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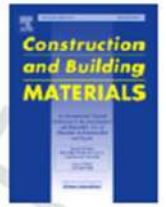
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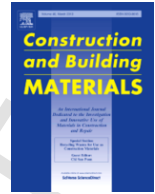
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Bitumen stabilized ballast: A potential solution for railway track-bed

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ABSTRACT

Railway ballast degradation under dynamic loads progressively leads to loss of mechanical performance and geometry of the track, so that maintenance interventions are frequently needed. In order to systematically avoid this issue, recently solutions have been proposed to reinforce track-bed by using polyurethane and/or resins as well as asphalt layers among others. Nonetheless, their main limitations are related to the high initial cost and low productivity.

To cope with these limitations, in this study, bitumen stabilized ballast (BSB) is proposed as a new solution for ballast stabilization. This method aims at improving durability and reducing settlement by modifying both stiffness and the ability of energy dissipation of the layer. The paper introduces the potential of this technology as material to be used in railway track-beds by presenting the results of a laboratory-based investigation using the Precision Unbound Material Analyser (PUMA). Different variables such as ballast grading, bitumen emulsion dosage, compaction method and stress levels are considered. Results showed a significant decrease in permanent deformation and deformation rate associated with modified stiffness and energy dissipation properties of BSB, which suggest the potential for improving long-term performance and sustainability of ballasted track.

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1. Introduction

1.1. Background of the problem and state of the art

Ballast is a granular structural layer of the railway substructure and it's composed of uniformly graded particles between 22 and 63 mm. The ballast layer's main functions are to provide a solid and uniform foundation for the sleepers, transmit and reduce the stress from passing trains to acceptable level for the subgrade, provide adequate drainage, provide a desirable degree of elasticity and an adequate level of noise and vibration adsorption [1,2]. Its ability to perform these functions is strongly related to the physical state of assembly, particle characteristics and load characteristics [2]. Nonetheless, stresses generated at contact points by traffic and maintenance progressively lead to particle degradation, a process known as fouling. The structural integrity of fouled ballast can be compromised leading to track loss of mechanical performance and accelerating geometry deterioration. Thus in order to keep the stability and geometry of the track at standard comfort and safety levels, frequent maintenance is needed, both ordinary (tamping) and extraordinary (renewal).

However, frequent tamping action, which is the conventional routine maintenance, contributes significantly to ballast degradation and consequently leads to a vicious circle where even more maintenance is needed [3]. Ballast maintenance accounts for a high proportion of maintenance costs (approximately 30% of annual maintenance budget) and material consumption [4]; therefore in order to shift towards more sustainable railway infrastructures, new methods at both design and maintenance strategy levels must be adopted.

In recent decades various authors have proposed innovative solutions and technologies in order to reinforce the track-bed and mitigate ballast degradation. In this regard, the use of elastic elements such as under sleeper pads, under ballast mats or crumb rubber mixed with ballast aggregates, from elastomeric materials or from tire rubber wastes, can provide a significant reduction in track deterioration and vibrations [2,5,6]. These solutions also allow adjusting track vertical stiffness to a desired level for each specific spot. However, the use of elastic elements within (in high proportion) or below the ballast layer can reduce the bearing capacity and thus may increase the global settlement [6,7].

Another solution widely investigated and applied over the past few decades is the use of geosynthetics, which by decreasing both vertical and lateral deformation can increase intervals between maintenance operations [8–11]. Within the same family are considered polyurethane-based techniques, which provide (when cured) a 3D reinforcement similar to geocells [12]. In this regard, Dersch et al. [13] used a material known as Elastrotrack® (rigid-compact type of polyurethane coating ballast particles) to reinforce the ballast layer obtaining an increase in the shear strength of treated specimens of 40–60% as well as a relatively small decrease in particle breakage (3–5%). Kennedy et al. [14] used a similar material (supplied in the United Kingdom by XiTrack™) injected into the ballast layer in order to reinforce a full-scale ballast layer. Their results showed decrease in ballast settlement of 95–98% with respect to the reference material. The same material in a rigid-foam version has been investigated by Keene et al. [15], highlighting the advantages in terms of application and curing time with respect to the other polyurethane-based techniques.

Ballast bonding is another stabilization technology towards different objectives: enhance mechanical properties of ballast layer, pre-

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vent flying ballast in the high speed lanes lifting of particles by high speed trains, increase track-bed lateral resistance on curves, among others [16,17]. Its applications, especially in transition areas, showed a reduced need for maintenance.

Most of these technologies have been successfully applied in railway hotspots such as bridge transition areas, railway points, level crossings, small radius curves, rail joints, etc. in order to mitigate the impact of ballast degradation. However the main limitations of their application are high initial cost [18] and low productivity [17], putting them in the category of extraordinary maintenance operations.

Another solution with worldwide application is the use of asphaltic layers within the railway substructure to enhance performance, improve the stress distribution, dampen dynamic overloads, and lower vibrations [19–23]. Nevertheless this kind of solution needs to be implemented at the construction stage or during track renewal.

1.2. Proposed solution: bitumen stabilized ballast (BSB)

In order to cope with the above-mentioned limitations in this paper the authors propose a structural solution for track-beds that aims at improving durability through a stabilization of ballast that can reduce vertical permanent deformation by modifying both stiffness and the ability of energy dissipation of the layer. This solution is bituminous stabilized ballast (BSB) (Fig. 1) [24].

This technology consists in the use of bitumen emulsion, poured from above in a similar fashion to that of stone filled emulsion asphalt [25]. The concept behind this solution is a reinforcement method applied during a routine maintenance operation that can increase ballast durability and keep good drainage properties, for a relatively low cost.

The technology development has to take into account several requirements, such as application method, maintainability, permeability of the stabilized layer, short-term and long-term properties among others. A large amount of variables has to be investigated: dosage of bitumen emulsion, bitumen emulsion properties, solid content and bitumen properties, ballast layer compaction, ballast fouling level, water damage and temperature among other. In this study, investigating the potential of this stabilization method to effectively improve track behaviour, only a few of them are considered, following a two steps methodology.

2. Methodology

The performance has been evaluated using the Precision Unbound Material Analyzer (PUMA) test [26] [27], a relatively practical test, similar to the K-Mould [28] and the Springbox [29] suited to both unbound and stabilized material, jointly developed between the University of Nottingham and Cooper Research Technology.

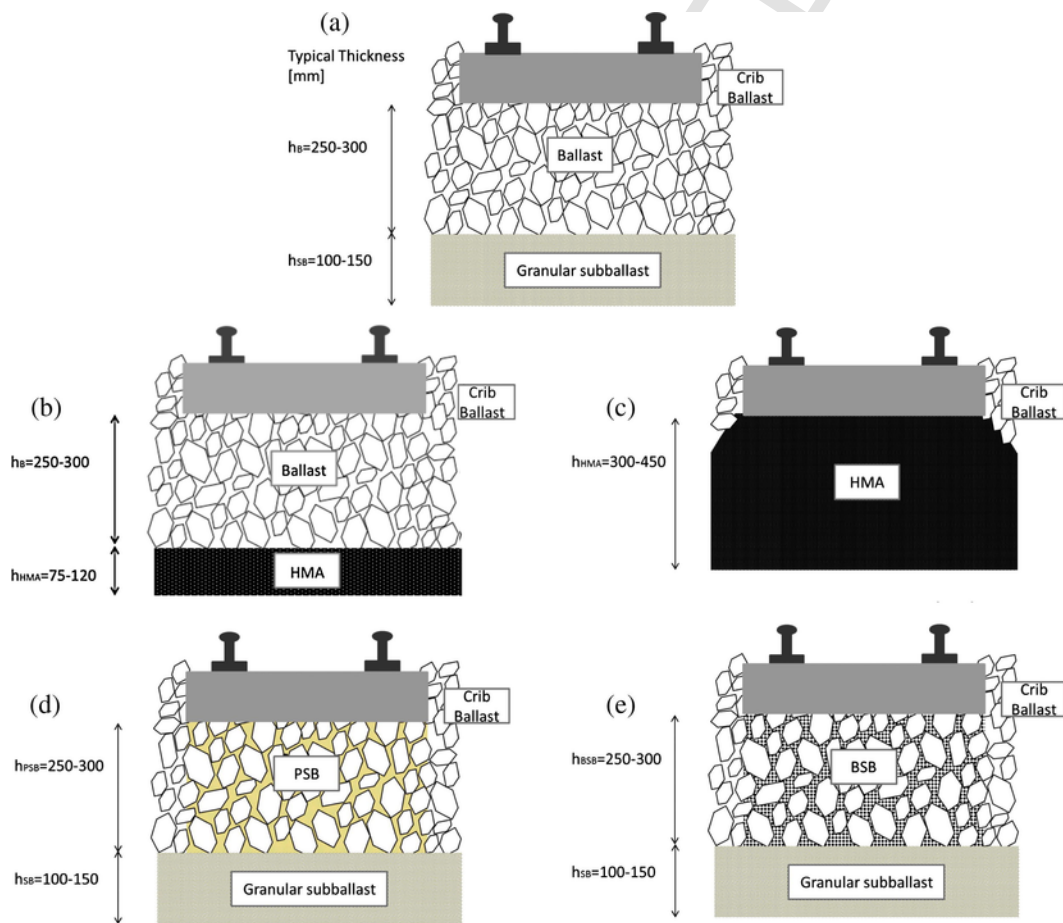


Fig. 1. Configuration of conventional ballasted track-bed, hot mix asphalt (HMA) used as underlayment and overlayer, polyurethane stabilized ballast (PSB), and proposed technology (BSB).

2.1. Materials

The materials used for this study include: virgin aggregate, bitumen emulsion and water. The ballast used in this study was granite aggregate sourced from Bardon Hill Quarry in Leicestershire, (United Kingdom). Table 1 shows the main physical and mechanical properties of the aggregates, which are compliant with European Standards.

In this study, ballast was tested for different conditions using two gradations: (i) clean ballast; (ii) fouled ballast. With its high percentage of particles lower than 22.4 mm the specimen can be considered highly degraded [30,31].

In order to have a maximum particle size smaller than 1/6th the diameter of the specimen, both clean and fouled ballast had to be scaled using the parallel gradation scheme [32]. Due to the dimensions of the PUMA mould (150 mm height, 150 mm diameter), the curves were shifted horizontally along the x-axis in order to have a maximum particle size of 20 mm, as shown in Fig. 2. To obtain the scaled gradations 4 different nominal sizes were combined (only mineral fouling from breakage of particle breakage was considered): 20 mm, 14 mm, 10 mm and 6 mm.

The bitumen emulsion (BE) used for stabilizing the ballast was a cationic bitumen emulsion that has affinity to a wide range of mineral aggregates and promotes adhesion of bitumen to a wide range of aggregate materials. This BE provides a bonding effect between particles, and is effective for use in all weather conditions [33]. Its name is Nymuls CP 50, supplied by Nynas Bitumen. The main properties of the emulsion are reported in Table 2. Pre-wetting water was used to lubricate the aggregate and activate the surface charges on aggregate

Table 1
Mechanical and physical properties of Bardon Hill Quarry granite ballast.

| Property | Standard | Test result | Network specification |
|---------------------------------------|-------------|-------------|-----------------------|
| Los Angeles abrasion [%] | EN 1097-2 | 16 | ≤20 |
| Micro Deval [%] | EN 1097-1 | 7 | ≤7 |
| Flakiness index [%] | EN 933-3 | FI25 | ≤35 |
| Length [%] | RT/CE/S/006 | LRBA | LRBA |
| Fine particle content [%] | EN 933-1 | GFRB A | GFRB A |
| Fines content [%] | EN 933-2 | fRB A | fRB A |
| Particle density [Mg/m ³] | EN 1097-6 | 2.77 | – |

particles before the BE was added. Based on Ojum [33], 2% was selected as optimum pre-wetting water content.

2.2. Test planning

The investigation was divided into two stages. In the first stage the effect of the percentage of bitumen emulsion used for stabilization was analyzed together with the influence of the compaction method used. The percentages studied were 2% and 3% by weight. This range of percentage was chosen according to typical bitumen stabilized materials used for cold mix purposes on roads [34].

Bitumen stabilized ballast (clean, C-BSB, and fouled, F-BSB) was compared to clean and fouled ballast used as references.

Since ballast behaviour depends upon its level of compaction [17], at this stage two different methods were used in order to analyze their influence on performance. In the first method (a) samples were compacted by manual shaking of the mould [27], carried out after each third of material was poured into the mould; in the second method (b) the whole sample was poured and then compacted by a vibrating hammer through a plate for approximately 60 s. These two methods simulated the situations when a dynamic track stabilizer is used or not used after construction or routine maintenance.

Traffic was simulated by applying dynamic loads equivalent to an average contact stress of 200 kPa, which is considered to be appropriate to simulate a typical train loading effect [8,35].

In the second stage of this study, performance of BSB under a higher level of stress (300 kPa) was predicted simulating dynamic loading of high-speed trains, freight train loads or dynamic effects caused by rail or wheel surface imperfections [2,15]. In this second stage, tests were carried out for only one compaction condition, namely compaction by vibrating hammer on F-BSB with 3% BE, as well as reference materials.

The test plan is summarized in Fig. 3. More test conditions were explored for fouled ballast stabilization in order to evaluate the potential of this method to improve performance of an already degraded material.

Both dry and wet conditions were tested for unbound material in order to understand the influence of moisture content for this type of test. For each test the compaction method is indicated as (K) for vibrating hammer (Kango) and (M) for Manual shaking.

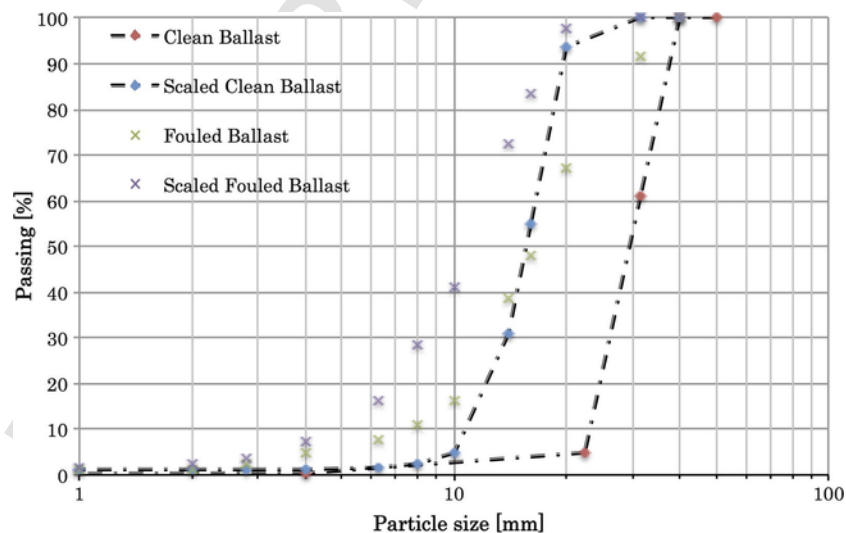


Fig. 2. Parallel gradation curves of clean and fouled ballast.

Table 2
Bitumen emulsion physical and rheological properties.

| Property | Standard | Nymuls CP 50 |
|----------------------------------|--------------------|-----------------------|
| Appearance | – | Black to brown liquid |
| Particle surface electric charge | – | Positive |
| Binder content [%] | EN 1428 or EN 1431 | 60 |
| Breaking behaviour [s] | EN 13075-1 | >170 |
| Penetration [dmm] | EN 1426 | 47 |
| Softening point [°C] | EN 1427 | 52 |

2.3. Test set up

After sieving operations ballast samples were poured into the PUMA mould and compacted. In the case of wet ballast, the sample was previously mixed with water in order to have moisture content (MC) of 2%.

In the case of BSB, after compaction, the emulsion was poured taking care to obtain an approximately homogenous distribution on the ballast surface. During this operation the emulsion flowed along the path of least resistance, through the pores within the ballast. After this, specimens were cured for 72 h at 40 °C, simulating long-term curing [33].

Fig. 4 shows the appearance of the stabilized ballast after the emulsion had set. It can be noticed that it appears similar to an open graded asphalt mix.

Once the set-up of the specimens was concluded they were tested using the NU loading frame, which is a piece of equipment com-

monly available in UK materials testing laboratories and widely used for the testing of asphalt samples [36].

The equipment was used to apply repeated compression load to the samples and to record the resulting vertical displacement, by means of a pair of Linear Variable Differential Transformers (LVDTs). A deeper description related to the PUMA apparatus is available in Thom et al. [26] and D’Angelo et al. [27].

Data were recorded during each cycle for the first 100 repetitions, each 10 cycles from cycle 100–1000 and then every 1000 cycles thereafter. Data readings taken during the cyclical load testing included axial load, axial deformation, circumferential deformation, and confining pressure. All the tests were conducted by applying a cyclic load as a 5 Hz haversine, bell-shaped loading pulse with peaks (200 kPa or 300 kPa) and rest loads (11.7 kPa) [37] for 200,000 repetitions. This frequency is considered corresponding to the frequency measured in situ for a train speed of 100 km/h [38] and is commonly used in laboratory dynamic tests simulating railway traffic loading [39]. A constant initial confining pressure of 10 kPa was applied to all the specimens as representative of the in-situ confining pressure of self standing ballast [40]. All the tests were carried out at a controlled temperature of 20 °C.

These conditions, even if they are not fully simulative of real track, are considered adequate to reach a stable behaviour as demonstrated for similar tests on granular materials [15].

The majority of the tests were carried out twice and for those a good repeatability was observed: test pairs always within 6% of each other.

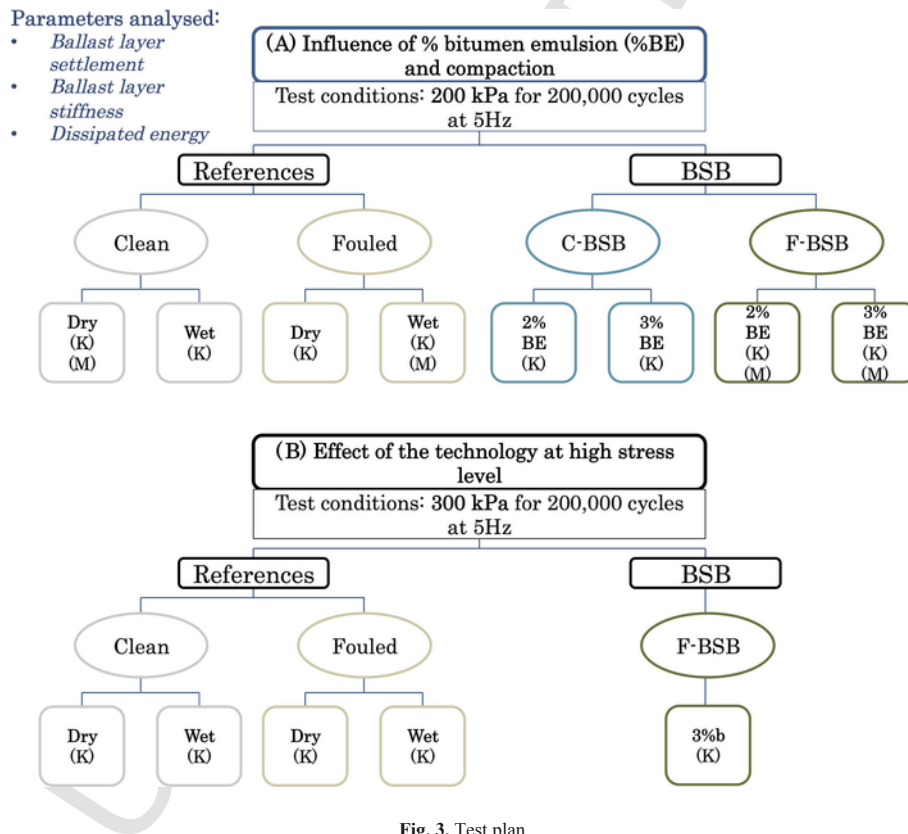


Fig. 3. Test plan.



Fig. 4. Visual appearance of the stabilized ballast after emulsion setting.

3. Results and discussion

3.1. Influence of the compaction method and the % BE on clean and fouled ballast

Figs. 5 and 6 show the ballast cumulative plastic strain for the reference fouled and clean ballast and the stabilized materials, recorded during the dynamic tests. Results shows that overall stabilized specimens exhibited lower plastic strains than the reference ones, as it happened for other stabilization techniques [12,13,15,41]. In particular: 0.53% and 0.61% for F-BSB (K) against 1.30% and 1.34% for Fouled ballast (K); 0.88% and 1.02% for F-BSB (M) against 1.53% for Fouled ballast (M); 0.39% and 0.40% for C-BSB (K) against 1.21% and 1.23% for Clean ballast (K). With the aim of evaluating also the long-term behaviour, Table 3 lists the plastic strain rate (PSR) measured over the last 20,000 cycles, when the behaviour was stable, according to Eq. (1):

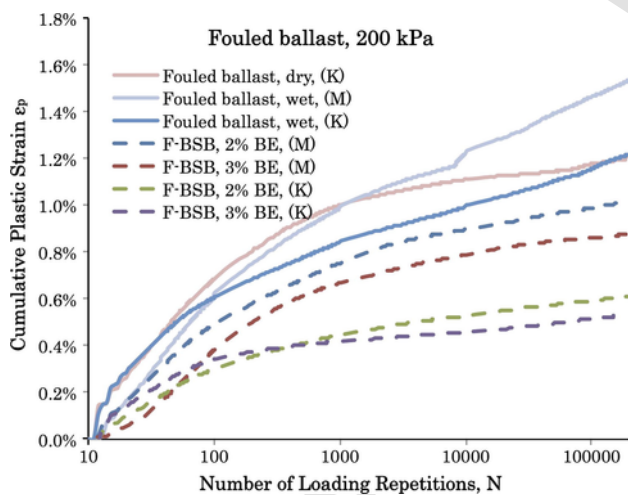


Fig. 5. Cumulative plastic strain over the cyclic vertical compression testing for Fouled ballast and F-BSB specimens.

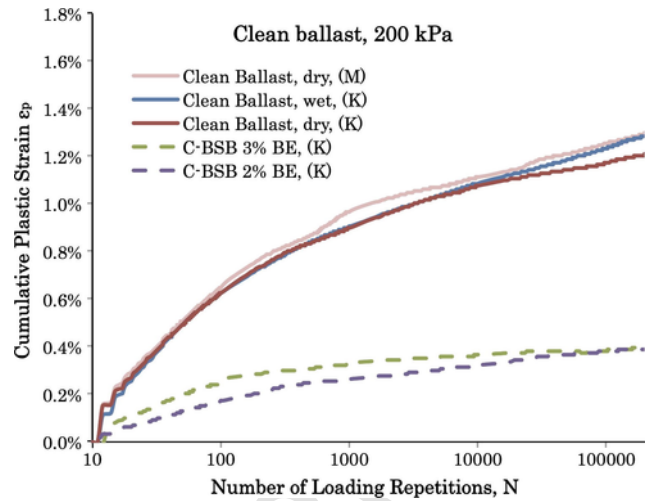


Fig. 6. Cumulative plastic strain over the cyclic vertical compression testing for Clean ballast and C-BSB specimens.

Table 3

Effect of ballast stabilization on the plastic strain rate (long-term behaviour) of clean and fouled ballast.

| Fouled | | | Clean | | | | | | | | |
|-------------------------------|---------|---------|------------|------------|------------|------------|---------|---------|---------|------------|------------|
| Wet (M) | Dry (K) | Wet (K) | BSB 2% (M) | BSB 3% (M) | BSB 2% (K) | BSB 3% (K) | Dry (M) | Dry (K) | Wet (K) | BSB 2% (K) | BSB 3% (K) |
| PSR: $\times 10^5$ [mm/cycle] | | | | | | | | | | | |
| 5.13 | 3.79 | 4.10 | 2.96 | 1.34 | 1.53 | 1.16 | 3.83 | 2.12 | 3.73 | 0.75 | 0.70 |

$$PSR = \frac{\Delta \epsilon_s}{\Delta N_s} \tag{1}$$

where ΔN_s is the number of cycles and $\Delta \epsilon_s$ is the plastic variation during the stable range considered.

In this regard, results show that the stabilization technique overall significantly decreased also the deformation rate and consequently could improve the durability of ballast layer.

The influence of the compaction method on vertical plastic deformation confirms its importance on the in-track behaviour [17]. Namely all specimens compacted by Kango (K) resisted permanent deformation better. Nonetheless this difference was greater for fouled ballast than clean ballast, which ties in with the findings of Thom and Brown [42] in relation to shear strength of materials with different uniformity coefficients. The underlying reason may be that single-sized materials require less compactive effort to achieve their maximum density.

Overall an increase of % BE corresponded to an important decrease in both permanent deformation and deformation rate, especially for F-BSB. This effect was less evident in the case of C-BSB and suggests that the amount of bitumen corresponding to 2% BE was already close to the maximum that could be retained due to the small number of particle contacts in clean ballast.

The effect of a small increase in MC both for clean and fouled ballast was a small increase in plastic strain, as expected [2].

From the data recorded during the dynamic tests it was possible to calculate the resilient modulus as in Eq. (2):

$$M_r = \frac{\Delta\sigma_v}{\epsilon_r} \tag{2}$$

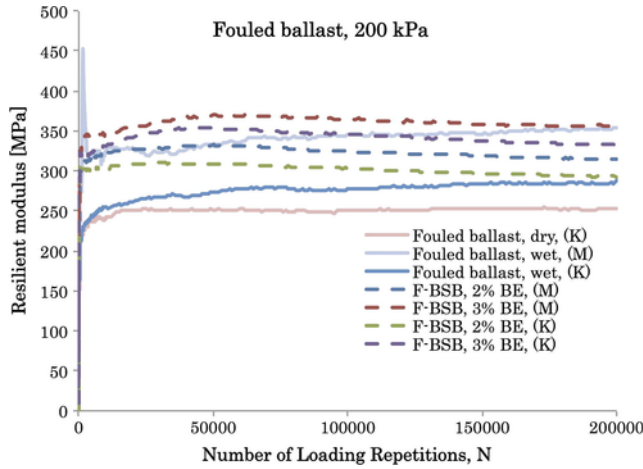


Fig. 7. Resilient modulus over the cyclic vertical compression testing for Fouled ballast and F-BSB specimens.

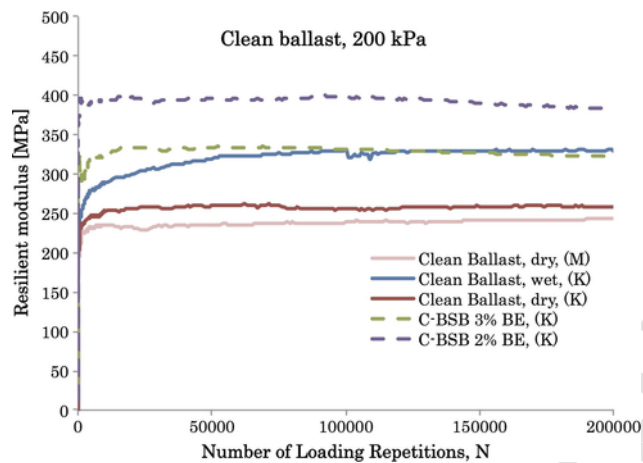


Fig. 8. Resilient modulus over the cyclic vertical compression testing for Clean ballast and C-BSB specimens.

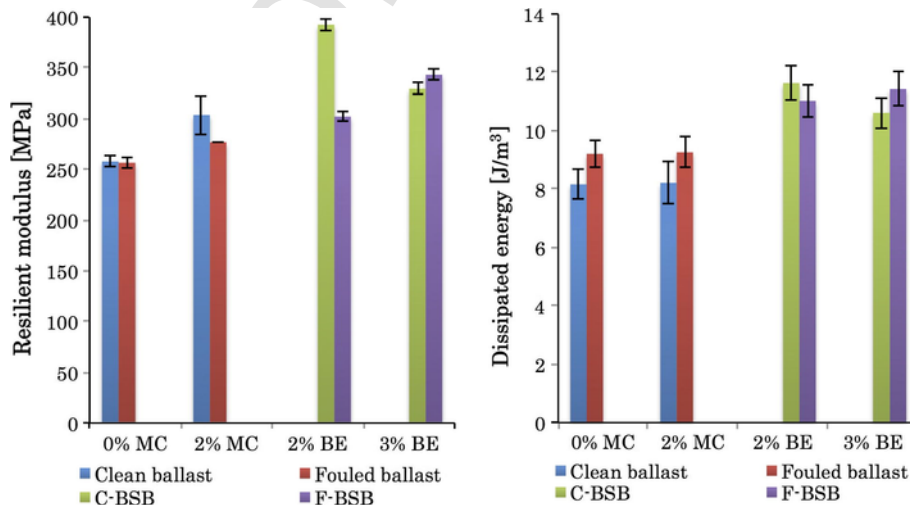


Fig. 9. Average resilient modulus over the cyclic vertical compression testing (left) and dissipated energy in each loading-unloading cycle (right) for clean ballast, fouled ballast, C-BSB and F-BSB specimens (K).

where $\Delta\sigma_v$ and ϵ_r represent the deviatoric stress and resilient (recoverable) strain, respectively.

Its plot against the number of loading repetitions is reported in Figs. 7 and 8. After 100,000 cycles when the behaviour is stable, from the hysteresis loop (strain-stress diagram) the dissipated energy values were calculated. The effect of % BE on the average resilient modulus and dissipated energy, under the same compaction method (K), is highlighted in Fig. 9.

Overall it can be noticed that there is an increase in the values of resilient modulus and dissipated energy in the BSB specimens with respect to reference materials. In this case, the % BE had a higher influence than the compaction method for the resilient modulus of BSB specimens. From Fig. 7, in fact, it can be noticed that F-BSB specimens with 3% BE had slightly higher stiffness values than those with 2%, regardless of the compaction method. In contrast C-BSB exhibited a higher stiffness with 2% BE. This last result is probably associated again with the maximum quantity of bitumen emulsion that can be retained within a nearly single-sized material.

The effect on dissipated energy seemed to be approximately independent of the % BE and the compaction method. However, BSB specimens exhibited an average increase of approximately 35% and 40% with respect to the fouled and clean ballast reference materials, respectively. In this sense, viscoelastic behaviour of bitumen added to the material very desirable hysteretic damping properties. This is to be expected since the presence of bitumen induces energy loss due to viscous effects, adding to the frictional energy losses taking place due to inter-particle slip within ballast [43,44].

Variation of both of these two parameters can improve track-bed performance: low levels of stiffness could increase flexural deformation and consequently the bending moment of the rail (and thus its stresses) as well as track-bed settlement [6,7,45]; on the other hand, increasing the stiffness can lead to higher dynamic forces transmitted by trains that, if not adequately damped, necessarily lead to the deterioration of all components of the track [46]. In this regard, increasing the energy dissipation is appropriate for damping dynamic overloads, reducing track-bed and ground vibrations and therefore maintenance costs [43]. Nonetheless it has to be also noted that on excessively flexible tracks, energy dissipation can also lead to important increase in rolling resistance and thus service costs [46].

In this case of BSB, the increase in dissipated energy per cycle is due to the viscoelastic behaviour provided by the bitumen component rather than a more flexible behaviour, as can be noticed from Fig. 10. This result correlates well with results obtained by Sol-Sanchez et al., who compared mechanical behaviour of track-bed sections with granular or bituminous sub-ballast [7]. Thus by modifying both the stiffness and damping characteristics of the ballast layer, BSB can effectively reduce deterioration and maintenance associated costs.

Looking at Figs. 7 and 8, as highlighted in the preliminary study of D'Angelo et al. [27], BSB specimens all exhibited the same behaviour, different from granular materials. Namely, their values of resilient modulus increased over the first 50,000 cycles and thereafter slightly decreased with approximately the same slope. Otherwise, all the other specimens, as expected from granular materials, after the first 10,000 cycles characterized by plastic hardening [47], exhibited approximately constant (or slightly increasing) values of resilient modulus. In this regard, BSB behaviour mirrors closely the fatigue experienced in cyclic tests by bituminous materials.

3.2. BSB properties under high stress level

After the first stage, from the obtained results it was decided to continue the investigation by comparing the optimum case of F-BSB with the reference ones, subjected to high stress level. Furthermore, due to the resulting better influence on predicted performance, only the vibrating hammer was used as the compaction method.

Figs. 11 and 12 show the results of the final plastic strain, average resilient modulus and dissipated energy for specimens cyclically loaded with a peak stress of 300 kPa.

Comparing these results with those obtained at 200 kPa highlights the non-linearity of unbound and stabilized behaviour [48]. Specimens, in fact, exhibited higher values of stiffness than those tested at lower stress, all other conditions being the same.

Moreover, under high stress level bitumen emulsion stabilization confirmed the improvements discussed in Section 3.1. It reduced the plastic deformation by approximately 50% and increased the stiffness by approximately 20%. Both results are comparable with other stabilization techniques [14,15,49]. However a major variation was found in terms of dissipated energy per cycle. If, under ordinary stress level, BSB showed the potential to dissipate approximately 40% more energy than the reference material, when the level of stress was in-

creased this value grew up to 150%. Nonetheless, as noticed from Fig. 10, this difference is not caused by an increase in deflection (which is not desirable as stated in Section 3.1) but by the modified viscoelastic mechanical behaviour of BSB.

In this regard, besides the general improvement to track-bed performance, ballast stabilization can be considered potentially more effective for severe conditions of loading.

4. Conclusions

This study presented the analysis of the potential of bitumen emulsion, poured at ambient temperature, as stabilization method for clean and fouled ballast. BSB aims to reduce track-bed settlement and increase durability by modifying ballast mechanical behaviour. The final scope is to propose an overall more sustainable solution for railway track-beds, which is more viable than the existing similar technology in terms of economics and applicability and therefore has the potential of improving existing ballasted tracks.

For this purpose, a laboratory study has been developed to analyze the effectiveness of this technology under different conditions with a relatively practical test suited to both unbound and stabilized materials (PUMA).

The obtained results led to the following conclusions:

- At ordinary stress level, the use of bitumen emulsion as stabilization method led to a significant decrease of ballast permanent deformation and deformation rate, higher when the dosage was increased. This suggests a good potential of this technology for improving both the short-term and the long-term characteristics to mitigate the problem of ballast settlement.
- At the same time, an important role was played by the compaction method: in particular, results indicated better and more stable behaviour when compaction by vibrating hammer was used. Therefore, in the second stage of the study only this compaction method was used.
- BSB specimens exhibited a relatively small increase in stiffness, which, especially in the case of fouled ballast, was related to the amount of BE poured (the higher the stiffer). In this regard, an optimum content that depends on the type of emulsion and ballast grading has to be evaluated. This stiffening effect can be beneficial for reducing rail deflection and stresses and track-bed settlement.

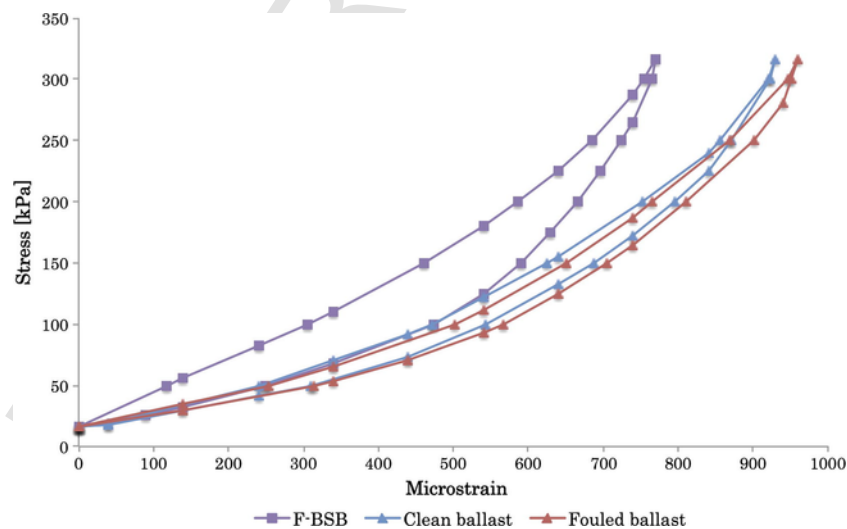


Fig. 10. Stress-strain hysteretic loops for different specimens at high stress level.

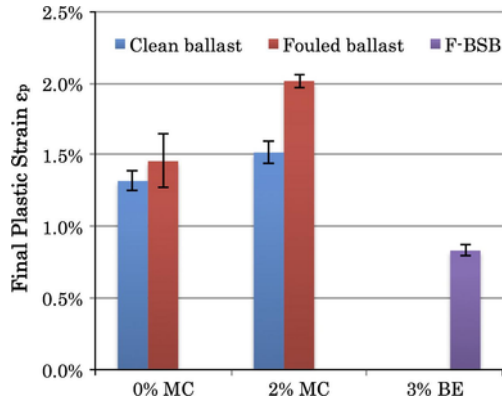


Fig. 11. Final plastic strain after 200,000 cycles (300 kPa).

- However, higher levels of stiffness can lead also to increased dynamic forces. In this regard, tests carried out at both ordinary (200 kPa) and high (300 kPa) stress levels showed a significant increase in dissipated energy with respect to reference materials. This was not related to higher elastic deflection (which could have affected also rolling resistance) but to the changed mechanical behaviour of BSB (see Fig. 10). Thus, BSB viscoelastic properties are highly desirable to dampen dynamic overloads.
- Moreover, by comparing results obtained at 200 kPa and 300 kPa an important variation in the damping characteristics of BSB can be noticed. This suggests that this technology can be even more effective for severe conditions of loading.

Based on this research BSB could represent a feasible solution to mitigate the problem of track-bed deterioration and settlement. The

obtained results suggest that this technology has the potential to significantly reduce ordinary and extraordinary maintenance, therefore reducing the lifecycle costs and increasing the environmental sustainability.

The authors are already working on the up-scaling of this technology based on a hypothetic scenario that in-track application of BSB could be carried out during a routine maintenance operation by lifting the sleeper and blowing the optimum amount of bitumen emulsion (related to ballast gradation) into the ballast/sleeper contact area. If track geometry correction becomes necessary, stoneblowing would be the ideal maintenance operation since it would not disturb the stabilized layer. Also tamping could be applied, if absolutely necessary; but loss of cohesion would result in the ballast reverting back to an unbound state. With regards to extraordinary maintenance, coated particles from BSB would not represent a problem since they would be available for recycling at the end-of-life. Further understanding of the BSB performance in real scale, its applicability and maintainability, optimization of the type of bitumen and emulsion properties as well as the influence and optimisation of other variables are in progress.

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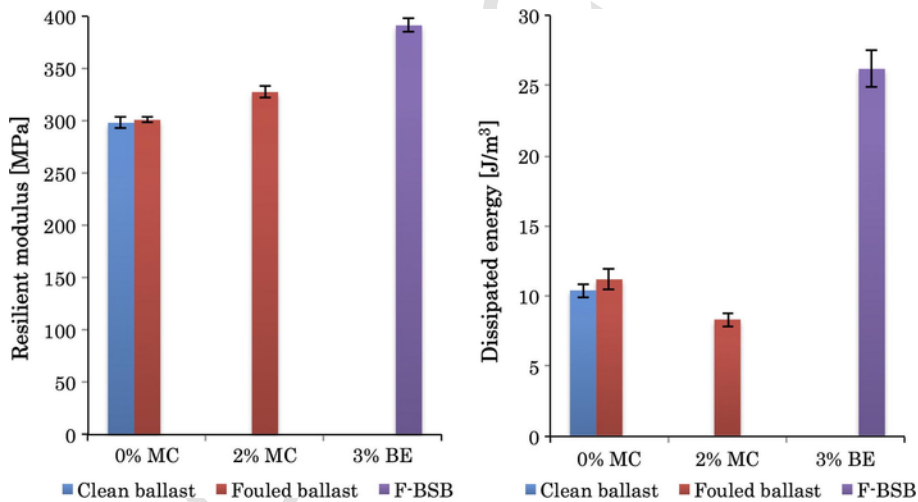


Fig. 12. Average resilient modulus over the cyclic vertical compression testing (left) and dissipated energy in each loading-unloading cycle (right) (300 kPa).

References

- [1] E.T. Selig, J.M. Waters, *Track Geotechnology and Substructure Management*, T. Telford, 1994.
- [2] B. Indraratna, W. Salim, C. Rujikiatkamjorn, *Advanced Rail Geotechnology – Ballasted Track*, 2011.
- [3] J. Pires, A.G. Dumont, *Railway ballast degradation*, In: 15th Swiss Transport Research Conference, 2015.
- [4] C. Paderno, *Ballast Behavior under Action of Tamping and Railway Traffic*, EPFL, Switzerland, 2010.
- [5] M. Sol-Sánchez, F. Moreno-Navarro, M. Rubio-Gámez, The use of deconstructed tires as elastic elements in railway tracks, *Materials (Basel)* 7 (2014) 5903–5919.
- [6] M. Sol-Sánchez, N.H. Thom, F. Moreno-Navarro, M.C. Rubio-Gámez, G.D. Airey, A study into the use of crumb rubber in railway ballast, *Constr. Build. Mater.* 75 (2015) 19–24.
- [7] M. Sol-Sánchez, L. Pirozzolo, F. Moreno-Navarro, M.C. Rubio-Gámez, A study into the mechanical performance of different configurations for the railway track section: a laboratory approach, *Eng. Struct.* 119 (2016) 13–23.
- [8] B. Indraratna, H. Khabbaz, W. Salim, D. Christie, Geotechnical properties of ballast and the role of geosynthetics in rail track stabilisation, *Proc. ICE – Gr. Improv.* 10 (3) (2006) 91–101.
- [9] B. Indraratna, S.K.K. Hussaini, J.S. Vinod, The lateral displacement response of geogrid-reinforced ballast under cyclic loading, *Geotext. Geomembr.* 39 (2013) 20–29.
- [10] S.F. Brown, J. Kwan, N.H. Thom, Identifying the key parameters that influence geogrid reinforcement of railway ballast, *Geotext. Geomembr.* 25 (6) (2007) 326–335.
- [11] B. Indraratna, S. Nimbalkar, N. Tennakoon, The behaviour of ballasted track foundations: track drainage and geosynthetic reinforcement, *GSP* 199 (2010) 2378–2387.
- [12] J. Kennedy, A full-scale laboratory investigation into railway track substructure performance and ballast reinforcement, January, 2011.
- [13] M.S. Dersch, E. Tutumluer, C.T. Peeler, D.K. Bower, Polyurethane coating of railroad ballast aggregate for improved performance, In: 2010 Joint Rail Conference, vol. 1, 2010pp. 337–342.
- [14] J.H. Kennedy, P.K. Woodward, G.M. Medero, J. McKinney, Full-scale cyclic geopavement & railway accelerated fatigue testing, In: 0th International Railway Engineering Conference, 2009.
- [15] A.K. Keene, T.B. Edil, J.M. Tinjum, Mitigating Ballast Fouling Impact and Enhancing Rail Freight Capacity, 2012.
- [16] S. Lakušić, M. Ahac, I. Haladin, Track stability using ballast bonding method, In: 10th Slovenski kongres o cestah in prometu, 2010.
- [17] S. Fischer, B. Eller, Z. Kada, A. Németh, *Railway Construction*, vol. 1, Universitas-Gyor Nonprofit Kft, 2015.
- [18] P.K. Woodward, D. Thompson, M. Banimahd, Geocomposite technology: reducing railway maintenance, In: Proceedings of the ICE – Transport 160, 2007pp. 109–115.
- [19] J.G. Rose, Selected in-track applications and performances of hot-mix asphalt trackbeds, In: 2013 Joint Rail Conference, 2013. pp. V001T01A017–V001T01A017.
- [20] S.-H. Lee, J.-W. Lee, D.-W. Park, H.V. Vo, Evaluation of asphalt concrete mixtures for railway track, *Constr. Build. Mater.* 73 (Dec. 2014) 13–18.
- [21] G. Di Mino, M. Di Liberto, C. Maggiore, S. Noto, A dynamic model of ballasted rail track with bituminous sub-ballast layer, *Procedia Soc. Behav. Sci.* 53 (2012) 366–378.
- [22] J.G. Rose, *Hot-Mix Asphalt Railway (Bituminous) Railway Trackbeds: In-Track Tests, Evaluations, and Performances – A Global Perspective*, 2014.
- [23] M. Fang, S.F. Cerdas, Y. Qiu, Numerical determination for optimal location of sub-track asphalt layer in high-speed rails, *J. Mod. Transp.* 21 (2) (Jun. 2013) 103–110.
- [24] G. D'Angelo, N.H. Thom, D. Lo Presti, Potential of bituminous emulsion for ballast stabilisation, *Constr. Build. Mater.* (2016). p. (accepted).
- [25] K. Khweir, A. Windmill, D. Fordyce, The potential of stone filled emulsion asphalt, In: *The Asphalt Yearbook 1995*, 1995pp. 25–30.
- [26] N.H. Thom, A. Cooper, P. Grafton, C. Walker, H. Wen, R. Sha, A new test for base material characterisation, In: 2nd MESAT Conference on Sustainable Asphalt Pavements in the Middle East, MESAT-055, 2013.
- [27] G. D'Angelo, N.H. Thom, D. Lo Presti, Using PUMA test to predict performance of stabilised ballasted trackbed, In: *The Third International Conference on Railway Technology: Research, Development and Maintenance*, 2016.
- [28] C.J. Semmelink, Use of the DRTT K-mould to determine the elastic and shear properties of pavement materials, South Africa, 1991.
- [29] J.P. Edwards, N.H. Thom, P.R. Fleming, Development of a simplified test for unbound aggregates and weak hydraulically bound materials utilizing the NAT, In: *Proceedings of the 6th International Symposium on Pavement Unbound*, 2004pp. 3–11.
- [30] A. Ebrahimi, J.M. Tinjum, T.B. Edil, Deformational behavior of fouled railway ballast, *Can. Geotech. J.* 52 (2015) 344–355.
- [31] E. Tutumluer, W. Dombrow, H. Huang, Laboratory characterization of coal dust fouled ballast behavior, In: *Proc., AREMA 2008 Annual Conf.*, 2008pp. 21–24.
- [32] A.F. Sevi, Physical Modeling of Railroad Ballast using the Parallel Gradation Scaling Technique within the Cyclical Triaxial Framework, Missouri University of Science and Technology, 2008.
- [33] C.K. Ojum, *The Design Optimisation of Cold Asphalt Emulsion Mixtures*, The University of Nottingham, 2015.
- [34] D. Collings, M. Hughes, J. Grobler, K. Jenkins, F. Jooste, F. Long, H. Thompson, *Technical Guideline: Bitumen Stabilised Materials*, vol. 2, no. 2. 2009.
- [35] D. Bach, P. Veit, Evaluation of attrition tests for railway ballast, 2013.
- [36] N.H. Thom, S.F. Brown, The mechanical properties of unbound aggregates from various sources, In: *Proceedings of the 3rd International Symposium*, 1, 1989University of Nottingham.
- [37] A. Ebrahimi, J.M. Tinjum, T.B. Edil, Large-scale, cyclic triaxial testing of rail ballast, In: *AREMA 2010 Annu. Conf. Expo.*, 2010pp. 1–24.
- [38] V.N. Trinh, A.M. Tang, Y.J. Cui, J.C. Dupla, J. Canou, N. Calon, L. Lambert, A. Robinet, O. Schoen, Mechanical characterisation of the fouled ballast in ancient railway track substructure by large-scale triaxial tests, *Soils Found.* 52 (3) (2012) 511–523.
- [39] Y. Momoya, T. Nakamura, S. Fuchigami, T. Takahashi, Improvement of degraded ballasted track to reduce maintenance work, *Int. J. Railway Technol.* 5 (3) (2016) 31–54.
- [40] B. Aursudkij, G.R. McDowell, A. Collop, Cyclic loading of railway ballast under triaxial conditions and in a railway test facility, *Granular Matter* 11 (6) (2009) 391–401.
- [41] J. Kennedy, P.K. Woodward, G. Medero, M. Banimahd, Reducing railway track settlement using three-dimensional polyurethane polymer reinforcement of the ballast, *Constr. Build. Mater.* 44 (2013) 615–625.
- [42] N.H. Thom, S.F. Brown, The effect of grading and density on the mechanical properties of a crushed dolomitic limestone, In: *Australian Road Research Board (ARRB) Conference*, 14th, 1988, Canberra, vol. 14, no. 7, 1988.
- [43] B. Su, *Effects of Railroad Track Structural Components and Subgrade on Damping and Dissipation of Train Induced*, 2005.
- [44] F. Goncu, *Mechanics of Granular Materials: Constitutive Behavior and Pattern Transformation*, 2012.
- [45] G.A. Hunt, J. Wood, Review of the effect of track stiffness on track performance, 2005.
- [46] A. Lopez Pita, P.F. Teixeira, F. Robuste, High speed and track deterioration: the role of vertical stiffness of the track, *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit.* 218 (1) (2004) 31–40.
- [47] W.L. Lim, *Mechanics of Railway Ballast Behaviour*, The University of Nottingham, 2004.
- [48] B. Aursudkij, *A Laboratory Study of Railway Ballast Behaviour under Traffic Loading and Tamping Maintenance*, The University of Nottingham, 2007.
- [49] P.K. Woodward, J. Kennedy, O. Laghrouche, D.P. Connolly, G. Medero, Study of railway track stiffness modification by polyurethane reinforcement of the ballast, *Transp. Geotech.* 1 (4) (2014) 214–224.