inside the tubes was placed wooden rods which could move independently from the tube, serving to monitor asphalt surface displacements (Figure 10-Figure 11). The sleepers were then placed on the ballast surface before pouring a second 200mm of ballast around them. The sleepers were constructed from metal with dimensions: 1,250mm x 285mm x 210mm, thus giving them a bending stiffness of 19.8 MNm^2 , which was slightly higher than concrete sleepers. Steel sleepers were used due to their ease of bespoke manufacture, thus allowing for straightforward connecting of the hydraulic rams.

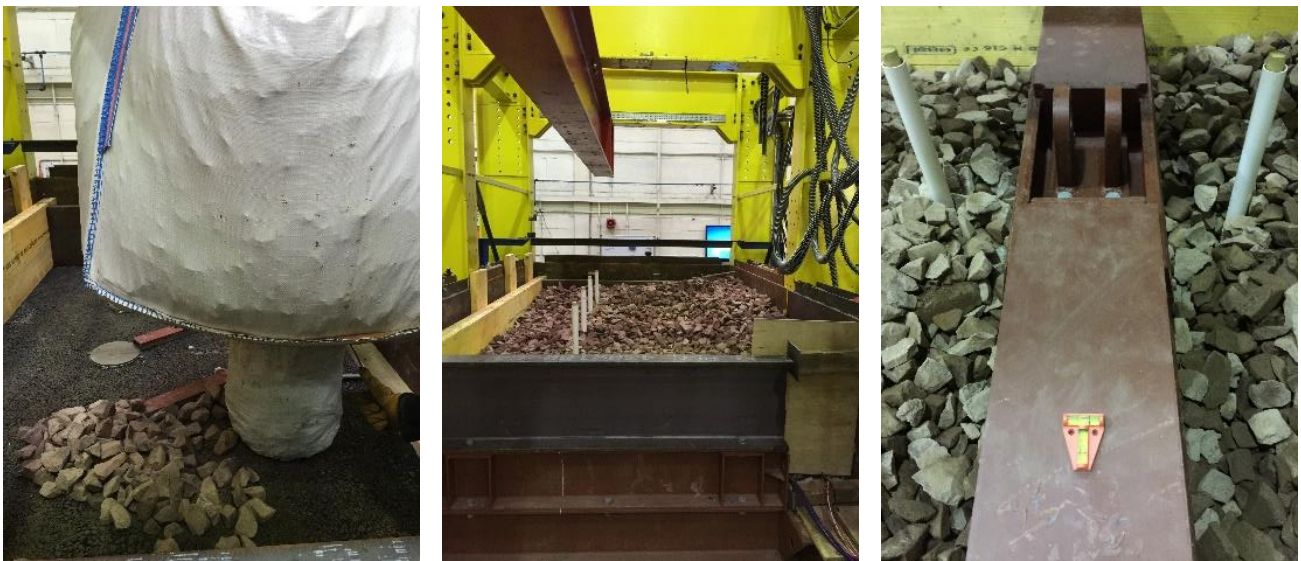


Figure 10. Installation of: ballast (left), LVDT poles (centre) and sleepers (right)

After the sleepers were in position, three hydraulic actuators (with built-in LVDT's) were connected to the sleepers using metal clutches (Figure 11 left). Then, LVDT's were fixed to the wooden poles to measure the asphalt displacement (Figure 11 right).



Figure 11. Installation of actuators (left) and Installation of LVDTs(right)

2.6 Test plan

The hydraulic actuators excited the individual half-width sleepers, mimicking a series of moving axle loads. Twelve stages of cyclic loading were considered (Table 2), up to a maximum cumulative load of 345 million gross tonnes (MGT) as defined in Equation (1), where F is static axle load (tonnes), T is total testing duration (seconds) and f is cyclic loading frequency (Hz). MGT indicates the cumulative load applied at the central sleeper, and the total loading was equivalent to 11.5 years' worth of passages on a high traffic intercity route [48]. To simulate a moving wheel force, each sleeper was loaded in a phased manner. This large number of cycles was applied for the purposes of:

- 1) Generating valuable data related to the very long-term behaviour of railway asphalt that is currently unpublished under controlled lab conditions
- 2) Giving the maximum opportunity for all layers to shakedown

For each stage, the loading was cycled between 1kN and its maximum force at a constant frequency (Table 2). Eight cyclic loading combinations were used, each with increasing maximum force. Then, the force was gradually ramped up to 40kN. Finally, a small reduction in force was undertaken before loading cyclically at 61kN (equivalent to 25 tonne axle load).

$$MGT = \frac{F \times (T \times f)}{1e^6} \#(1)$$

Stage number	Loading description	Max force (kN)	Cyclic frequency (Hz)	Total MGT
1	Steady cyclic	1.5	0.2	0
2	Steady cyclic	2	6	0
3	Steady cyclic	4	6	0.03
4	Steady cyclic	6	6	0.06
5	Steady cyclic	10	6	0.11
6	Steady cyclic	14	6	0.18
7	Steady cyclic	20	6	3.34
8	Steady cyclic	25	6	4.66

9	Ramped cyclic	30	6	11.04
10	Ramped cyclic	40	6	19.57
11	Ramped cyclic	14	6	22.43
12	Full cyclic	61	6	345.91

Table 2. Loading plan

3 Results and discussion

3.1 Ballast vs asphalt track settlement

When testing the hybrid asphalt-ballast track, the full 12 stages of loading (Table 2) were successfully performed. However, due to the lower bending stiffness of the ballast track structure, large displacements were experienced before all stages were complete, causing the test to be halted early (during stage 10 at a force of 40kN).

Therefore Figure 12-Figure 14 compare the results for both tracks after 16 MGT, with the mean value of both locations used for the transition zone edge curve. Further, mean values of the sleeper, ballast and subgrade settlement, at transition edge and centre are shown in Table 3. Settlement was calculated using a moving average, meaning it represented the test sample position half-way between the loaded and unloaded state. It should be noted that measuring settlement considering the loaded or unloaded state resulted in a very similar curve because the dynamic displacements were significantly lower than overall settlement (e.g. the mean dynamic sleeper deflections were 0.74mm and 0.11mm for ballast track and asphalt-ballast track respectively, while the equivalent settlements were 54.14mm and 8.0mm).

Figure 12 and Table 3 show that the hybrid track sleepers experienced 7.76mm settlement at the transition edge and 8.24mm at the transition centre, while the ballasted track experienced 51.74mm at the transition edge and 56.53mm at the transition centre. This equates to an 85% reduction at both the transition edge and centre, in the presence of the asphalt layer. Figure 12 also shows that for the hybrid track, regardless of the stiffness of foundation (i.e. soft vs stiff), settlements were similar. However, for the ballasted track, the displacements were more greatly influenced by foundation stiffness, with the transition edge showing on average 5mm lower settlement compared to the softer transition centre after 16MGT.

Figure 13 shows the effect of MGT on subgrade settlement for both tracks. For the transition edge locations above the stiffer subgrade, the settlements of ballast and hybrid tracks are both low and of similar magnitude. The small discrepancy is likely due to initial compaction, caused by the fact that the asphalt track sample was tested before the ballasted track, but using the same subgrade. Regarding the soft subgrade, there was a marked difference in response. The ballasted track resulted in a settlement of 14.97mm at the transition centre, while the hybrid track resulted in a settlement of 3.09mm at the transition centre. The subgrade settlement was a 79% reduction by use of asphalt layer and was due to the higher bending stiffness of the asphaltic layer.

Figure 14 shows the effect of increasing MGT on the pressure at the base of the ballast layer. Overall the pressures transmitted to the subgrade in the presence of the ballasted track were much larger than for the hybrid asphalt track. For the ballasted track, the pressures started from a higher initial value, and the transition edge and centre locations had significantly differing responses. For the transition centre, the pressure increased relatively steadily. However, for the transition edges, there was a large, localised increase in pressure which peaked at 2MGT (58.1kPa) and then decreased until 6MGT (27.96kPa). After this it began to increase again, albeit at a lower rate, that was more comparable to that of the transition centre. This occurred because the entry and exit locations were above stiffer subgrade and experienced greater levels of compaction during loading. As they continued to undergo compaction, the load was then redistributed more evenly across the three locations, due to the rearrangement of ballast, causing a drop in pressure at these positions. Then, after 16MGT cyclic loading, the mean foundation pressure was 40.6kPa in the ballasted track,

with even higher pressures at the transition centre. For the asphalt-ballast track, the foundation pressure was low when the test commenced, and increased gradually. The increase was more prominent at the stiffer, transition edge locations, however still relatively low. This was due to the pressure redistribution characteristics of the asphalt layer, thus making the adjacent areas (i.e. stiff subgrade) contribute to supporting the force, in the same manner as [38]. Then, after 16MGT of cyclic loading, the mean foundation pressure was 11.7kPa in the hybrid asphalt-ballast track. This was equivalent to a 72% reduction.

Table 1 shows that ballast settlement at the transition centre was equal to 74% and 63% of the sleeper settlement, considering the ballast and asphalt tracks respectively. This indicated that the majority of settlement over the soft subgrade was due to ballast settlement. Further, subgrade settlement on the stiff subgrade (0.21mm) was much lower than that on the soft subgrade (14.97mm). This was true for both ballast and asphalt-ballast track, indicating that compression of the soft subgrade also occurred. However, the presence of the asphalt layer increased the stiffness of the track above the subgrade in comparison to the ballasted track, resulting in reduced ballast settlement and subgrade settlement. This was also found by [30], and is beneficial for long term stability.

	Ballasted Track (mm)		Asphalt-ballast Track (mm)	
	Transition edge	Transition centre	Transition edge	Transition centre
Sleeper settlement	51.74	56.53	7.76	8.24
Ballast settlement	51.53	41.56	7.2	5.15
Subgrade settlement	0.21 ¹	14.97 ¹	0.56 ²	3.09 ²

Table 3. Settlement comparison between asphalt-ballast track and ballasted track after 16MGT

¹ Measured at subgrade-ballast interface

² Measured at subgrade-asphalt interface

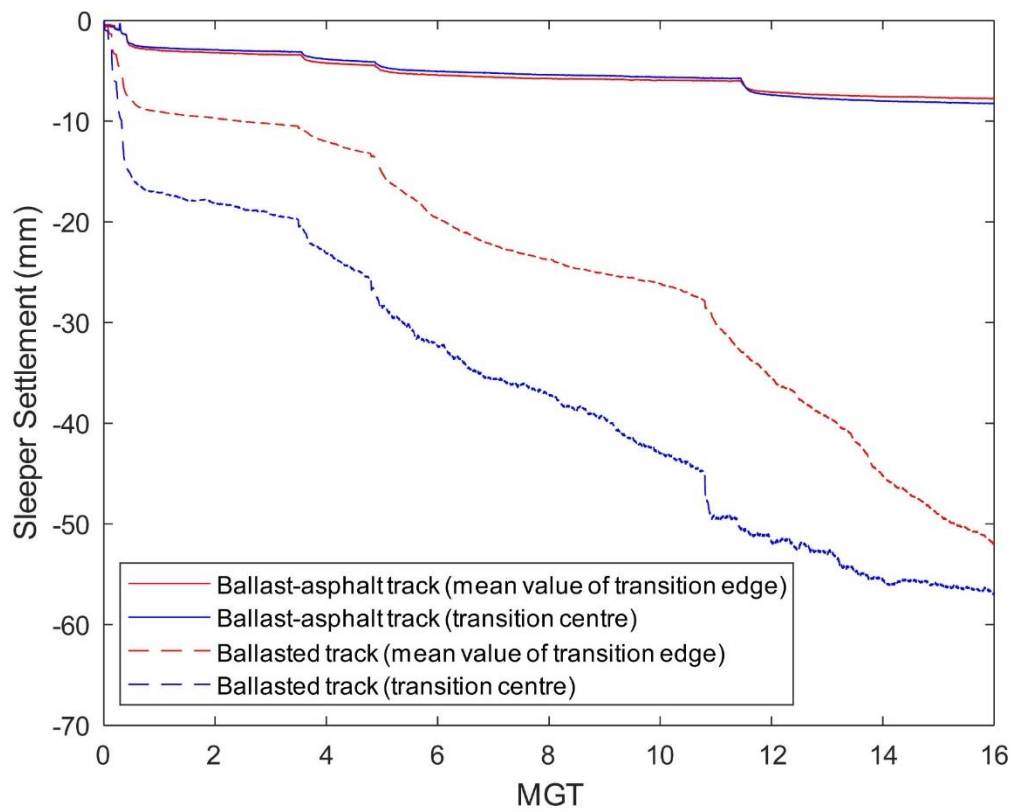


Figure 12. The effect of track type on sleeper displacement

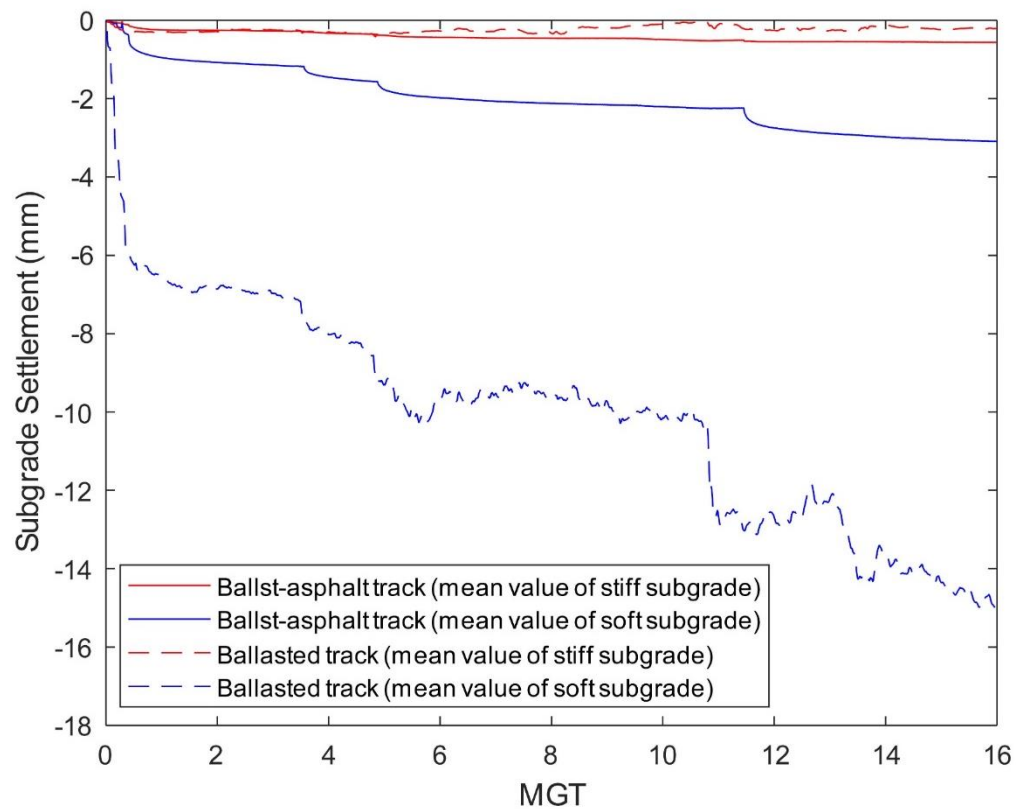


Figure 13. The effect of track type on subgrade surface displacement

	Ballasted track	Asphalt-ballast track
Mean change in soft subgrade settlement	0.80	0.06

(mm/MGT) ³		
Mean change in stiff subgrade settlement (mm/MGT) ⁴	0.04	0.01
Mean change in sleeper settlement (mm/MGT) ⁵	2.13	0.1

Table 4. Mean displacement gradient comparison between ballasted track and asphalt-ballast track after 14MGT

³ Calculation based on subgrade displacement at pre & post-transition.

⁴ Calculation based on subgrade displacement at transition.

⁵ Calculation based on sleeper displacement at transition entry, centre and exit.

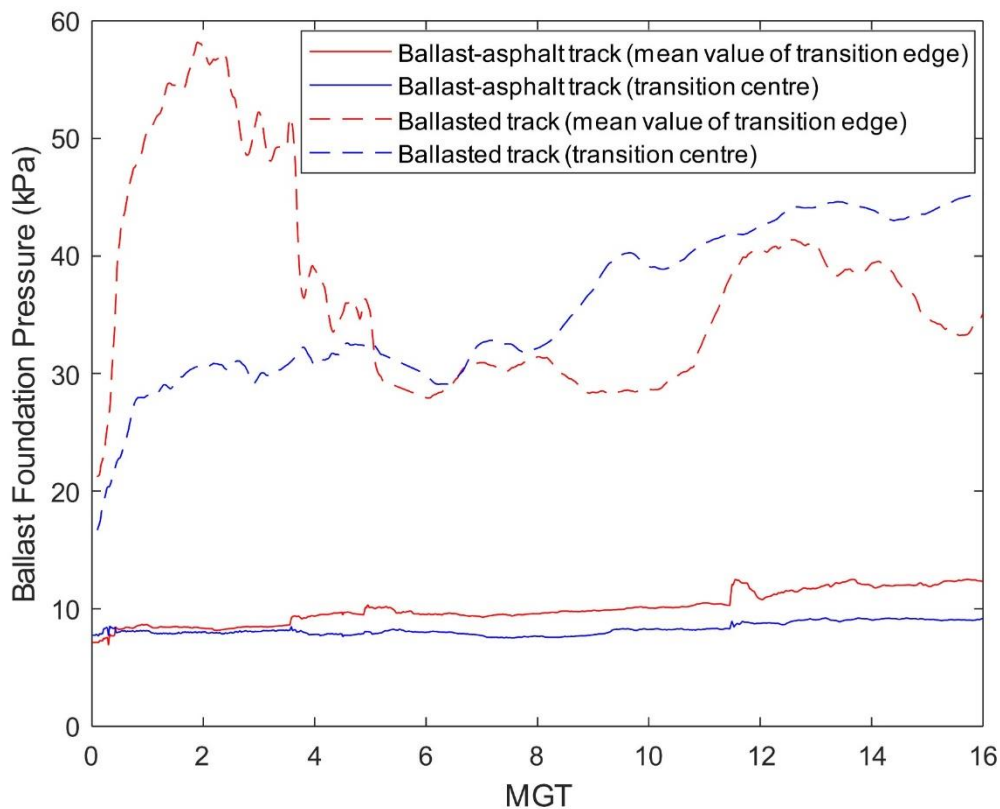


Figure 14. Ballast foundation pressure comparison in asphalt-ballast track (asphalt surface) and ballasted track (subgrade surface)

3.2 Long-term asphalt track settlement

The ballasted track failed due to excessive deflection after 16MGT, however the asphalt track's behaviour was tested to 345MGT without failure. Therefore this section discusses the longer-term behaviour of the hybrid asphalt track only.

Figure 15 shows the sleeper displacements for the hybrid asphalt track. There was a steady increase in displacements and at 345MGT the settlement of the sleeper at the transition centre was larger (23.37mm) than the transition edge (16.92mm). This was due to the presence of the low-stiffness subgrade layer, compared to the relatively stiff subgrade at either side. The largest changes in settlement occurred prior to 50MGT and were most likely due to ballast shakedown. This change was 0.415mm/MGT at transition centre and 0.423mm/MGT at transition edge, during

the initial 20MGT. In contrast, after 345 MGT of cyclic loading, the mean change in settlement was only 0.008mm/MGT at the transition centre and 0.008mm/MGT at the transition edge.

Compared to the previous work of [49], where cyclic loading (equivalent to an axle load of 20 - 25t) was applied to ballast in absence of subgrade, after 20MGT loading, settlement varied between 11.6mm and 32.2mm for 4 types of ballast with different particle shape (i.e. different flakiness index and particle length index) and Los Angeles Abrasion values. However, in the current research, sleeper settlements were 7.7mm and 8.1mm after 20MGT, and 16.92mm and 23.37mm after 345MGT at stiff and soft subgrade respectively. This provides a qualitative indicator that the presence of asphalt improved settlement.

Additionally, after 345MGT the soft subgrade experienced 7.9mm settlement which was 564% greater than that the stiff subgrade (1.19mm). Further, during the first 20MGT, the change in settlement was 0.098mm/MGT at the transition centre, and only 0.032mm/MGT at the transition edge. Then, after 345MGT, the change in subgrade settlement was 0.0017mm/MGT at transition centre, and 0.00002mm/MGT at transition edge. This shows that the test sample had undergone additional shakedown after 20MGT, thus justifying the high number of load cycles.

Ballast settlements were not directly measured during testing, but instead calculated as the sleeper settlement minus subgrade settlement. Their mean values were 15.47mm and 14.64mm, at centre and edge respectively. This indicated that the asphalt layer acted as a bridge across the transition, resulting in similar ballast settlement over both stiff and soft subgrade.

Regarding asphalt surface pressures, the mean pressures after 345MGT were 15kPa and 30KPa for the soft and stiff subgrade respectively. Therefore the pressures were 100% greater when the support was stiff rather than soft. This was because the softer zone underwent greater vertical displacement, thus granting greater scope for particle rearrangement. This load distribution effect allowed the track materials (i.e. ballast) to spread the load over a larger surface area, thus resulting in an overall lower pressure being recorded.

Finally, it should be noted that after testing, the ballast and sleepers were removed. Upon inspection, the asphalt surface did not shown signs of degradation due to ballast penetration. This was consistent with [37] and [38]. Similarly, the sleeper also did not show signs of bending or damage.

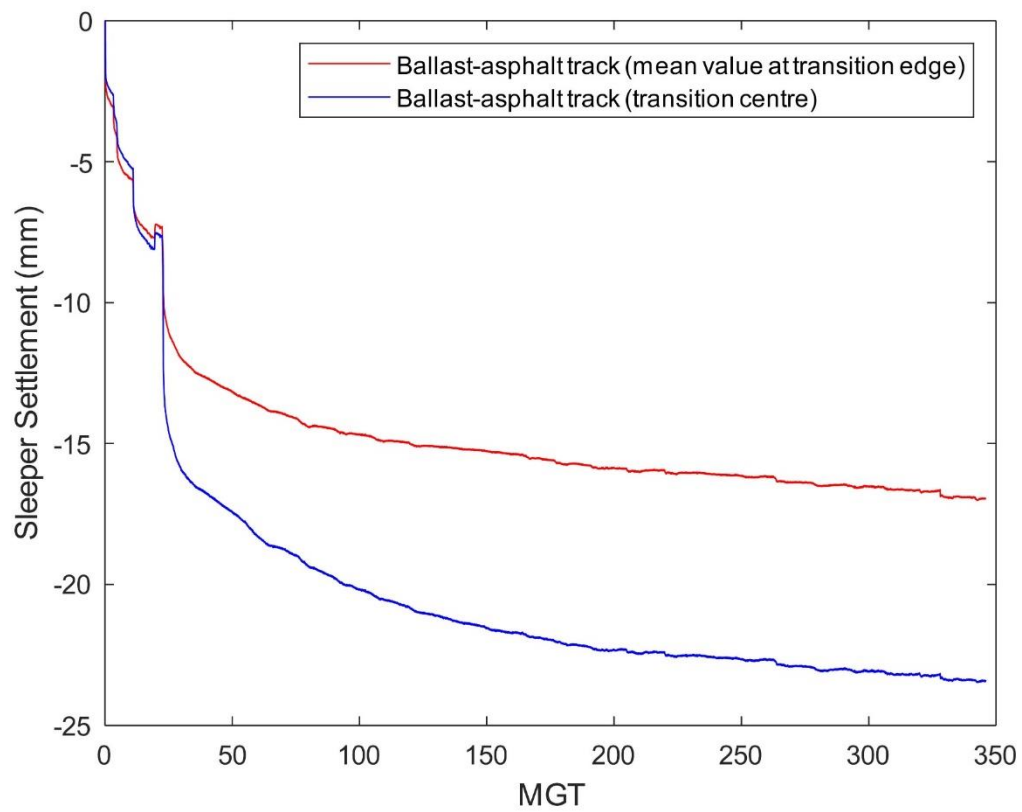


Figure 15. Sleeper displacement during 345MGT cyclic test

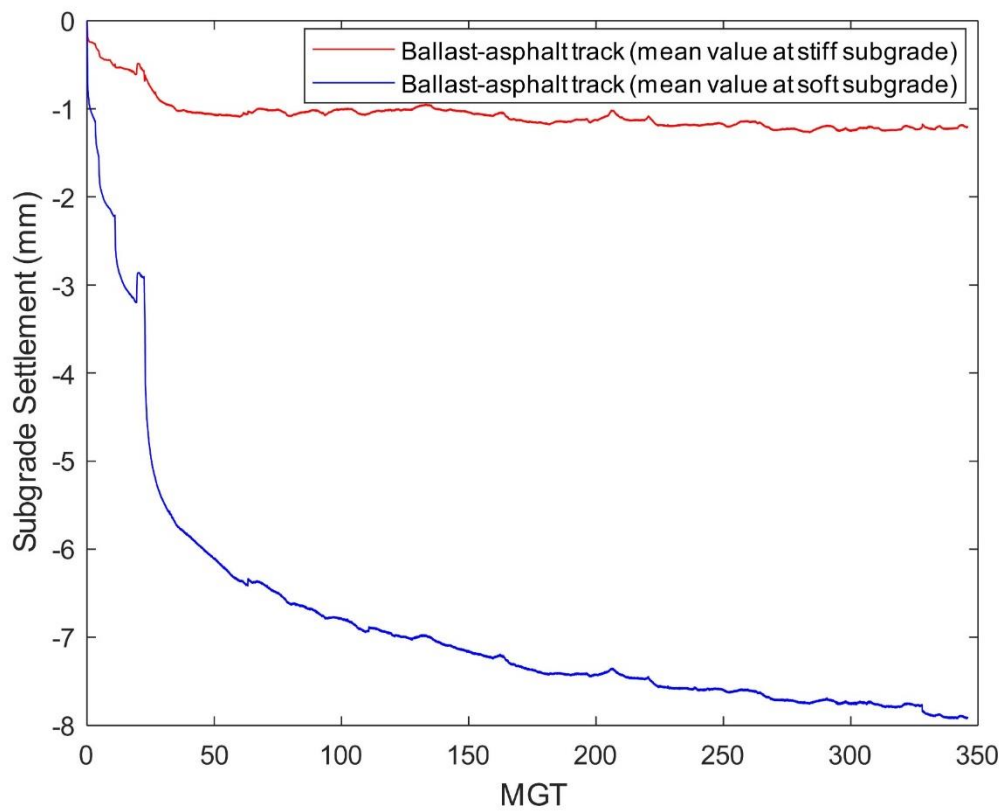


Figure 16. Subgrade displacement during 345MGT cyclic test

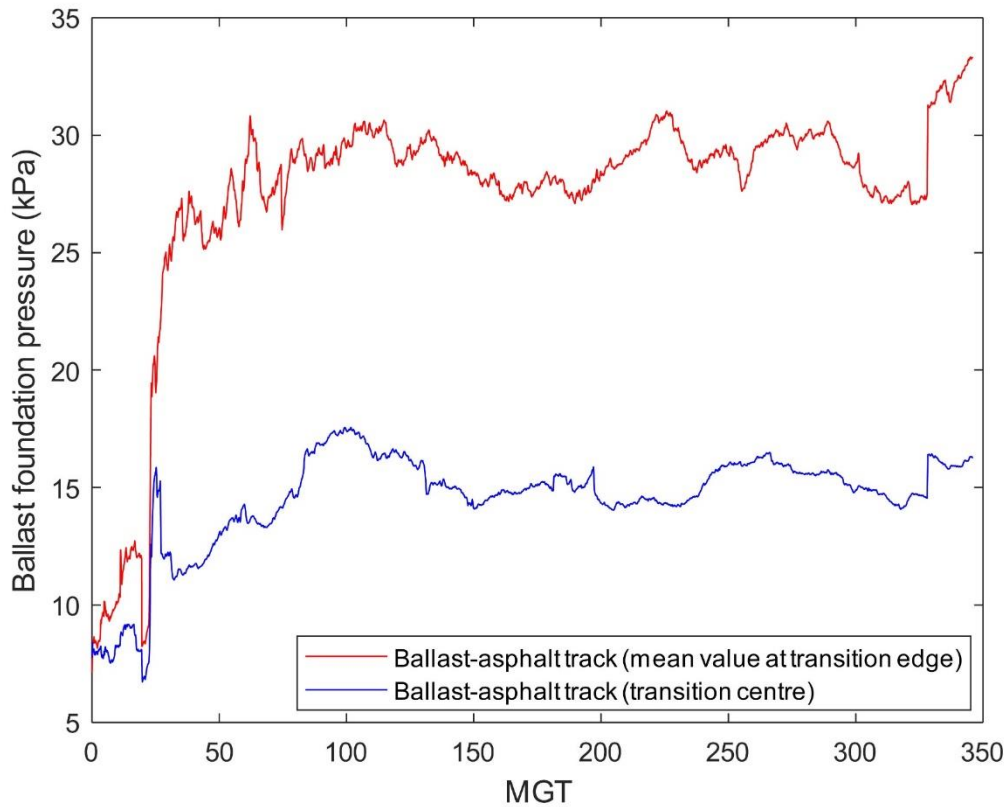


Figure 17. Ballast foundation pressure during 345MGT cyclic test

4 Conclusions

The use of asphalt within railway track structures is becoming of increased interest due to its potential to improve track performance in terms of long-term settlement. However, quantifying these benefits is challenging due to the lack of data from large-scale laboratory tests. Therefore to assess the performance of asphaltic railway tracks, phased cyclic compression laboratory tests were performed on a large-scale hybrid asphalt-ballast track, which was supported by a subgrade transition zone. Tests were performed on a solely ballasted track (i.e. the control condition), and a ballasted track with a 0.2m thick asphaltic layer. The key findings were:

1. The asphaltic layer helped bridge across the low-stiffness subgrade transition zone. This is because the asphalt had a higher bending stiffness in comparison to the solely ballasted track
2. The mean foundation pressure was 40.6kPa in the ballasted track, and 11.7kPa in the hybrid asphalt-ballast track. This was a 72% reduction and occurred because the asphalt helped spread the loading over a wider area. This shows the ability of the asphaltic layer to shield the subgrade from high stress levels
3. The asphaltic track reduced track settlements, particularly in the presence of low stiffness subgrade. This was due to its high stiffness contrast relative to the low stiffness soil and its ability to redistribute the load

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