Bitumen Stabilised Ballast: a novel track-bed solution towards a more sustainable railway

By

Giacomo D'Angelo

Thesis submitted to the University of Nottingham for the degree of Doctor of Philosophy

October 2018

"A scientist in his laboratory is not a mere technician: he is also a child confronting natural phenomena that impress him as though they were fairy tales."

Marie Curie

Abstract

Ballasted track represents by far the most used infrastructure for railway transportation system, its main benefits being the relatively low construction costs, the maintainability, the relatively high damping capacity, noise absorption and high flexibility, the self-adjusting properties and high hydraulic conductivity. These are related to the structure of ballast layer as assembly as well as to particle properties. However, the unbound nature of ballast layer is also responsible for the reduction of geometric quality of the track, and therefore, its safety and ride comfort. The passage of trains causes cyclic movements of the unbound particles that result in permanent vertical and lateral deformations. For this track form, vertical settlement of granular layers and ballast particles degradation represent the major problems, affecting frequency of maintenance and track durability.

In this context, reducing minor and major maintenance frequency while effectively using available resources by developing innovative technologies is a challenge for current and future railway research. After reviewing the most relevant existing solutions to improve ballasted track-bed behaviour and main factors affecting their performance, the aim of this research was to investigate the possibility of stabilising ballast with bitumen emulsion, as novel solution to slow down the loss in track quality associated with ballast settlement and particle degradation.

In this regard, firstly the feasibility of the proposed alternative and main factors affecting its performance have been assessed through model-scale testing (small-scale Precision Unbound Material Analyser - PUMA). Results showed a good potential for this technology to reduce both the short-term and the long-term permanent deformation. It was also observed that bitumen stabilisation could modify mechanical properties due to the presence of a viscoelastic component (bitumen). The type of emulsion and its dosage played important roles in BSB

properties: increasing the dosage of bitumen emulsion provided a better resistance to permanent deformation; increasing the viscosity of bitumen emulsion decreased the percentage of material lost, thereby providing improved stabilisation efficiency. Thus, depending on the field condition a specific bitumen emulsion could be designed to obtain the desired results in terms of BSB behaviour and stabilisation efficiency. At the same time, the use of harder bitumen for BSB seemed to improve the resistance to permanent deformation while polymer modification provided a more stable behaviour over time.

Model-scale results provided important guidance on the influence of the factors analysed on the proposed technology. Nevertheless, to understand to what extent BSB could represent a solution to improve sustainability and performance of ballasted track-beds, findings had to be verified at full scale. Thus, full-scale box tests have been employed to assess how this technology could be effectively applied to existing ballasted tracks during maintenance operations and to investigate the practicability and maintainability of the presented technology. Results showed that bitumen stabilisation was more effective when applied at an early stage of ballast life (clean ballast), especially when coupled with tamping, providing a significant decrease to permanent deformation and to deformation rate (long-term behaviour).

Nonetheless, in comparison with results obtained at model-scale, a slightly different behaviour of BSB in relation to unbound material was observed. Thus, with the aim of correlating previous model-scale PUMA and full-scale ballast box findings and evaluating long-term performance, full-scale PUMA testing was carried out. Results on clean ballast indicated that scale factor instead of the test type was the main factor controlling the effectiveness of Bitumen Stabilised Ballast (BSB) in terms of permanent deformation reduction. On the other hand, results obtained when using lower size aggregate confirmed that increasing the number of contact points increases also the influence of viscoelastic properties given by the bitumen, indicating that the use of different gradations combined with higher dosages (and types) of bitumen emulsions, could potentially modify full-scale track-bed mechanical properties.

Key findings obtained from laboratory experiments, consistently showed evidence of the fact that bitumen stabilisation can reduce number of maintenance interventions due to geometry corrections and excessive particle degradation. In this regard, to estimate the environmental and economic impacts of BSB, a performance-based integrated model was developed to predict maintenance strategies of proposed technology in comparison to traditional ballast. This model, by combining the evolution of track irregularities with traffic and the level of contamination of ballast, allowed evaluation of the timing of corrective maintenance activities.

Based on these, life-cycle environmental and economic costs of these alternatives have been carried out. Life Cycle Assessment (LCA) results showed that BSB is overall more sustainable than traditional ballasted track, only when considering also its impact on major maintenance operations. Sensitivity analysis carried out showed that BSB advantages are generally higher when the tolerance on the track quality level increases and with heavy traffic lines. LCCA results showed that BSB can provide important savings with respect to traditional ballasted track-bed. Sensitivity analysis showed that BSB would be more profitable for important and congested lines rather than peripheral ones. The influence of carbon conversion factor on results is relatively low while decreasing the discount rate corresponds to higher savings provided by the BSB.

Overall, both LCA and LCCA results showed that BSB could offer a more sustainable solution from a life cycle perspective than traditional ballasted track-bed.

Acknowledgment

First, my gratitude goes to my supervisors, Dr Nick Thom, Dr Davide Lo Presti and Prof Glenn McDowell, for all their support, valuable advices, guidance and help since the first days I started working at the NTEC for the SUP&R ITN project. The research presented in this thesis was carried out as part of the Marie Curie Initial Training Network (ITN) action, FP7-PEOPLE-2013-ITN. This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement number 607524. Thank you for giving me the opportunity of taking part to this great experience. All supervisors and colleagues in this project made this experience unforgettable.

As part of this research project I had also the chance to be seconded at LabIC group (University of Granada) and at AECOM (Nottingham Office), where I spent great time that helped me to develop a substantial part of this thesis. In particular, I would like to thank Dr Miguel Sol-Sanchez and Craig Govan for all the technical discussions, support and suggestions given over this time. I would like also to thank all professors, colleagues and technicians at NTEC, LaBIC and AECOM for making these years easier.

Thanks to the University of Palermo, to Prof Gaetano Di Mino, Prof Mario Di Paola and Dr Francesco Pinnola, who first introduced me to the research in transportation engineering, for their advice, knowledge and many insightful discussions.

I wish to express my gratitude to all friends I have met in Nottingham, thanks Ana, Alessio, Laura, Domenico, Giulia, Gaspare, Sara, Andrea, Mo, Diana, Gustavo, Emily, Maria, Antonio, Claudia, Patricia, Alex, Breixo, Federico, Camilla and all the amazing people who made me feel like home in this place. Thanks a lot. Thanks also to all my friends from Cefalù, for being always there supporting me from distance and making me feel like nothing has changed each time we met. Thanks in particular to Basilio and Davide.

A special thank goes to my partner Helena, for understanding me, encouraging me and being by my side through all this period. Thanks for your love and for being an essential part of my life.

Finally, I would like to express my deepest gratitude to my family, especially to my sister Francesca, my mother Cettina and my father Nino, and also to Federico. Thanks for supporting, listening, motivating and driving me, making me carrying on for every single moment of my life, I will be always grateful.

Thank you.

Declaration

I declare that the contents and the work described in this thesis were performed at the University of Nottingham, Faculty of Engineering from June 2014 to December 2017. I hereby certify that this thesis is my own, except where work which has formed part of jointly-authored publications has been included, and has not been submitted in whole or in part to any other university or any other educational association for a higher degree.

Giacomo D'Angelo

Nottingham, 2018

We declare that the contents and the work described in this thesis were performed at the University of Nottingham, Faculty of Engineering from June 2014 to December 2017 and under our supervision.

Dr Nick Thom

Dr Davide Lo Presti

Prof Glenn McDowell

Nottingham, 2018

Table of contents

List of Figures

List of Tables

Chapter 1 - Introduction

1.1 Background of the thesis

The increasing evidences of the impact of greenhouse gas (GHG) emissions on global warming and its negative effects has urged the international community to strength the worldwide commitment to implement fair-reaching actions towards low-carbon and climate-resilient growth. For instance, at the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. Among other measures, governments agreed on keeping the increase in global average temperature to well below 2°C above pre-industrial levels (EC 2017a).

With transport sector contributing to around a quarter of the European Union's (EU's) GHG emissions, making it the second-biggest emitting sector after energy, it surely holds the keys to decarbonize the European economy (EC 2017b). Although within this sector, road transport is by far the biggest emitter accounting for more than 70% of all GHG emissions from transport in 2014, the role the railway system, and particularly its infrastructure, can play in the EU's low-emission mobility strategy cannot be neglected (EC 2016). First, the construction of new and the improvement of the existing railway infrastructures is expected to continue its growing trend in the years to come as the EU aims for implementing and completing the Trans-European Transport Network (TEN-T) core network by 2030 and the TEN-T comprehensive network by 2050 (EC 2016). Second, as the EU's answer to the emission reduction challenge in the transport sector comprises the deployment of low-emission alternative energy sources, it is likely that vehicles become more energy-efficient, and then energy use and GHG emissions during the construction, maintenance and disposal of railway infrastructure might increase their share in the environmental impact of the life cycle's railway system. Last, but not the least, as a considerable portion of the Europe's rail network was constructed in a time where the construction methods were not as advanced as those currently available, it is likely that the combined effects of inadequate levels of investment, poor maintenance strategies, and adverse climatic events, result in important elements of the existing rail networks, such as the track-bed structure, requiring frequent maintenance activities (Bizjak et al. 2017), thereby increasing the environmental footprint associated with the railway infrastructure's life cycle.

Ballasted track, which consists of track superstructure supported on a layer of granular material (ballast), represents by far the most used infrastructure over other alternatives such as concrete slab. Over the 1.4 million km of track worldwide, only approximately 1% is slab track (Michas 2012, UIC 2016). Apart from the longer experience with this solution (slab track has been adopted only in the last 4 decades), its main benefits concern the low construction costs, the high maintainability at a relatively low cost (for single operation) (CEMOSA 2014), the possibility of using indigenous material, the relatively high damping capacity, noise absorption and high flexibility, the self-adjusting properties (in the case of non-homogeneous subgrade) and the high hydraulic conductivity of the track structure (Selig and Waters 1994, Michas 2012, Sugrue 2013, Profillidis 2016).

These advantages are related to the structure of ballast layer as assembly as well as to particle properties, which are also necessary to fulfil its main functions. The ballast layer, in fact, is demanded to transfer traffic loading from sleeper to the subgrade at reduced and acceptable levels while adequate lateral resistance is provided to avoid sleepers' displacement in curve sections (Indraratna et al. 2011). In this regard, the use of crushed angular stones, by increasing the shear strength, contributes to have a better stress distribution and provides at the same time a better lateral and longitudinal resistance. Besides, the use of uniform gradation generates a relatively high air voids content (around 40%) that is essential to have free draining conditions as well as a desirable degree of flexibility and high capacity of damping loads (increasing with aggregate grain-size), which are main requirements of ballast layer (Selig and Waters 1994, Indraratna et al. 2011). In addition, the uniform gradation and coarse size facilitate maintenance operations (to restore track geometry) by the possibility to re-arrange ballast particle with tamping (Ionescu 2004).

At the same time, the use of good quality hard stones (generally, Los Angeles coefficient lower than 14% for high speed lines) is necessary to reduce breakage and degradation of ballast particles, which would negatively affect all these essential properties for the granular layer (especially shear strength and high volume of voids), and therefore, reduce safety and durability of ballasted tracks.

However, the unbound nature of ballast layer, which helps to fulfil the above-mentioned functions, is also responsible for the reduction of the geometric quality of the track, and therefore, its safety and ride comfort (Marsal 1967, Raymond 1985, Jeffs and Tew 1991, Dahlberg 2004, Salim 2004, Boler 2012). The passage of trains causes cyclic movements of the unbounded particles that result in permanent vertical and lateral deformations. For this track form, indeed, vertical settlement of granular layers and ballast particles degradation represent the major problems affecting frequency of maintenance and track durability. In particular, differential settlement, due to abrupt changes in vertical stiffness of the railway track that typically characterises bridge approaches, leads to increased dynamic loading, which can further increase permanent deformation, leading to a self-perpetuating mechanism (Figure 1.1) (Read and Li 2006).

Figure 1.1 – Example of differential settlement of a freight railway in a bridge approach (Read and Li 2006).

Vertical settlement is given by the sum of the deformation of all the layers, among which ballast participates with the highest contribution (up to 50–70% of the total vertical deformation) (Selig and Waters 1994). Ballast layer settlement can be divided in two major phases (Dahlberg 2004): (i) the first one, faster, occurs when ballast is in a loose state (after tamping or new construction) and is the manifestation of a first major consolidation (re-compaction); (ii) the second one is due to different mechanisms that occurs under cyclic loading: densification, distortion and degradation. The densification is characterised by a progressive consolidation; the distortion is the mechanism where individual particles slide and roll; and the degradation represents the change in particle size determined by attrition and breakage (Sun et al. 2010).

Aside from contributing to permanent deformation, the degradation mechanism can also prevent the ballast layer to fulfil its main functions. Indeed, mineral fouling from particle breakage and wear due to traffic loading and maintenance represents the highest source (with more than 70%) of ballast layer fouling (Selig and Waters 1994, Pires and Dumont 2015). This phenomenon jeopardises the fast draining and elastic characteristics of ballast layer as well as its ability to be effectively maintained by tamping (Selig and Waters 1994, Calla 2003).

These disadvantages are stressed by the continuous increase of tonnage and speed in the railway system (55% of High Speed lines are ballasted) (Steenbergen 2009, Banimahd et al. 2013, Sugrue 2013, Indraratna et al. 2014). In this regard, depending on the applied load (passenger train or heavy haul), a critical train speed could drastically accelerate the rate of deformation and particle degradation, leading to a plastic collapse. In addition, high speed (when beyond 260 km/h) can also generated the phenomenon of 'ballast flying', considered potentially very harmful (Jing et al. 2012).

The above mentioned issues contribute to make life expectancy of ballasted track of about 40 years (approximately 30% lower than slab track) (Lechner 2011). Thus, for some specific line, ballasted track can be considered less convenient in a lifecycle cost analysis due to the high frequency of maintenance and the lower durability, presenting higher maintenance costs (up to 20-35%) than current slab tracks (Esveld 2001, Sugrue 2013, CEMOSA 2014, Profillidis 2016). As an example, in Europe, the construction cost of ballasted track ranges from 350,000 to 600,000 €/km for single track, while the maintenance costs can vary from 30,000 to 100,000 €/km per year (Baumgartner 2001, Jimenez–Redondo et al. 2012), the main part of which arises from the track-bed. Furthermore, the aggregates used for the ballast must comply with strict requirements. For this reason, when satisfactory quality aggregates are not available nearby the construction/rehabilitation site the environmental and economic burdens increase as a consequence of, for instance, longer hauling distance.

Notwithstanding the facts pointed out above, ballasted track continues to be widely adopted because of the skills acquired by railways authorities in implementing this solution and the relatively low construction costs (Selig and Waters 1994, Michas 2012, Sugrue 2013, Profillidis 2016).

However, in order to not compromise the global efforts to lower the environmental impacts produced by the transportation sector, and the railway transportation mode in particular, it is of paramount importance to develop innovative technologies that prove to be efficient in reducing the ballasted track-bed maintenance burdens, and thereby attenuating the effects related to the shifting of environmental burdens from one railway system's life cycle phase to another. In addition, the progressive reduction of raw material with adequate properties requires immediate solutions to decelerate the degradation of the in-service ballast in tracks (increasing therefore its durability and reducing the need for renewal) as well as solutions to allow for the use of aggregates that are disqualified, according to the current Standards, because of their mechanical properties.

For these reasons, in recent decades ballasted tracks have been the object of diverse researches focused on decelerating the loss in geometrical quality associated to ballast settlement and its progressive degradation. Some solutions, providing deeper changes need to be applied at the construction level or during a major maintenance intervention, which implicates long traffic disruptions. Other technologies, focusing mainly on existing tracks, offer quicker solutions to effectively reduce the subsequent need for maintenance and extend track-bed durability.

In this context, given the need to further advance towards novel and more sustainable technologies, the present thesis investigated the possibility of stabilising ballast with bitumen emulsion (BSB), as a relatively economic solution to slow down the loss in track quality associated with ballast settlement and particle degradation. BSB consists of pouring bitumen emulsion uniformly over the ballast at ambient temperature, gluing contact points between particles, potentially offering thus an increased resistance to permanent deformations. This technology, which could be used for new track-beds as well as to reinforce existing ones, has been developed through model-scale and full-scale laboratory tests simulative of field conditions, optimising the main factors affecting the stabilising process and bitumen stabilised ballast (BSB) behaviour.

"Bitumen Stabilised Ballast: a novel solution towards a more sustainable railway" is part of the European project SUP&R ITN (Sustainable Pavements and Railways Initial Training Network) within the Marie Curie Initial Training

Network (ITN) action, FP7-PEOPLE-2013-ITN. This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement number 607524.

1.2 Research Objectives

Within the context described in Section 1.1, the scope of this thesis is to contribute to increase sustainability of railway transportation system. For this purpose, the overall aim is:

✓ To develop and propose a novel solution to decrease costs and burdens related to minor and major maintenance of traditional ballasted track-bed.

In this regard, the specific objectives of the thesis are:

→ To review current design and maintenance solutions to reduce ballasted track maintenance, and main factors affecting their performance.

→ To propose an innovative technology to overcome the main limitations of existing solutions.

→ To evaluate its feasibility through model-scale tests.

→ To investigate the main factors affecting performance and application of proposed technology at model scale, in order to select the most desirable conditions for full scale application.

→ To collect reliable and realistic data at full scale, investigating the applicability and maintainability, and long-term behaviour of the proposed technology. These data should be used to work towards guidelines and recommendations on how best use and further develop this technology.

→ To create a performance-based integrated model, based on these data, in order to predict future maintenance of proposed technology in relation to traditional ballasted track-bed.

→ To assess economic and environmental impacts of proposed solutions, including their sensitivity to main factors affecting lifecycle analysis.

1.3 Thesis Outline

The present thesis covers the process followed to develop and study bitumen stabilised ballast (BSB), a novel technology proposed to increase sustainability of ballasted track. To this end, the thesis is divided into eleven chapters. An overview of the methodology followed and described in these chapters is given in Figure 1.2.

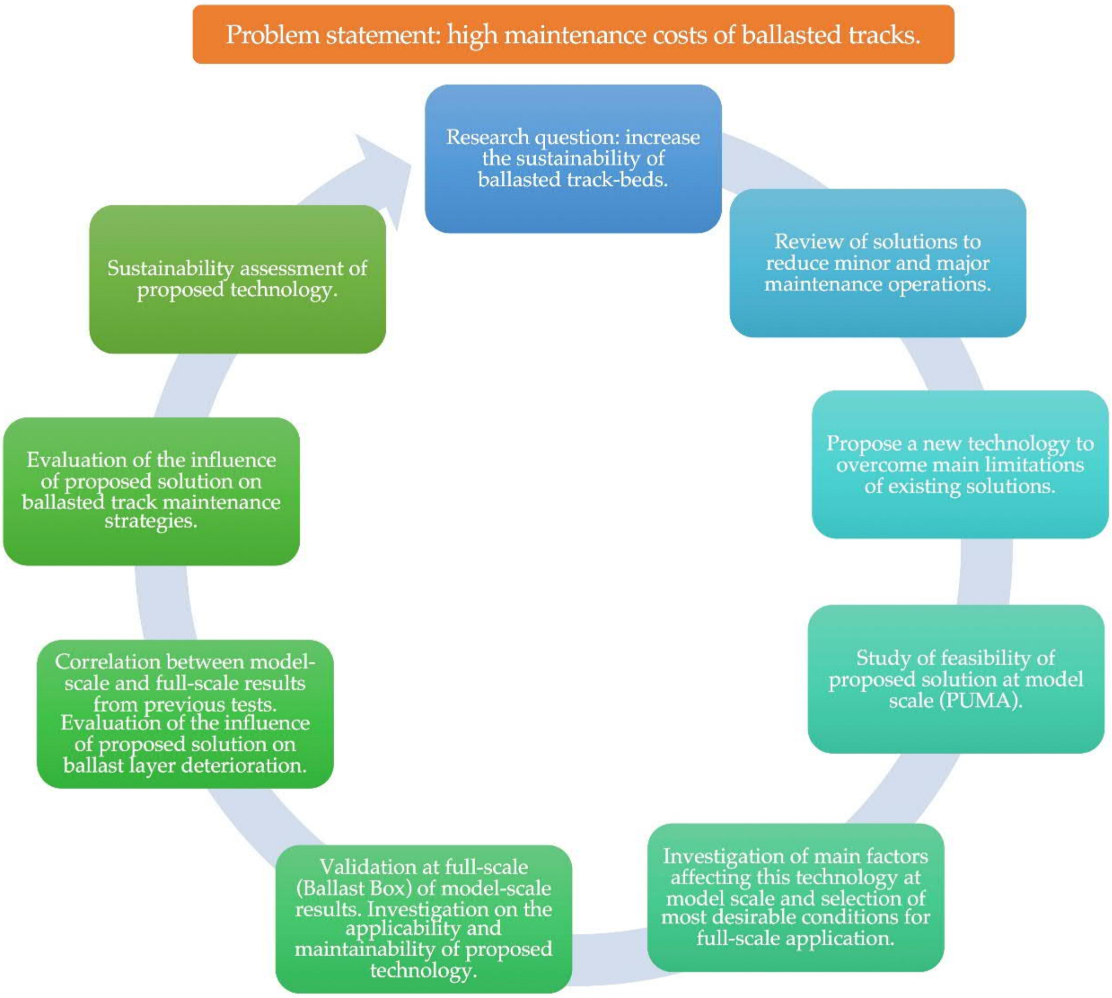

Figure 1.2 – Summary of thesis methodology.

In Chapter 1, the statement of the problem, the objectives and the overall methodology followed during the development of the thesis are explained.

In Chapter 2, existing literature about main the main topic addressed is reviewed: ballasted track overview, main factors influencing ballast behaviour, main solutions proposed to decrease maintenance frequency and bitumen emulsions for stabilisation purposes.

Chapter 3 to 7 show the results and discussion obtained during the development of the present thesis.

Chapter 3 describes a laboratory survey in which the main maintenance operations carried out to restore track-bed, namely tamping and stoneblowing, were simulated and their influence on track-bed behaviour was compared in a simplified and controlled manner.

Chapter 4 focuses on the assessment of the viability of using bitumen stabilised ballast (BSB) in order to reduce the need for maintenance associated with ballast settlement and degradation while in Chapter 5 the optimisation of bitumen emulsion characteristics to effectively stabilise ballast is reported. In this phase of technology development, model-scale testing was used, offering an attractive and economical means to evaluate many factors at the same time: the influence of dosage, the influence of curing time, the influence of stress level, the influence of ballast gradation, the influence of bitumen emulsion type on the effectiveness of the stabilisation method and on BSB mechanical behaviour.

Chapter 6 focuses on the full-scale validation of model-scale results, investigating the applicability of such a technology to existing ballasted tracks during maintenance operations or to newly constructed track-beds. Other aspects such as maintainability, influence of ballast gradation and influence of water for fouled ballast are also explored.

To have a better understanding of the relation between the two scales used it was decided to carry out full-scale PUMA tests. The test methodology and findings are described in Chapter 7. This phase focused also on the influence of bitumen stabilisation on the long-term ballast behaviour (more than one million cycles).

In Chapter 8, a novel integrated method used to estimate minor and major interventions for both traditional ballast (unbound) and stabilised ballast BSB (bound) is described.

Based on maintenance strategies evaluated through this model, Chapter 9 and 10 analyses the potential environmental and economic benefit provided by the use of BSB.

Finally, Chapter 11 draws the conclusions of the work carried out and recommendation for future studies along the same research topic.

Author's declaration: Some chapters of this thesis have been partly based upon the following published scientific contributions:

1. G. D'Angelo, N. Thom, D. Lo Presti, Laboratory Simulation of Field Loading Conditions and Maintenance Operations, in: Int. Conf. Railw. Eng. 2015, Edinburgh, 2015.

2. G. D'Angelo, N. Thom, D. Lo Presti, Using PUMA test to predict performance of stabilised ballasted trackbed, in: Third Int. Conf. Railw. Technol. Res. Dev. Maint., Cagliari, Italy, 2016.

3. G. D'Angelo, N. Thom, D. Lo Presti, Bitumen stabilized ballast: A potential solution for railway track-bed, Constr. Build. Mater. 124 (2016) 118–126. doi:http://dx.doi.org/10.1016/j.conbuildmat.2016.07.067.

4. G. D'Angelo, N. Thom, D. Lo Presti, Optimisation of bitumen emulsion properties for ballast stabilisation, Mater. Construcción. 67 (2017). doi:http://dx.doi.org/10.3989/mc.2017.04416.

5. G. D'Angelo, M. Sol-Sánchez, N. Thom, D. Lo Presti, M.C. Rubio-Gámez, Bitumen Stabilized Ballast: A Full-Scale Investigation on its Use for Existing and Newly Constructed Railway Trackbeds, in: Transp. Res. Board Annu. Meet., 2017.

6. G. D'Angelo, M. Sol-Sánchez, F. Moreno-Navarro, D. Lo Presti, N. Thom, Use of bitumen stabilised ballast for improving railway trackbed conventional maintenance, Geotechnique. (2017) 1–10. doi:http://dx.doi.org/10.1680/jgeot.17.P.022.

7. M. Sol-Sánchez, G. D'Angelo, Review of the design and maintenance technologies used to decelerate the deterioration of ballasted railway tracks, Constr. Build. Mater. 157 (2017) 402–415. doi:https://doi.org/10.1016/j.conbuildmat.2017.09.007.

8. G. D'Angelo, S. Bressi, M. Giunta, D. Lo Presti, N. Thom, Novel performance-based technique for predicting maintenance strategy of bitumen stabilised ballast, Constr. Build. Mater. 161 (2018) 1–8. doi:https://doi.org/10.1016/j.conbuildmat.2017.11.115.

Chapter 2 - Ballasted track design and maintenance technologies to increase ballast durability: a state-of-the-art

The role of a railway track structure is to provide safe and comfortable train transportation. For this purpose, each component of the system must fulfil adequately its specific functions in relation to the traffic loading and all the other environmental factors.

This chapter presents an overview of ballasted track components, the current state of research on ballast behaviour and main issues, ballast maintenance and main solutions proposed to mitigate ballast-related problems.

2.1 Components of ballasted railway tracks

Track structure has not changed substantially over railway history. Its components can be grouped in two main categories: superstructure and substructure. The first one refers to the top part of the track which includes the rails, the rail pads, the fastening system and the sleepers, while the second one refers to the lower part of the track composed by the ballast, the subballast and the subgrade (formation) (Figure 2.1 and Figure 2.2). The most important element of the track governing the load distribution is the sleeper-ballast interface, which separates the superstructure from substructure, both being mutually important in ensuring the safety and comfort of passengers.

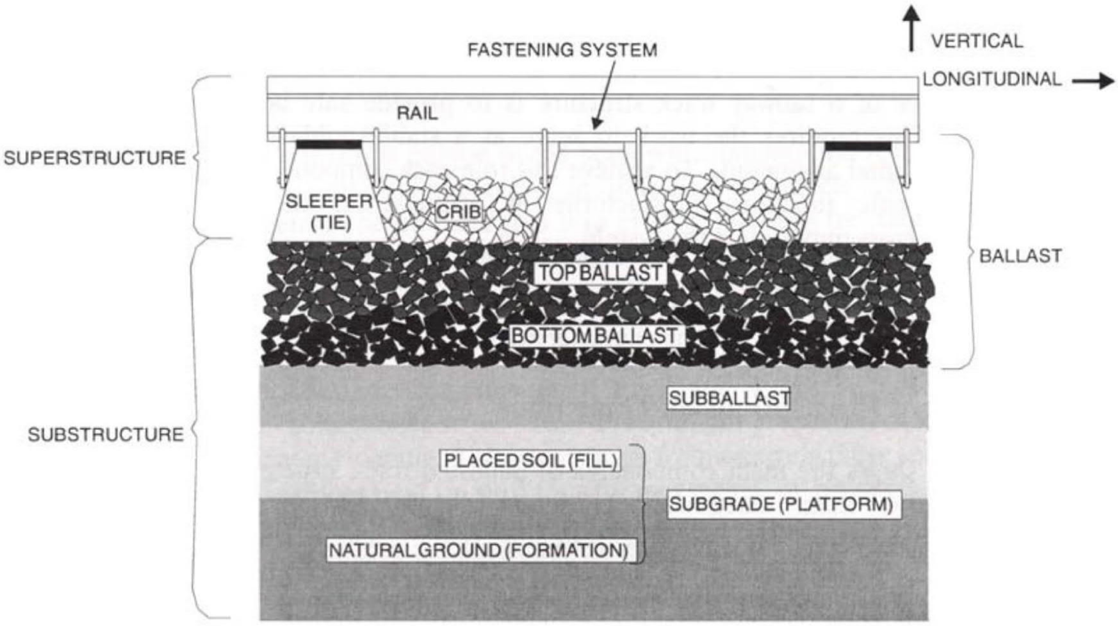

Figure 2.1 - Track layout of a typical ballasted track – longitudinal cross section (Selig and Waters 1994).

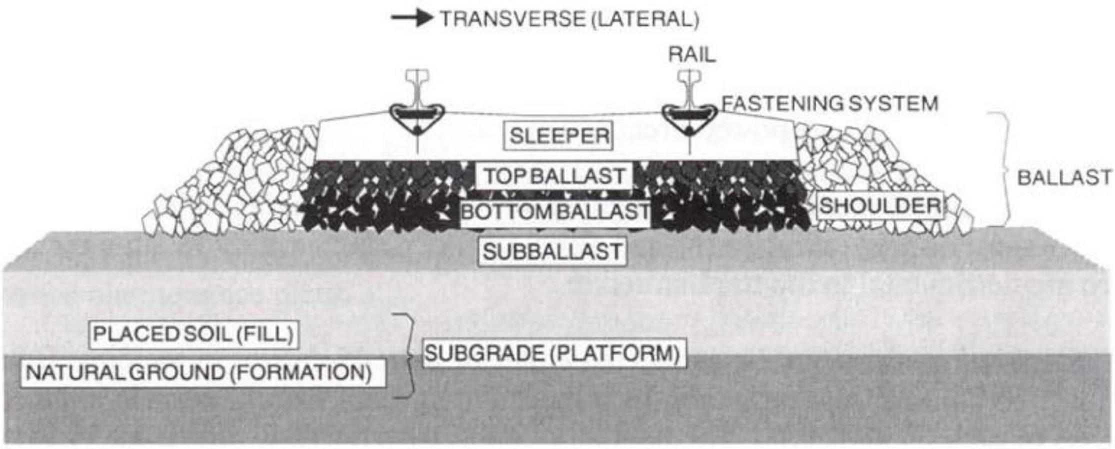

Figure 2.2 - Track layout of a typical ballasted track – transverse cross section (Selig and Waters 1994).

2.1.1 Rails

Rails are the longitudinal steel members which are in direct contact with the train wheels. The function of the rails is to guide the train and transfer concentrated wheel loads to the sleepers. Thus, rails must have sufficient stiffness to distribute wheel loads over sleepers and limit deflection between the supports.

The vertical and lateral profiles of rails and the wheel profile govern the smoothness of traffic movement as the wheels roll over the track. Consequently, any defect on the rail or wheel surface can cause a significant magnitude of dynamic load on the track structure related to the train speed, which can significantly damage the components of the track.

Rail sections may be connected by bolted joints or welding. In the case of bolted joints, the rails are linked by means of plates known as ‘fishplates’. However, vibration and extra dynamic loads occur from discontinuities resulting from this type of joint. As a result, ballast and subgrade experience high stress that increases the rate of ballast degradation, fouling and settlement. In fact, many track problems are found at bolted rail joints where frequent maintenance is required. Therefore, most important passenger and heavily used freight lines use continuously welded rail (CWR), which among other advantages needs less maintenance and improves riding quality (Selig and Waters 1994).

2.1.2 Fastening system and rail pads

The fastening system, or ‘fastenings’, includes every element connecting the rail to the sleeper, which is ensured not to move vertically, longitudinally, or laterally (Selig and Waters 1994). Fastenings absorb forces from the rails and transfer them to the sleepers while dampening vibrations and impacts generated by traffic.

Various types of fastening system are used by railway organisations throughout the world as a function of the kind of sleeper and geometry of the rail section.

The major components of a fastening system include coach screws to hold the baseplate to the sleeper, clip bolts, rigid sleeper clips, spring washers, nuts to attach the sleeper to the rail (Esveld 2001).

Rail pads have been introduced beneath rail to filter and transfer the high-frequency dynamic forces from rail to the sleepers, reducing then the stresses on ballast surface (Kaewunruen and Remennikov 2008a) (Figure 2.3). A more in-depth description about rail pads is given in Section 2.4.2.1.

Fastening systems could be direct (the rail and the baseplate are connected to the sleeper by means of the same fastener) or indirect (the rail is connected to the baseplate with one fastener and in turn the baseplate is fastened to the sleeper by a different one).

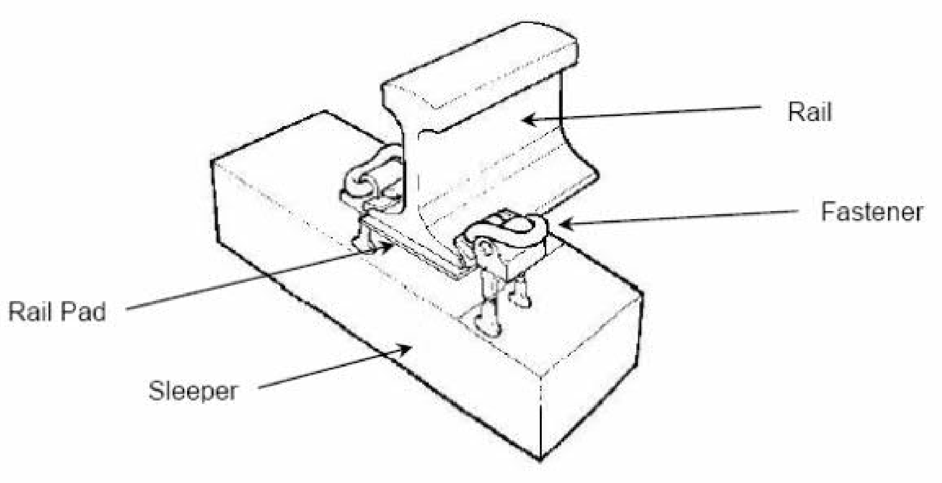

Figure 2.3 – Typical fastening system for concrete sleeper including rail pad (Kaewunruen and Remennikov 2008a).

2.1.3 Sleepers

The main functions of sleepers are to distribute the wheel loads transferred by the rails and fastening system to the supporting ballast and restrain rail movement by anchorage of the superstructure in the ballast (Selig and Waters 1994). They hold the rails in position and maintain the designed rail gauge. Mechanically, they receive concentrated vertical, lateral and longitudinal forces from the wheels and rails, and distribute them over a wider volume (ballast layer).

In the past, sleepers were mainly made by wood because of the high timber availability in the local area. However, in modern railways, concrete (most widely used due to their high resilience to climate or weather) and steel sleepers have been adopted because of their higher durability and longer service life.

Sleepers are laid on the top of the compacted ballast layer, perpendicularly to rails, at a specific distance apart, which has an important role in the global stiffness of the track (Bogacz et al. 2014, Powrie and Le Pen 2016).

2.1.4 Ballast

Ballast is one of the most important component of the railway track. Ballast layer is traditionally composed by natural or crushed granular material, which are angular, hard stones and rocks, uniformly graded, free of dust and dirt, not prone to cementing action. However, due to the lack of universal agreement on the specifications for ballast materials, frequently availability and economic considerations have been the main factors considered in the selection of ballast materials (Ionescu 2004). Thus, a wide range of ballast materials of diverse petrographic origin can be found, such as granite, limestone, basalt, gravel, ophite, slag, etc.

The ballast layer structure can be partitioned into four zones:

- Crib zones between the sleepers;
- Shoulder, which is the zone beyond the end of the sleeper, sloping down to the top of sub-ballast;
- Top ballast, which is the top portion of the ballast beneath sleeper level which is usually exposed to tamping;
- Bottom ballast, which is the bottom and lower part of the ballast which supports the overall structure; depending on the quality of the sub-ballast material, loading condition, presence of water and drainage properties, it is likely to be the more fouled part than the rest of the structure.

The main functions demanded to the ballast layer can be summarised as follows (Kaewunruen and Remennikov 2008a, Lu 2008, Nurmikolu 2012):

- Retain the track in its position by resisting vertical, lateral and longitudinal forces transmitted by the sleepers;
- Transmit and reduce stresses to acceptable levels for sublayers;
- Provide adequate flexibility absorbing shocks and impacts;
- Facilitate routine maintenance operations such as geometry adjustment and sleeper replacement as well as major operations (cleaning, reconstruction);
- Provide fast drainage through the layer;
- Absorb noise and vibration generated from traffic.

In order to fulfil these functions, ballast particle together with the physical state of the assembly must meet several requirements in terms of gradation, stability (bulk density), durability, shape and surface characteristics, resistance to weathering, etc. (Raymond and Gaskin 1975, Ionescu 2004). The influence of these properties on ballast performance will be further discussed in section 2.3.

2.1.5 Subballast

Typically, subballast is a layer of granular material separating the ballast and the subgrade. It reduces the stress to the subgrade, offering a cheaper option to the otherwise thicker ballast. However, the most important function of the subballast is to prevent interpenetration between the subgrade and the ballast. Thus, subballast is generally composed of broadly-graded slag or crushed aggregate, which must fulfil the filter requirements for the ballast and the subgrade. Where there is no subballast or where poorly designed sub-ballast is used, subgrade clay and silt size particles become mixed with ground/infiltrated water to form a slurry, which is pumped up into the ballast layer under cyclic loading (clay pumping).

In recent decades, the use of bituminous subballast has been gaining favour with designer in order to cope with the increasingly performance demanded from railway traffic. This specific solution will be further discussed in Section 2.4.3.

2.1.6 Subgrade

Subgrade, also referred as ‘formation’, is the foundation for the track structure. It can be existing natural soil or specially placed material.

The main function of the subgrade is to provide a stable support for the track structure and distribute the dynamic loading downward along its depth; therefore, it must be stiff and have sufficient bearing capacity to resist traffic induced stresses at the subballast/subgrade interface.

Even with excellent ballast and sub-ballast layers, failure of subgrade will result in unacceptable distortions of track geometry and alignment. Thus, excessive settlement in the subgrade should be avoided. In this regard, synthetic materials such as geotextile, fabric, etc., have been introduced over last decades to improve subgrade bearing capacity.

2.2 Track-bed loading

In order to analyse and design the track-bed, it is essential to understand the loading environment that the ballast layer might be subjected to during its lifetime. However, due to the various uncertainties related to traffic vehicles characteristics, operating conditions, and track conditions among others, only an estimate of the loading level can be possible (Profillidis 2000).

2.2.1 Loading type

The loading can be either mechanical (both static and dynamic) or thermal and is applied in the form of repeated vertical, lateral and longitudinal forces resulting from traffic and changing temperatures.

The lateral forces (parallel to the axis of the sleepers) appear essentially in curves due to addition of the non-compensated centrifugal forces and the wheel flange contact against the rail. However, also on straight there might be lateral forces due to the hunting phenomenon and to the action of cross-wind (Profillidis 2000). Lateral forces are mainly transmitted to the sublayers by the frictional contact between sleeper and ballast. Only a small contribution is given by the crib and shoulder ballast (Ionescu 2004).

The longitudinal forces (parallel to the rail) are usually due to speed variation of trains as well as thermal expansion or contraction of the rails, especially in CWR tracks.

Nevertheless, due their predominant impact on track-bed, only vertical forces resulting from traffic loading are considered for the testing carried out in this thesis.

Vertical forces, combination of a quasi-static and a dynamic component, are due to the action of traffic loading (Equation 1.1). The first one is composed of three components, as in Equation (1.2):

$$Q_{total} = Q_{quasi-static} + Q_{dynamic} \tag{1.1}$$

$$Q_{quasi-static} = Q_{static} + Q_{centr} + Q_{wind} \tag{1.2}$$

in which Q_{static} is equal to half of the static axle load; Q_{centr} is the increase in wheel load on the outer rail in curves due to non-compensated force; Q_{wind} in the increase in wheel load due to wind; and $Q_{dynamic}$ is the dynamic wheel load component due to: sprung mass (0-20 Hz), unsprung mass (20-125 Hz) and wheel flats, welds, and corrugations (0-2000 Hz).

From the equilibrium of forces acting on the vehicle, as shown in Figure 2.4, the following equations (1.3 and 1.4) can be written:

$$Q_{centr} + Q_{wind} = G\frac{p_c h_d}{s^2} + \frac{H_w p_w}{s} \quad (1.3)$$

$$h_d = \frac{sv^2}{gR} - h \quad (1.4)$$

where,

G = weight of vehicle per axle;

H_w = cross wind force;

s = track gauge;

v = speed;

g = acceleration due to gravity;

R = curve radius;

h = cant;

p_c = vehicle centre of gravity;

p_w = distance of lateral wind force resultant.

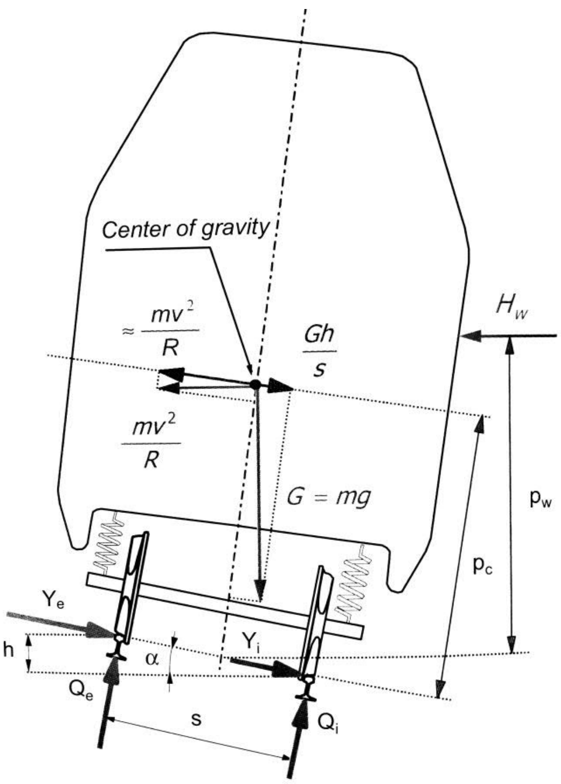

Figure 2.4 – Forces in curve (Esveld 2001).

The proportion of Q_{centr} is usually 0 to 25% of the static wheel load.

The most uncertain load component is that due to the dynamic effects $Q_{dynamic}$. Field measurements proved that the dynamic forces could increase the wheel load by a factor of three (Frederick and Round 1985, Harrison et al. 1986). As an example, Sun et al. (Sun et al. 2010) found that for an axial load of 25 t train speed from 220 to 300 km/h (depending of the confining pressure) could determine plastic deformation from two to three times higher than those exhibited for 70 km/h. At the same time, passing from 70 to 300 km/h could approximately triple the particles breakage (Lackenby et al. 2007). Similar effects could be produced for a same train speed by an increase in load from 25 to 40 t (Sun et al. 2010).

For this reason, dynamic component is usually taken into account as an amplification factor (otherwise known as the impact factor) for the design vertical wheel load (Jeffs and Tew 1991). The main factors influencing the magnitude of dynamic load component are:

- Speed of train;
- Vehicle unsprung mass;
- Track and vehicle conditions;
- Track-bed properties.

There are many empirical formulae used by different railway agencies and practitioners for the design vertical wheel load, usually expressed as a function of static load. Among all the methods, the most common are the Eisenmann method and the AREA method.

2.2.1.1 Eisenmann method

According to the Eisenmann method, dynamic factor can be obtained with the Equation (1.5) (Esveld 2001):

$$\phi_d = 1 + \delta\, t\, \eta \tag{1.5}$$

where δ is a factor depending on the track condition (0.1 = very good; 0.2 = good; and 0.3 = poor); t is the chosen upper confidence limit; and η is a parameter accounting for the vehicle speed:

$$\eta = 1 \quad if\ v < 60 km/h \tag{1.6}$$

$$\eta = 1 + \frac{v-60}{140} \quad if\ 60 \leq v \leq 200\frac{km}{h} \tag{1.7}$$

2.2.1.2 AREA method

Based on the recommendation by the American Railway Engineering Association (AREA), Li and Selig (Li and Selig 1998) proposed the following Equation (1.8) for the dynamic factor:

$$\phi_d = 1 + \frac{0.0052\, v}{D_w} \tag{1.8}$$

where D_w is the diameter of the wheel expressed in meters.

By using one of these expressions for the dynamic factor is possible to obtain an equivalent vertical dynamic wheel load to be used for design purposes as follows:

$$P_d = \phi_d\, P_s \tag{1.9}$$

where P_s is the static wheel load.

2.2.2 Sleeper/ballast contact pressure

The static axle load applied from the wheel to the rail is distributed between underlying sleeper and adjacent sleepers. This distribution depends upon several factors including rail weight, sleeper spacing, track modulus, etc. (Raymond and Bathurst 1994, Esveld 2001).

In case of a stiff track-bed about 42% of the wheel load is transmitted to the sleeper directly below the wheel and 26% is to the adjacent sleepers (Cope 1993). Similar results are reported by Hunt (2005), AREMA (2006) and Kennedy (2011).

In addition, sleeper/ballast contact pressure varies along the sleeper bottom: when ballast is in a loose state (after tamping), the contact stress between the sleeper and ballast is maximum at the rail seat and smaller towards the middle and ends of cross-sleeper (Ionescu 2004). After compaction provided by traffic, the contact pressure distribution between the sleeper and ballast tends to be more uniform along the sleeper (Pires 2016). It is important, thus, to estimate the effective sleeper support area in order to evaluate the stress distribution over ballast layer. This area depends mostly on the effective sleeper length L. Two of the most used way of calculating this parameter are: (i) difference between the total sleeper length and the gauge; and (ii) one third of the total sleeper length (Pires 2016).

For the calculation of the sleeper/ballast contact stresses, uniform contact pressure distribution between the sleeper and ballast is assumed to occur in practice. In this way, the average contact pressure can be derived by the Equation (1.10) (Pires 2016):

$$\sigma_a = \frac{Q_r}{BL} f \qquad (1.10)$$

where B = width of the sleeper; Q_r = maximum rail seat load; f = factor depending on the track maintenance and sleeper type.

Although the measurement of actual sleeper/ballast contact stress is extremely difficult, (according to Shenton there are 100-200 contact points), British Railways attempted to measure the contact stress in real track (Figure 2.5) obtaining an erratic distribution.

Indraratna et al., (Indraratna et al. 2010) conducted a field trial on an instrumented track at Bulli, New South Wales, Australia, with the aim of studying the benefits of geocomposite on performance of fresh and recycled ballast. They used rapid-response hydraulic earth pressure cells, installed into the ballast layer under the rail, in order to measure the vertical and horizontal stresses developed under repeated loads. Figure 2.6 shows the maximum vertical cyclic stress plotted with time. It can be noted that, apart from one peak at 415 kPa due to the arrival of a wheel-flat, most of the maximum vertical stresses ranged up to 230 kPa. Their findings were in line with results of analytical models and other field studies reported in the literature (Figure 2.7 and Figure 2.8).

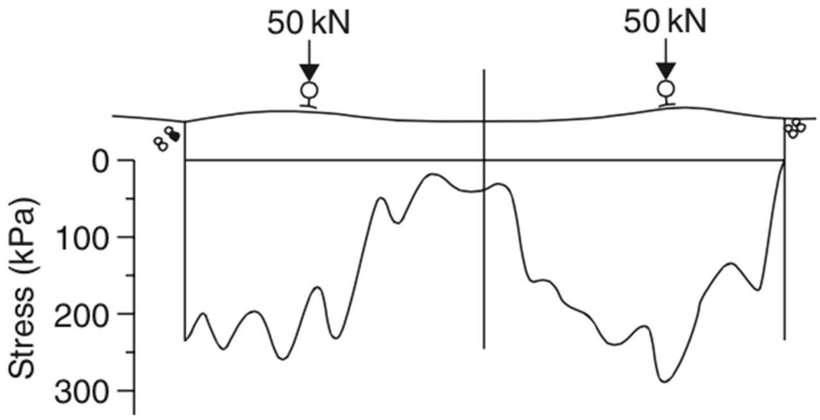

Figure 2.5 – Measurement of sleeper/ballast interface contact stress – Axle load = 200 kN (Shenton 1975).

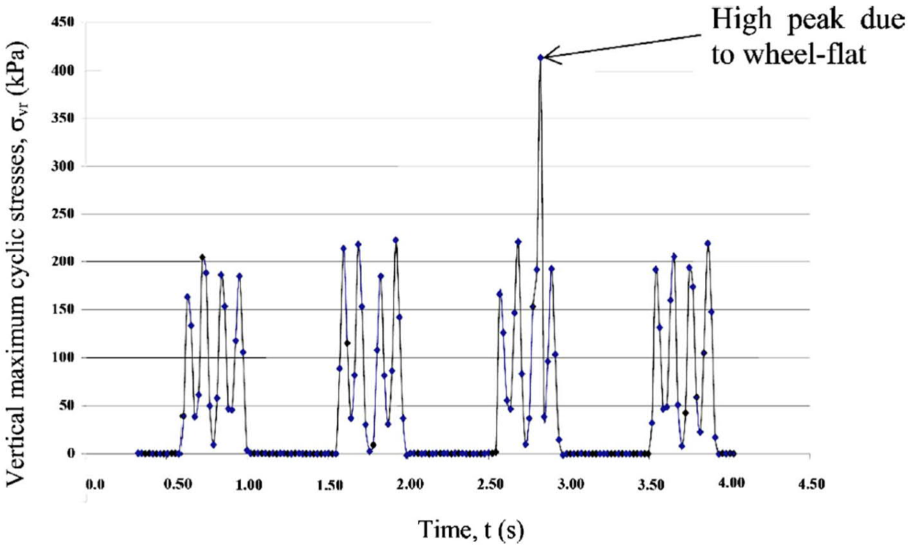

Figure 2.6 – Vertical maximum cyclic stresses measured into the ballast layer underneath the rail due to a passage of a train with 25 t axle loads (Indraratna et al. 2010).

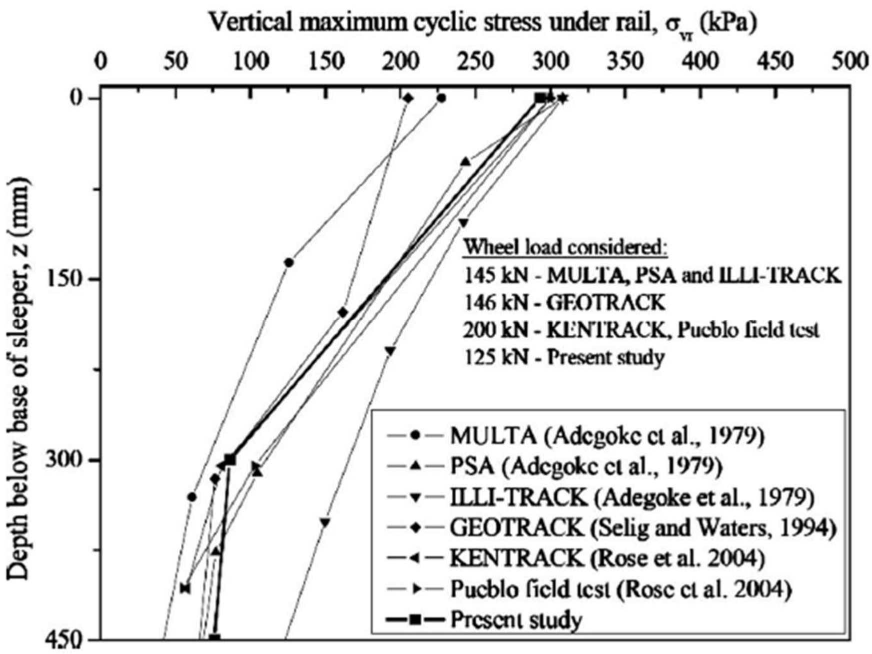

Figure 2.7 – Comparison of vertical maximum cyclic stresses measured in the ballast layer at Bulli with analytical models predictions (Indraratna et al. 2010).

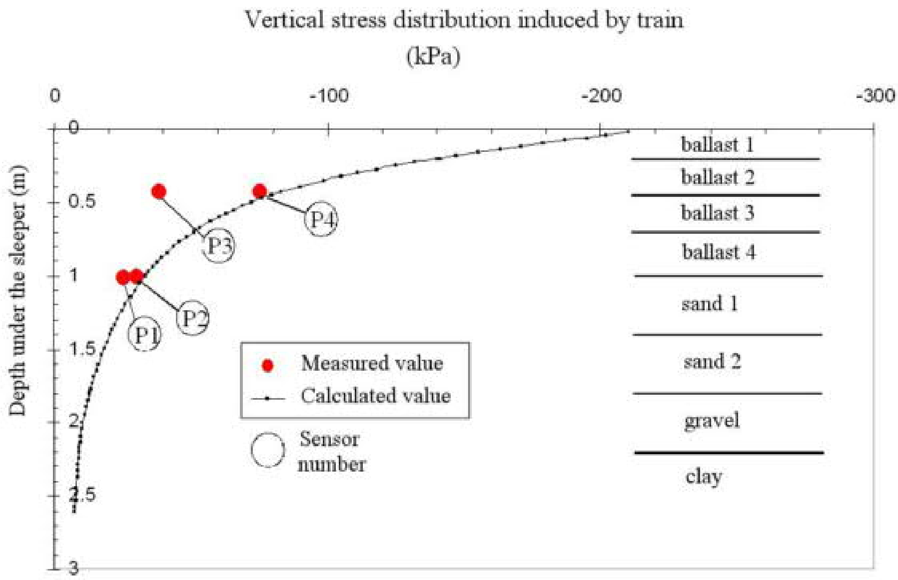

Figure 2.8 – Vertical stresses distribution measured under 250 kN axle load for the Kouvola-Koria railway section and vertical stresses obtained from the BISAR linear-elastic multi-layer program used to model the section (after Nurmikolu 2005).

2.3 Ballasted track-bed main issues and factors influencing ballast behaviour

The use of ballasted track form is related to the several advantages such as relatively low construction costs (CEMOSA 2014) and use of indigenous materials, high maintainability at a relatively low cost (for a single operation), high damping capacity and noise absorption, self-adjusting properties (in the case of non-homogeneous subgrade) and fast drainage (Selig and Waters 1994, Michas 2012, Sugrue 2013).

To fulfil these functions, crushed angular stones as well as good quality hard stones are required. These characteristics increase the shear strength of the granular layer, providing, thus, a better stress distribution and lateral and longitudinal resistance. At the same time, to provide drainage, uniform gradation with relatively high air voids content (around 40%) is used. This gradation ensures also a desirable degree of flexibility and high capacity of damping loads (increasing with aggregate grain-size) (Selig and Waters 1994, Indraratna et al.

2011) while ensuring automatized maintenance operations to correct track geometry (Ionescu 2004).

Ballast structure as assembly as well as particle properties are, thus, the key factors to ensure the above-mentioned properties. However, ballast is also the weakest layer of the track superstructure. Its particles, indeed, are subjected to continuous degradation due to cyclic loads and external actions. As a result, ballast densification, aggregate degradation, and lateral spread of the ballast material underneath the sleepers takes place inducing permanent deformation (settlement) in the railway (Raymond and Bathurst 1987), so that repeated maintenance is needed in order to restore the original geometry of the track.

Indeed, this degradation process can be divided into three phases: burn-in, useful life, and wear-out (Soleimanmeigouni et al. 2016). The first phase, which is the most unpredictable, starts immediately after a maintenance operation to correct geometry. Because of existing gaps among ballast particles, degradation is high with a decreasing rate, until the gaps are removed. Nevertheless, this phase is relatively short compared to the other two phases. In the second phase, geometry degradation occurs more slowly and progress approximately linearly with time or traffic. In the third phase, the degradation rate increases with time, thus, corrective maintenance should be applied before entering this phase.

In his research, Shenton (Shenton 1985) demonstrated that track geometry condition during its life time is strongly dependent on the initial level of the track and that maintenance activities such as tamping cannot affect the internal properties of track geometry quality. Maintenance tries to restore the track geometry condition, but it cannot change a low-quality track section to a high quality one. As a result, the track sections with higher quality have longer maintenance cycles.

As reported by Indraratna et al. (Indraratna et al. 1998), maintenance and rehabilitation costs of rail tracks due to problems related with ballast performance are substantial, and millions of dollars are spent annually around the world on these activities.

In this regard, ballast settlement plays the most important role in track degradation (Soleimanmeigouni et al. 2016). It represents the primary geotechnical component of railway track, its performance being governed by the particle characteristics and bulk properties of granular assembly. The influence of main factors affecting ballast layer behaviour are described in the following sections.

2.3.1 Particle size

Past research on the effect of particle size on ballast performance appears to be inconclusive. For instance, according to Kolbuszewski and Frederick (Kolbuszewski and Frederick 1963) and Dunn and Bora (Dunn and Bora 1972) the angle of shearing resistance increases with large particle size. Marachi et al. (Marachi et al. 1972) and Indraratna et al. (Indraratna et al. 2011), instead, presented experimental data to show that the angle of internal friction decreases with an increase in the maximum particle size. Other studies (Holtz and Gibbs 1956, Vallerga et al. 1957, Bertacchi and Bellotti 1977) concludes that no definite influence of the particle size on shear strength and, consequently on settlement could be established. More recently, a study conducted by Naziur (Naziur 2017) found that higher top size aggregate leads to higher shear strength. In the same study, for the same top-size aggregate, the effect of coarser or finer gradation was investigated, finding that the size effect depends on the level of stress.

Thus, despite the general agreement about the use of a narrow gradation, the different standards used worldwide discord about the particle size range that would offer best performance in terms of deformation and degradation (Ionescu 2004).

2.3.2 Particle shape

The shape of the grains, which is mainly dictated by the nature of the deposit itself while a limited degree of control is achievable during the production process, can have an important influence on ballast layer mechanical properties and resistance to permanent deformation (Salim 2004). There is a general agreement on the important role played by the particle shape in the shear strength. Diverse studies showed that the shear strength increases with angular aggregates in relation to sub-rounded aggregates (Holtz and Gibbs 1956, Vallerga et al. 1957, Indraratna et al. 1998). The percentage of flat and elongated particles is generally limited in standards (RT/CE/C/006 2002, BS EN 933-3 2012).

On the other hand, it was observed that, at a given initial void ratio, a granular media having angular particles compressed more than that having rounder particles due to higher grains degradation (Raymond and Gaskin 1975).

2.3.3 Particle surface roughness

Another key factor governing shear strength is the surface roughness of particle, which is related to the grain degradation (Raymond 1985). In this regard, the durability of ballast particle is typically evaluated by tests such as Los Angeles Abrasion (LAA) (BS EN 1097-2 2010) and Micro Deval (BS EN 1097-1 2011), which indicate minimum values of particle resistance to abrasion and breakage depending on the type of railway line (Indraratna et al. 2005). Indeed, overall major problems of track stability, settlement and drainage problems are the result of ballast breakdown.

2.3.4 Ballast gradation

As reported by diverse studies (Ionescu 2004, Indraratna et al. 2011), there is a general agreement about the influence of gradation on plastic deformations: for the same test conditions (material, initial density, moisture content and load range), a material having a broader gradation displayed smaller plastic strains as compared with a uniform coarser grading. The crushing of coarser grains and the subsequent movement of resultant particles towards more stable positions in the structure of granular materials is believed to be the cause of this behaviour. At the same time, the use of broad gradation could limit the ballast capacity of damping loads, its ability to be maintained effectively by automatized maintenance while reducing its drainage properties (Selig and Waters 1994, Indraratna et al. 2011). In this regard, despite the uniform gradation recommended by ballast specification worldwide, several research worldwide have been aiming to optimise the railway ballast gradation in order to meet future requirements of heavy traffic and freight movements (Anbazhagan et al. 2012).

2.3.5 Ballast bulk density

Also the bulk density of aggregate plays an important role on deformational behaviour. In this regard, Kjærnsli and Sande (Kjærnsli and Sande 1963) in their comprehensive research into the compressibility characteristics of coarse aggregates have shown that independently of the shape, roughness and gradation of the grains, the specimens having lower initial porosity deformed less, provided the strength of the particles was the same. Similarly, other studies (Schultze and Coesfeld 1961, Raymond and Gaskin 1975) concluded that specimens of railway ballast subjected to repeated confined compression would exhibit lower plastic deformation if they were initially subjected to higher degree of compaction (higher density).

2.4 Design-based technologies to increase track durability

Previous sections focused on the description of main issues related to ballasted tracks and major factors affecting its behaviour. Such issues are reflected into ever more frequent and costly maintenance, which could make overall ballasted track less convenient than other track forms. In addition, due to the strict requirements for ballast (as described in section 2.3), these burdens can significantly increase when good quality aggregates are not available in close proximity to the construction/rehabilitation site (longer hauling distance, raw material consumption, etc.).

Therefore, due to ballasted track widespread and its other specific advantages in relation to other track forms, in recent decades many researches have focused on decelerating the loss in geometrical quality associated with ballast settlement and its progressive degradation.

Given the wide range of technologies, this section aims to provide a review of the effectiveness of the main design-based solutions and their main characteristics for optimising track behaviour. These solutions, described in the following sections, have in common the fact that they need to be applied during the construction process, or during major maintenance operations. For this reason, these technologies are referred here as ‘design-based’.

2.4.1 Ballast stabilisation by geogrids

The use of geosynthetics has been widely investigated and applied over the past few decades to mitigate particle degradation and decrease both vertical and lateral deformation of track-bed (Raymond and Williams 1978, Anderson and Fair 2008, Aursudkij et al. 2009, Indraratna et al. 2009, 2012, Horníček et al. 2010, Chen et al. 2012).

Depending on their draining properties, these elements can be divided between geotextiles, which are permeable to fluids, and geomembranes, which are substantially impermeable to fluids (Figure 2.9) (Indraratna et al. 2011). In this regard, the latter ones are mainly used for retention purposes, whereas geotextiles dissipate the excess pore pressure developed in saturated subgrade.

Apart from dewatering, geotextiles, such as geogrids, geomesh, geonets, and geomats among others, have the main functions of filtration and reinforcement. (Selig and Waters 1994, Indraratna et al. 2006, Fischer et al. 2015). These properties aim to minimise track settlement by providing a lateral movement restriction and to keep the ballast layer clean from contamination from sublayers. The combination of two or more of geosynthetics earlier mentioned is called geocomposite (Figure 2.9 g). The advantage of using geocomposites is to combine different functions as for example waterproofing and reinforcement.

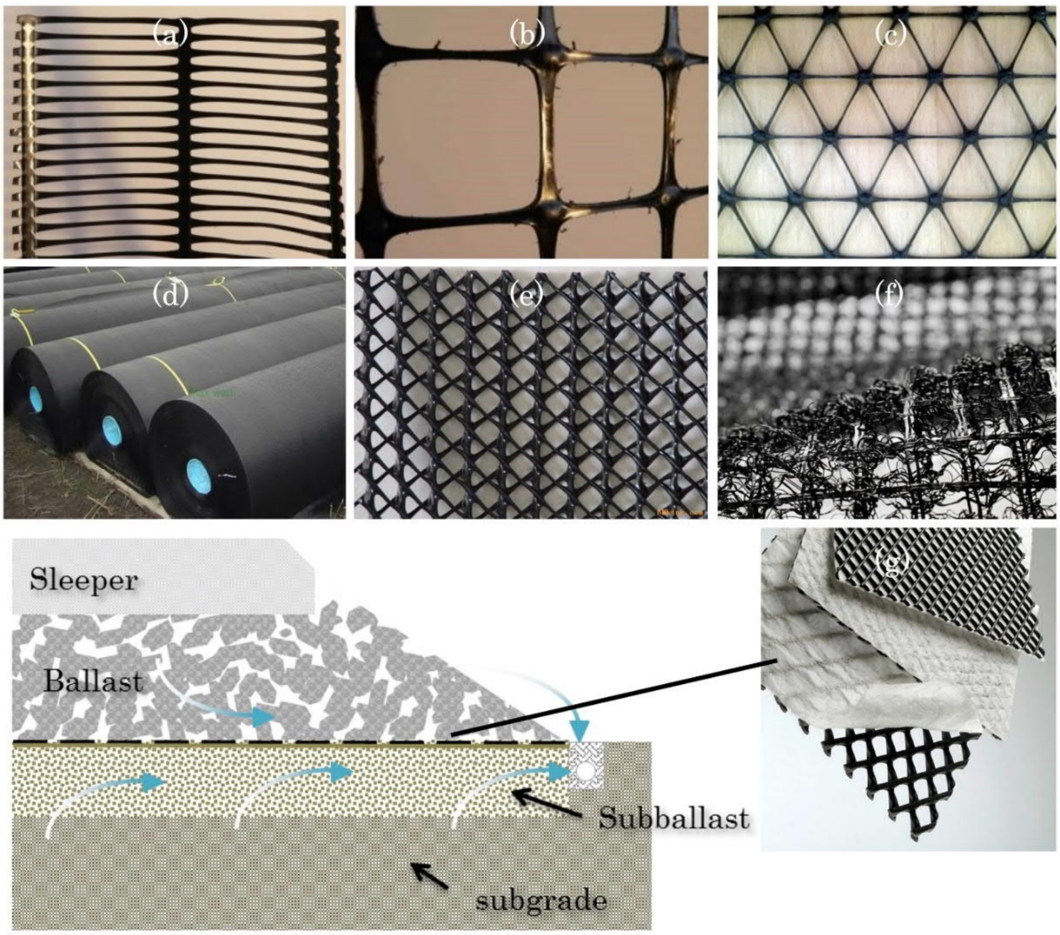

Figure 2.9 – (a,b,c) One axial, two axial and three axial geogrids; (d) geomebranes; (e) geonets; (f) geomats; (g) geocomposite.

Of particular interest, because of their functions and wide use within railway track-bed, are geogrids. Quadratic, rectangular or triangular shaped geogrids are used for strengthening ballast layer (Figure 2.9 a,b,c). Their scope is to increase the shear strength and bearing capacity due to lateral movement restriction for aggregates (Kwan 2006), particularly over soft sub-grades. Another function of these elements is to keep ballast layer clean, acting like a filter between layers (Selig and Waters 1994, Indraratna et al. 2006).

Diverse experiences (particularly in United Kingdom) have shown that the application of geogrid can effectively reduce ballast settlement and increase its durability (Horton 2014).

These elements consist of connected sets of tensile ribs, made of polymers with reduced flexibility and capacity to deform. This allows to develop an interlocking effect, which can be divided in three zones. The shear strength gradually increases from a zone where there is not a sensible effect to a zone (approximately 10 cm deep) where the interlocking effect is maximised (Figure 2.10) (Fischer et al. 2015). In order to extend this effect, more than one geogrid can be installed within the ballast layer (Atalar et al. 2001, Fischer et al. 2015).

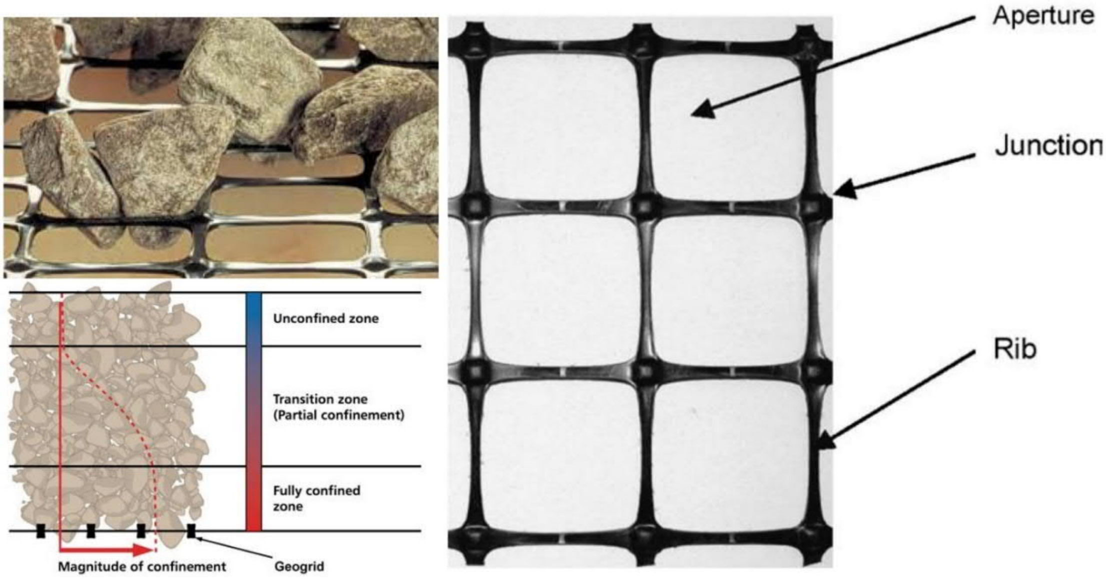

Figure 2.10 – Geogrid reinforcement and key parameters (Brown et al. 2007, Fischer et al. 2015).

The main parameters that influence geogrids effect on ballast settlement and degradation are: the grid geometry (circular, squared and rectangular are the most common), the axial restriction (uniaxial and biaxial geogrids), the grid tensile strength (which generally range from 15 to 45 kN/m), grid stiffness, rib cross-sectional shape and junction strength (Figure 2.10) (McDowell et al. 2006, Brown et al. 2007, Indraratna et al. 2014). However, the most relevant factors are considered to be the aperture size (which determines the interlock with the surrounding soil) and the position of the geogrid into the ballast layer (commonly placed in one of two ways, at the bottom or within ballast layer) (Raymond and Bathurst 1987, Shin et al. 2002, Raymond and Ismail 2003, Brown et al. 2007, Fischer and Horvát 2011, Fischer and Szatmári 2016).

The aperture size has to be determined according to the aggregate's particle size in order to optimise the interlocking effect resulting from these harmony (Indraratna et al. 2014, Fischer et al. 2015). Nimbalkar and Indraratna (Nimbalkar and Indraratna 2016) found that an aperture size of 1.1 times D_{50} may be the optimal configuration in terms of permanent deformation of ballasted tracks. However, Wilson-Fahmy and Koener (Wilson-Fahmy and Koerner 1993) from their models concluded that the aperture size should be 1.4 times the nominal size of ballast particles, higher, thus, than the aggregates size. Similarly, according other authors (Brown et al. 2007, Thom 2009), which studied the effect of geogrid parameters on ballasted track degradation, the effectiveness of geogrid is optimised with an aperture size of 1.2 to 1.6 times D_{95} (Figure 2.11). In addition, they found that the higher reinforcement provided by stiffer geogrids can reduce settlement and increase durability of ballast layer. Similar results in terms of both vertical and lateral deformation have been found on field trials (Amsler 1986, Indraratna et al. 2010, 2016).

As regard the geogrid position, Indraratna et al. (Indraratna et al. 2013), after an extensive laboratory study with different types of geogrid placed at depths into the ballast layer, indicated that the optimal (not compromising future maintenance) realistic position is approximately 65 mm upper the interface between ballast and subballast. Using this configuration settlement and particle breakage were reduced by half with respect to a reference layer without geogrid.

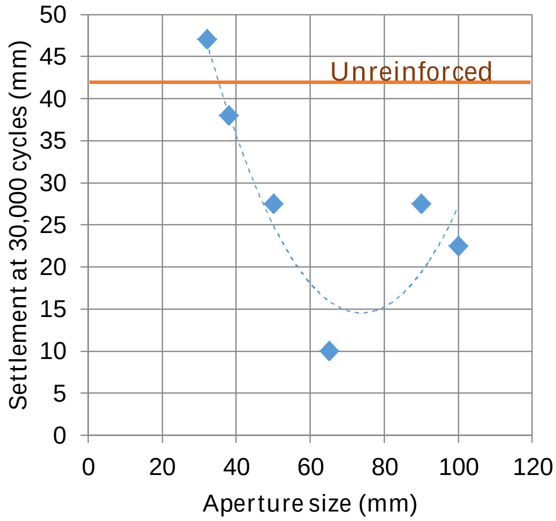

Figure 2.11 – Aperture size influence on geogrid effectiveness (adapted from Brown et al. 2007).

Another important application for geosynthetics is with recycled ballast, which usually exhibits higher plastic deformation (approximately double than fresh ballast) due to the lower shear strength of the layer. In this regard, the use of geosynthetics can reduce degradation of recycled ballast by approximately 45%, thus reducing both maintenance and material consumption (Indraratna and Salim 2003, Indraratna et al. 2010) (Figure 2.12). This advantage could lead to important economic and environmental benefits associated with the reduction of consumption of raw material.

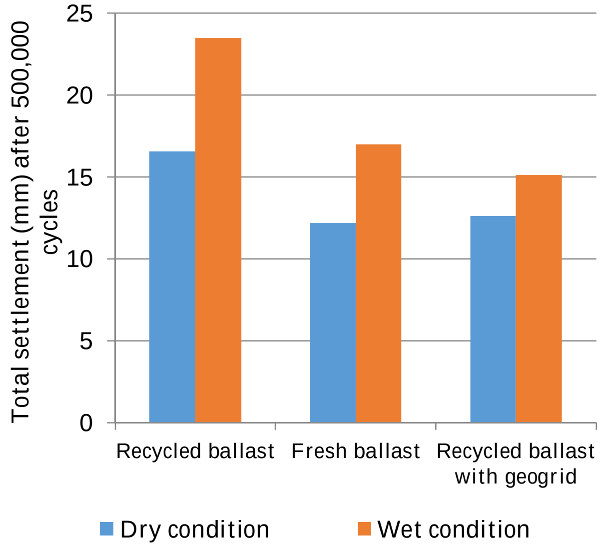

Figure 2.12 – Geogrid effect on recycled ballast settlement (adapted from Indraratna et al. 2010).

However, despite its advantages, main concerns about the use of geogrids are the low confidence about long-term performance and its initial cost (which limits its application to specific sections). In addition, the method of installation limits its application as a routine maintenance operation. Therefore, further research should focus on increasing the knowledge about its durability and possibly on the development of geogrids from waste materials. This would reduce their costs and the consumption of raw materials.

Over recent years, research on geosynthetics attempted to extend the concept of reinforcement from a 2D plan to 3D. In this regard, geocells have been introduced as confinement system interlocking cells integrated in a honeycomb structure into which granular materials are placed and compacted in order to reduce ballast layer settlement (Figure 6) (Kennedy 2011, Dash and Shivadas 2012, Leshchinsky 2012). Also in this case, the optimal size is about twice that of the average size of ballasts (D_{50}) (Dash and Shivadas 2012).

However, full-scale laboratory tests conducted by Kennedy (Kennedy 2011) highlighted significant difficulty in compacting the material within the cells which can lead to reduced track stiffness.

Thus, to overcome this issue, a further evolution is represented by polyurethane stabilisation techniques, which will be further discussed in section 2.6.1.

2.4.2 The use of elastic elements

2.4.2.1 Rail pads

Rail pads, which are the most used elastic elements in railway, are mostly composed of polymers with good elastic behaviour and durability while their thickness generally ranges from 4.5 mm to 15 mm (Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2015).

Their design, in terms of stiffness, is related to the track section design and its expected global performance (Sussmann et al. 2001, Hunt and Wood 2005, Powrie and Le Pen 2016, Sol-Sánchez, Pirozzolo, et al. 2016). Depending on their flexibility, they can be classified as soft (close to 80-130 kN/mm), stiff (around 500 kN/mm), medium (between soft and stiff) and very stiff (much higher than 500 kN/mm) (Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2015).

Being introduced for high speed lines, soft rail pads (with static stiffness around 80-125 kN/mm) are currently used and standardised in modern railway tracks, in order to protect the sublayers from the dynamic overloads (UIC 2009, López-Pita 2010, Indraratna et al. 2011, Sol-Sánchez, Moreno-Navarro, and Rubio-Gámez 2014a, 2015).

In this regards, several authors (Kaewunruen and Remennikov 2008b, Carrascal et al. 2011, Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2014) have shown that the use of softer rail pads allows for an important reduction (higher than 50%) in the energy and stress transmitted to the ballast layer when impact loads, due to irregular rail-wheel contacts, take place.

In addition, soft rail pads could lead to a more homogeneous track behaviour along sections with different bearing capacity, reducing, thus, the stress transmitted to ballast layer, and therefore, its particle breakage (Teixeira 2003, López-Pita 2006).

2.4.2.2 Under sleeper pads

Under sleeper pads (USPs) have been introduced during last decades to reduce settlement and ballast degradation due to the high contact stress at the interface sleeper/ballast (higher contact area) (Sol-Sánchez, Moreno-Navarro, and Rubio-Gámez 2014b).

Typically made of polyurethane elastomer, rubber and ethylene vinyl acetate, their thickness ranges from 10-20 mm, and, in relation to their static bedding modulus (defined as the stiffness per unit area), USPs can be qualified as stiff (0.25-0.35 N/mm3), medium (0.15-0.25 N/mm3), soft (0.10-0.15 N/mm3) and very soft (less than 0.10 N/mm3) (UIC 2009, 2013). According to the UIC (International Union of Railways) recommendations, the use of medium to soft USPs is appropriate to reduce vibrations and stress over the ballast layer. Different experiences with soft USPs, indeed, showed important reduction in of the vibrations, stress transmitted to the granular layers and track geometry deterioration (López-Pita 2006, Schilder 2006, UIC 2013).

In this regard, Sol-Sánchez et al. (Sol-Sánchez, Pirozzolo, et al. 2016) found that there is a linear relationship (Figure 2.13) between the variations in track stiffness due to changes in elastic elements, such as rail pads and USPs, and the settlement of ballasted tracks and its capacity to dissipate the stress in granular layers. Specifically, lower deformations and higher damping properties can be obtained when softer elastic elements are used in the track superstructure. However, the use of very soft pads (or soft pads applied in sections with low bearing capacity) could lead to important rail deflections, resulting in higher rolling resistance and resistance to fatigue of the superstructure elements (Fortin 1982, Teixeira 2003).

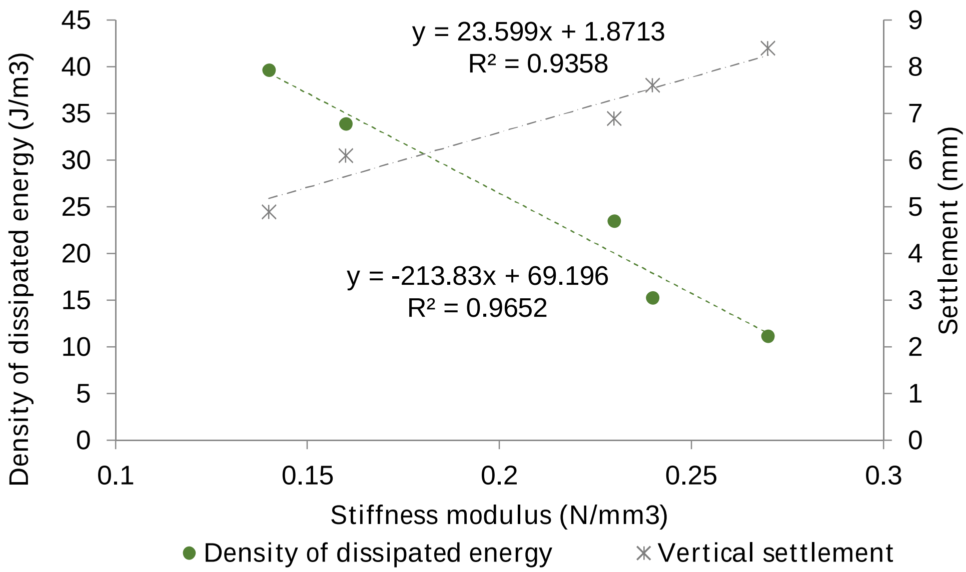

Figure 2.13 – Track performance depending on variations in track stiffness due to changes in elastic elements properties such as rail pads and USPs (adapted from Sol-Sánchez, Pirozzolo et al. 2016).

The ability of USPs of modifying the global vertical stiffness of track-bed promoted their application for zones where remarkable changes in vertical track stiffness take place in order to obtain a smoother transition (Witt 2008, Dahlberg 2010). However, due to their relatively high initial cost, their application is currently limited to these transition zones as well as other specific areas such as switches, tight curves, where high degradation generally occurs.

2.4.2.3 Under ballast mat (UBM)

Under Ballast Mat is another elastic element that has been adopted to damp vibrations and decrease stress into ballast layer as well as those transmitted to sublayers (Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2015). Because of these properties, this element has been used also to reduce the thickness of ballast layer while increasing vertical flexibility (UIC 2011).

Typically, UBMs have a thickness of around 15-30 mm and their characteristic parameter is the dynamic bedding modulus (C_{dyn}) which commonly ranges from

0.05 N/mm^3 to 0.22 N/mm^3, depending on its main function (Teixeira 2009, UIC 2011).

Diverse applications showed that the use of an elastic material under the ballast on rigid structures (such as tunnels or bridges) can lead to important reductions in ballast stress, (lower particle breakage) and therefore in the maintenance frequency (Dold and Potocan 2013, Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2015).

Nonetheless, these benefits are less pronounced or even absent when ballast mats are installed on a weak subgrade (Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2015). In addition, the use of soft UBM can lead to an important decrease in bearing capacity of the substructure, increasing movements of ballast particles, which results in higher settlement (Sol-Sánchez, Pirozzolo, et al. 2016). In this regard, the use of these elements to decrease particle breakage seems to be preferable when it is strictly necessary also to reduce ballast layer thickness and over rigid substructures such as tunnels or bridges (Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2015).

2.4.2.4 Use of elastic elements from waste materials

Despite their benefits, elastic elements described in previous sections present relatively high economic and environmental costs associated with the use of high-performance polymers that limits their widespread application. To cope with these limitations, research is moving towards more sustainable technologies such as elastic elements from alternative materials (generally end-of life substances).

In this context, waste tires have been widely used to develop innovative elastic elements with adequate mechanical behaviour and durability. Among different solutions there are elastic elements from crumb rubber obtained by grinding up the waste tires (Carrascal et al. 2010), or directly from tread layers (Figure 2.14)

(Sol-Sánchez, Moreno-Navarro, and Rubio-Gámez 2014a, 2014b, 2015, Sol-Sánchez, Moreno-Navarro, et al. 2016a).

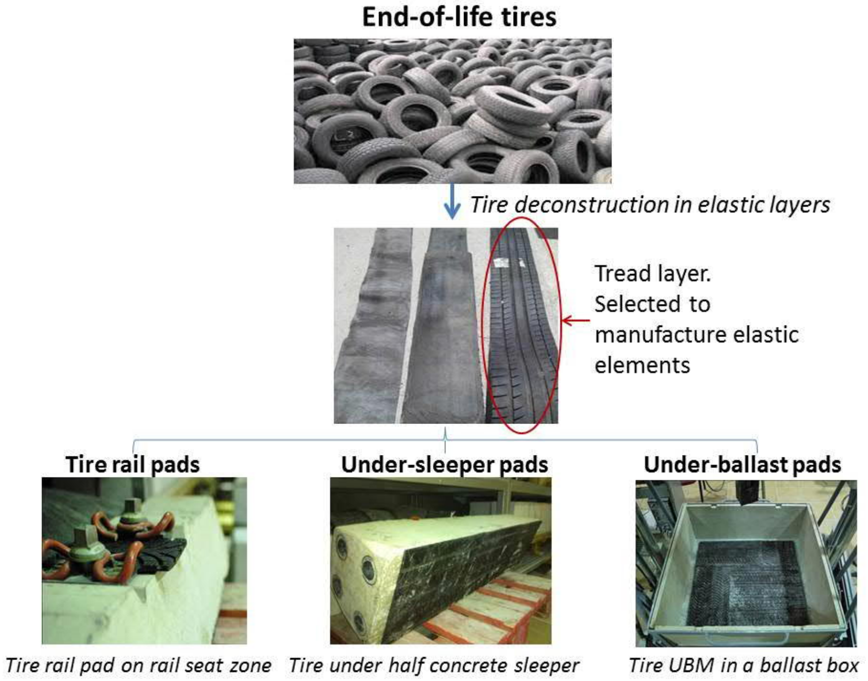

Figure 2.14 – Elastic elements made from waste tire layers (adapted from Sol-Sánchez, Moreno-Navarro and M. Rubio-Gámez 2014a).

As alternative to conventional elastic elements (rail pads, USPs and UBMs), new technologies made from waste tires have been proposed to improve the track behaviour and ballast durability while reducing dynamics overloads that accelerate deterioration.

In this regard, the most used material is the crumb rubber, due to its desirable elastic properties. Ho et al. (2015) proposed the use of an elastic block, called Resiliently Bound Ballast (RBB) (Figure 2.15a) composed by crumb rubber (tyre chips) mixed with small aggregates and proprietary resilient epoxy cement to be used as an under sleeper mass/block in ballasted tracks in order to reduce vibrations while damping dynamic loads to protect ballast layer. Depending on the mix design, different solutions in terms of flexibility can be obtained. Full-scale laboratory studies showed that the use of this material can lead to lower degradation of track geometry due its increased resistance to plastic deformations under high stresses.

A different use of crumb rubber in railway track is given by Neoballast®. This technology consists of small particles of waste rubber (size of few millimetres) bonded to ballast aggregates by using a polyurethane glue. The main objectives of this solution are to decrease aggregate degradation (since they are protected with an elastic layer) and improve the noise and vibration behaviour of ballast layer (Figure 2.15b) (Manzo-Constanzo et al. 2015). These properties can be optimised by varying dosage of rubber and binder as well as the characteristics of the elastic particles (size, composition, shape, etc.) (Manzo-Constanzo et al. 2015). The increased resistance to breakage exhibited during laboratory tests (Los Angeles coefficient reduced from 15 to lower than 5) encourage the use of this technology to recycle aggregate that do not meet the requirements for their application as ballast. As a result, issues related to the availability of appropriate aggregates for ballast in the proximity of the construction, would be significantly limited. In addition, this solution would not jeopardise ballast main advantages such as the high permeability and the possibility of being maintained by automatized tamping machine.

Nonetheless, to apply extensively this technology, increased initial construction due to the manufacturing process and the use of binder should be balanced by the reduction in maintenance. Therefore, the development of this technology is currently focused on the design optimisation (minimising costs while improving performance) by the modification of conventional structure: reduction in ballast thickness, elimination of some components, etc.

In order to cope with these limitations (use of binder agents), another solution to reduce the issue of particle breakage is the use of elastic elements obtained from rubber waste as flexible particles mixed directly with ballast aggregates (Ballastic) (Figure 2.15c) (Sol-Sánchez, Thom, Moreno-Navarro, Rubio-Gámez, et al. 2015). In this case, the size of rubber particles ranges from 14-22 mm in order to avoid their percolation through ballast voids.

The main factor affecting the effectiveness of this technique is the dosage of rubber particles. The global stiffness and resiliency of ballast layer is also highly influenced by this value. In this regard, results from full-scale laboratory tests showed that particle breakage sensibly decreases with increasing amount of crumb rubber. However, excessively high dosage can result in reduction of bearing capacity, leading to settlement much higher than untreated ballast. An optimal configuration was found to be a 10% of crumb rubber into the ballast. In this case, an appreciable decrease in ballast deterioration without significantly affecting, or even improving, the resistance to permanent deformations was observed (Sol-Sánchez, Thom, Moreno-Navarro, Rubio-Gámez, et al. 2015).

Nonetheless, further research is ongoing to optimise its application in existing tracks by conventional machinery avoiding, thus, additional costs during construction/renewal process.

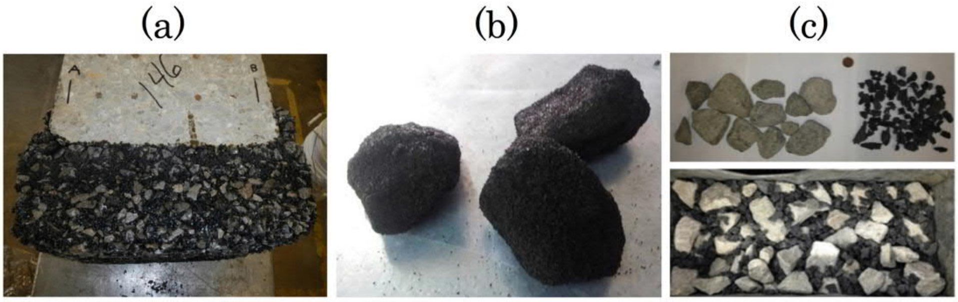

Figure 2.15 – Visual appearance of (a) Resiliently Bound Ballast (Ho et al. 2015), (b) Neoballast® (Manzo-Constanzo et al. 2015), and (c) Ballastic (Sol-Sánchez, Thom, Moreno-Navarro, Rubio-Gámez, et al. 2015).

2.4.3 The use bituminous layers

During last decades, the use of asphalt layers within railway track-bed has been gaining favour with designer in order to cope with higher performance required from railway transport. This alternative solution has been increasingly used in countries such as Austria, France, Italy, Japan, United States or, more recently, Spain, among others, getting to be considered as an appropriate technology to improve track quality in high speed and heavy traffic lines (Teixeira 2009, Rose and Souleyrette 2014a, 2014b).

Among the different asphaltic configurations developed worldwide (Teixeira 2009, Rose et al. 2011), the application of bituminous subballast to replace conventional granular layer under ballast get the highest favour from designers and researchers. For this configuration, asphalt mixes similar to highway Hot Mix Asphalt (HMA) applied in base and binder pavement courses are used. Bituminous subballast typically consists of a dense-graded mixture composed of coarse aggregate (maximum size 25-37.5 mm), presenting an air void content lower than 3-4%, providing adequate vertical track strength and impermeability to protect the sub-layers from water action (Hensley and Rose 2000, Rose and Souleyrette 2014b).

Subballast thickness is one of the main factors affecting track-bed performance and its ability to reduce track settlement and degradation (Hensley and Rose 2000). In this regard, this parameter has been widely analysed in diverse studies as in 1999 at the Transportation Technology Centre in Colorado, where two HMA thicknesses (100 mm and 200 mm) were used over soft subgrade soil. After one hundred Million Gross Tons (MGT), it was found that higher thickness provided higher track modulus and protection for the subgrade. In addition, both bituminous subballast configurations exhibited higher track modulus (20 MPa and 23 MPa for 100 mm and 200 mm HMA, respectively) than that measured for granular subballast (around 14 MPa). This allowed also for the reduction in subgrade stress from 83kPa to 55-50 kPa (Figure 2.16a). As a consequence of increasing the bearing capacity of the sub-structure, the final track-bed settlement of the 200 mm HMA was about 15% lower than that of the 100 mm HMA case), which led to less frequent maintenance requirements to recover track geometry in comparison with the all granular case (Li et al. 2001).

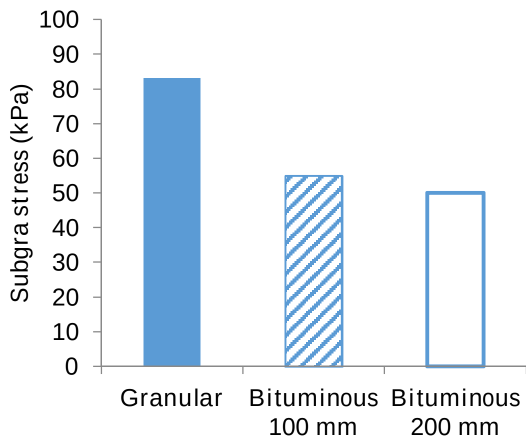

Figure 2.16 – Capacity of bituminous sub-ballast to reduce stress on subgrade (adapted from Li et al. 2001).

The use of HMA underlayment was proven to provide also other advantages such as an optimal values of track deflection (1.5 mm) as well as preventing water to enter and weaken subgrade, keeping, thus its moisture content close to the optimum (because of the HMA waterproofing) (Rose et al. 2002, Rose and Bryson 2009). To this last benefit is associated a reduction in variations of the humidity of the subgrade, which allows for lower displacements amplitude and permanent deformations (Ferreira 2007), reducing, thus, track geometry deterioration.

For design purposes, differently from pavements, it has to be considered the lower level of stress and the presence of ballast layer acting as protection from environmental action as well as important temperature variations (Rose et al. 2002, Rose and Bryson 2009). In this regard, typical pavement distresses such as rutting, bleeding and flushing are of little concern for bituminous subballast (Rose et al. 2011, Rose and Souleyrette 2014b). Nevertheless, it must be taken into account that other phenomena as punching deformation can take place, which, as shown by Sol-Sánchez et al. (Sol-Sánchez, Pirozzolo, Moreno-Navarro, and Rubio-Gamez 2015), could be highly affected by severe environmental conditions.

Bituminous subballast main concern is related to its relatively high initial costs in comparison with granular subballast. Depending on the configuration, local conditions, access, and project size, the initial specific cost of the layer can raise by 2.5 to 5 times when conventional subballast is substituted by HMA (Hensley and Rose 2000, Rose and Anderson 2006). In this regard, an economic study (Teixeira et al. 2009) showed that the bituminous subballast starts to be more effective and profitable when the transportation distances for appropriate aggregates for granular subballast are above 60-80 km since the asphalt material can be manufactured with poorer aggregates (closer to the construction site) coated with bituminous binder that protects such mineral particles.

However, by considering the entire lifecycle, because of the reduced routine maintenance, initial cost is typically recovered within 7 years (Hensley and Rose 2000), or even within the firsts years in cases where conventional track-bed exhibits severe maintenance problems (Rose and Anderson 2006). In addition, the maintenance reduction (by reducing ballast deterioration) could extend track-bed life by 50-100% (Hensley and Rose 2000).

In this context, with the aim of improving the technical aspects and the cost effectiveness of bituminous subballast while increasing the durability and mechanical performance of ballasted tracks, diverse studies have been carried out to develop alternative asphalt materials with longer fatigue life and lower environmental impact. In this regard, in order to develop more environmentally-friendly asphalt mixtures for railway tracks, Pirozzolo et al. (Pirozzolo et al. 2017) designed a Warm Mix Asphalt (WMA) for subballast that allows for lower manufacturing temperatures (around 30°C lower). This would allow for important economic and energy savings at the time that less toxic fumes are generated during the manufacturing process. Initial laboratory results indicate that the WMA presents a comparable performance to that obtained for conventional hot bituminous subballast, leading to similar durability and protection for the rest of substructure.

The use of crumb rubber from waste tires to modify bitumen properties represent another technique which aims to increase sustainability of track-bed. Buonanno and Mele (Buonanno and Mele 2000) showed that this solution allows for an important increase in capacity to damp vibrations. At the same time, crumb rubber was proven to improve fatigue resistance and dynamic modulus (Xiangwu 2005) as well as resistance to plastic deformations, and to reduce stress and strains at the bottom of the bituminous layer (Moreno-Navarro et al. 2013).

2.5 Track geometry maintenance

Conventional rail tracks continuously deform both vertically and laterally under traffic cyclic loads resulting. These deviations from the design geometry, apparently small, progressively deteriorate riding quality and increase dynamic loads, which in turn, further contribute to worsen the track level and alignment (Indraratna et al. 2011). In order to keep adequate safely levels and comfort of ride, track geometry has to be maintained to a certain standard.

Several authors are of the opinion that, if the formation is adequately specified, ballast is the controlling factor of loss of track geometry (Shenton 1984, Selig and Waters 1994). In addition, ballast, because of its properties (single size unbound aggregate), is the layer that facilitates the use of mechanised maintenance equipment. Worldwide, ballast maintenance represents a major part of track maintenance costs (Raymond and Gaskin 1975, Indraratna et al. 1998). As example, in the UK normal maintenance intervals to correct track geometry range from one to two years for main lines and three to four years for branch lines (Aursudkij 2007).

In this context, reducing maintenance costs while effectively using available recourses by developing innovative technologies is a challenge for current and future railway research.

There are essentially two methods of track geometry maintenance, tamping and stoneblowing, which are described within this section.

2.5.1 Tamping

Automatic tamper, which is the evolution of the beater packing (used in the earliest days of railway), is the machine most used to correct track geometry from the 1960s to date. This operation mechanises the process of lifting and laterally squeezing the ballast to fill the void space generated beneath the sleeper (Selig and Waters 1994). Tamping process is effective for re-adjusting the track geometry, having an average working rate of approximately 864 m/h (Pires 2016).

However, this maintenance operation is accompanied by some detrimental effects: vibrating tines, indeed, disturb and dilate the densely packed ballast layer, deteriorating particles and reducing track stability (Calla 2003, Indraratna et al. 2011). In this regard, tamping can affect durability of track geometry, and track profile can quickly revert back to its original position, a phenomenon known as 'ballast memory' (Selig and Waters 1994). This phenomenon prevails when a small lift is applied, since the small void space limits the re-arrangement of ballast, which can be easily re-compacted to their original position by the passage of traffic (Calla 2003).

In this regard, a possible solution to reduce this phenomenon is the 'high lifting' tamping defined as a lift that exceeds the D_{50} size of the ballast (Selig and Waters 1994). This process is claimed to produce up to triple durability than conventional tamping. Nevertheless, the limited headroom availability in some railway lines may limit its applicability (McMichael and Strange 1992).

An alternative solution to reduce quick ballast re-compaction after tamping is the Dynamic Track Stabilisation (DTS). This method consists of vibratory process, which causes a controlled initial settlement of ballast (Figure 2.17), avoiding thus a higher plastic deformation due to the passage of the first trains. In this way, durability of corrected track geometry can be significantly extended (Selig and Waters 1994).

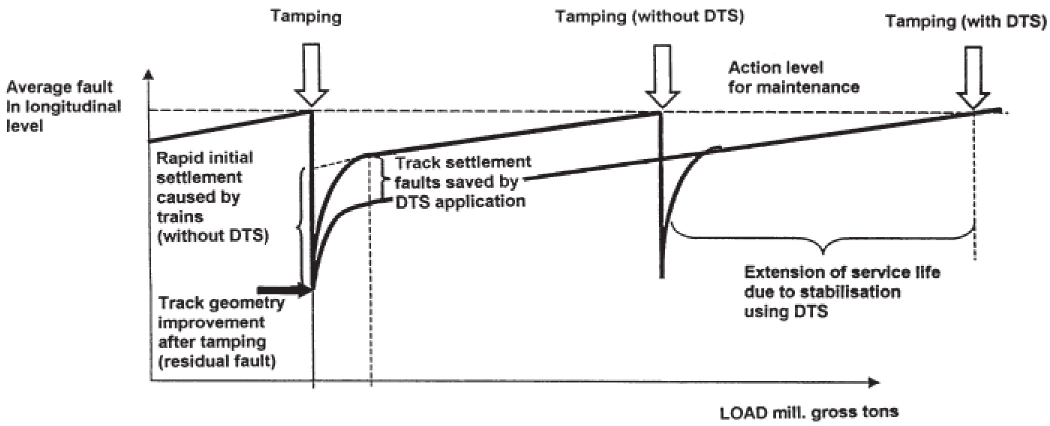

Figure 2.17 – Effect of dynamic track stabilisation on reducing ballast settlement (Selig and Waters 1994).

Another issue related to tamping is the production of a high amount of fines (Calla 2003, Lim 2004, Sol-Sánchez, Moreno-Navarro, et al. 2016b). Diverse studies showed that a typical ‘tamp’, due to the vibrating action, can produce up to 4 kg of fines/sleeper/tamp (Selig and Waters 1994, Fair 2003, Zaremsbki and Newman 2008), increasing progressively the contamination (fouling) of ballast layer. Furthermore, as reported by Selig and Waters (Selig and Waters 1994), the reorganisation of ballast due to the loosening caused by tamping can double the degradation with respect to a compacted not disturbed layer subjected to the same traffic (100,000 cycles after each tamping for this study).

Contaminated (fouled) ballast presents a series of problems such as impairing drainage and layer ability to hold track geometry (track-bed settlement) due to the reduction in frictional and shear strength, while increasing the difficulty of effectively carry out the tamping process.

All these factors simultaneously contribute to progressively reduce tamping effectiveness and increase the frequency between maintenance operations. To overcome these issues alternative maintenance operations (such as stoneblowing) and technologies to improve the effectiveness of maintenance have been developed.

2.5.2 Stoneblowing

Stoneblowing has been introduced as alternative maintenance operation to correct track geometry to cope with the problem of 'ballast memory' and degradation. As evolution of the measured shovel packing (Calla 2003), this practice was developed by Harsco Rail in cooperation with Network Rail and mainly implemented over the recent decades in United Kingdom (McMichael 1986, Fair 2003, McMichael and McNaughton 2003, Zaremsbki and Newman 2008).

This maintenance operation consists of lifting the sleeper to the target level (original track geometry), inserting stoneblowing tubes into the ballast and air injecting or 'blowing' a carefully measured quantity of stones into the space between the sleeper and the ballast (Figure 2.18) (Aursudkij 2007).

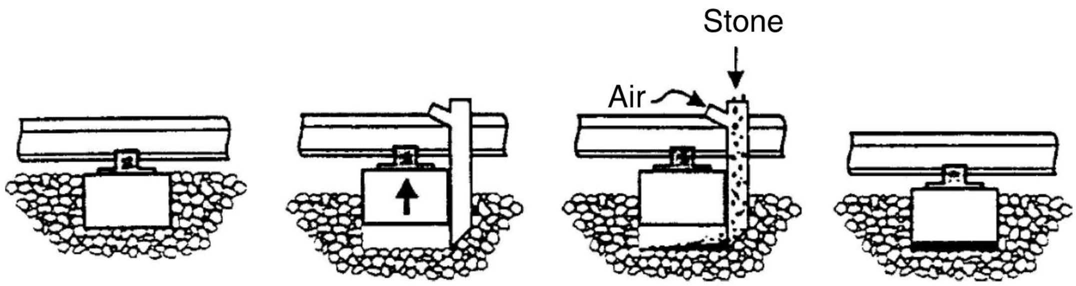

Figure 2.18 – Schematic illustration of the stoneblowing process (Indraratna et al. 2011).

Stones blown size generally ranges from 14 to 22 mm in order to avoid the percolation of stones through ballast layer (Andersson et al. 2013), limiting, therefore, drainage problems and reduction in damping capacity. In this regard, stoneblowing can even improve the drainage properties of the track by reducing the pumping effects caused by poorly supported sleepers (McMichael 1998). The amount of stones injected generally ranges from 0.5 to 22 kg per sleeper end (depending on the gap to be filled). Commonly, the area of support where the small stones are applied is around 230 mm x 460 mm under rail seat, with approximately 0.45 kg of stones being needed for every 0.8 mm of gap under the sleeper (Chrismer, 1990).

Several field investigation showed the potential of stoneblowing to improve durability of track quality and reduce track degradation (Fair and Anderson 2003, McMichael and McNaughton 2003, Zaremsbki and Newman 2008, Tutumluer et al. 2015). This process, indeed, mitigated the problem of ballast memory problem, associated with tamping, since it does not disturb the already compacted ballast layer.

In addition, despite the higher maintenance costs per km and the lower working rate (on average 560 m per hour - McMichael & McNaughton 2003), its effectiveness reducing post-maintenance ballast settlement could lead to important life cycle savings in comparison to tamping (Zaremsbki and Newman 2008).

However, it must be taken into account that, when high lifts (higher layer of loose stones) need to be applied, the resistance to permanent deformation becomes quite similar to that observed after tamping maintenance (Anderson and Key 2000). In this regard, further studies are required to determine the maximum lift height to effectively perform stoneblowing process.

In addition, it should be considered that the inclusion of stones over the compacted ballast layer can lead to track stiffening and changes in track behaviour (Sol-Sánchez, Moreno-Navarro, et al. 2016b). In this regards, research is moving towards the inclusion of rubber particles mixed with the small stones (as flexible aggregates), which could vary gradually its track-bed mechanical response and avoid abrupt changes in track stiffness that accelerates its degradation (Sol-Sánchez et al. 2017). This solution, similarly to the use of under-sleeper pads, would reduce also settlement and ballast contamination (from abrasion).

2.6 Maintenance-based solutions to mitigate track-bed degradation

In order to contain overall maintenance costs by decreasing its frequency without prolonged traffic interruptions, many solutions have been investigated and applied as palliative maintenance operations. Some of them are also coupled with traditional maintenance tasks used for correcting geometry in order to increase their effectiveness.

Since the main cause of deterioration and settlement problems is addressed to the unbound nature of ballast layer itself, in recent decades many studies have focused on the use of techniques that stabilise ballast by bonding particles together, increasing shear strength of ballast layer and protection of particles from frictional wear. The main requirements for these techniques, are related to the gluing capacity of the coating material and its ability to be easily applied during maintenance operations. Besides, the properties of ballast particles play an essential role in the effectiveness of this technique. In this sense, it has been proven that the smaller the aggregates, the higher the effect of stabilizer to decelerate track degradation due to the higher number contact points (Rostler et al. 1966), reducing as well particles movements and thus prevent ballast aggregates from abrading through attrition.

However, most of these solutions are only cost effective for specific track sections where settlement reduction is required but conventional maintenance tasks are difficult to carry out (such as in switches and crosses) (Thomson and Woodward 2004, Woodward et al. 2007, 2012, Lakušic et al. 2010, Keene et al. 2013, Kennedy et al. 2013, Fischer et al. 2015). The cost of the stabiliser and its installation, indeed, often limit its application along the track, and research is thus focusing on maximising the cost-effectiveness of bonding agents or more productive application processes in order to improve the cost-effectiveness of its life cycle.

2.6.1 Polyurethane-based stabilisation techniques

These technologies have been widely proposed and applied in order to increase the shear strength and reinforce ballast layer in 3-dimensions via creating a net that holds aggregates or through chemical bonds at particle contacts. This fact is due to the capacity of polyurethane to assume the forms of coating, which is an essential characteristic for materials to be used in ballast stabilisation. These technologies can be classified in three main types that vary essentially in curing time and final form while the dosage of bonding agent applied is essential in all of them to optimise track behaviour.

The first one is a rigid-compact type of polyurethane called Elastrotrack® (Figure 2.19a), which consists of two components, isocyanate and resin, that are mixed to create the polyurethane mixture (Dersch et al. 2011). Ballast aggregates become bound after pouring such mixture over ballast layer surface, the process of coating usually occurring within 30-60 minutes, in function of the catalyst (Boler 2012). This technique can significantly increase the shear strength of ballast layer up to 60% greater than uncoated ballast, which continues to increase during its curing time (up to 14 days) (Dersch et al. 2010, 2011). As a result, both breakdown is reduced (3-5% less breakage than untreated ballast) as well as particle reorientation which could lead to a reduction in ballast settlement (Dersch et al. 2010). In addition, Elastrotrack® do not prevent drainage since no voids are clogged; only a thin coat is formed on the particle surface.

Another proprietary technology is a polyurethane geocomposite form called XiTRACK® (Figure 2.19b), supplied mainly in UK. The resin used is a urethane-cross linked polyurethane that is supplied as two components (isocyanate and polyol). These two components are mixed in situ in the presence of a catalyst, and injected on the ballast layer (Woodward et al. 2011b). The range of properties of the polymer, such as stiffness, hardness, viscosity, tensile strength, can be controlled through the polymer rheology (Woodward et al. 2011a). The polymer starts curing in about 10 seconds. Its faster curing time allows the layer to reach the 90% of its optimum strength within one hour (Boler 2012). Also, by adjusting the polymer rheology to modify its penetration into the ballast layer, this technology can be applied to clean or fouled ballast (Boler 2012). Rather than bonding particles, XiTRACK® aims to create a 3-D reinforcing polyurethane net, occupying only approximately 30% of the void space, which avoid drainage problems (Woodward et al. 2007, 2014, Dersch et al. 2011, Boler 2012, Kennedy et al. 2013). Several laboratory surveys and field applications have shown the drastic reduction in need for maintenance (Woodward et al. 2007, 2011b, Kennedy et al. 2013, Kelly 2015). For instance, an extensive laboratory campaign conducted with a full-scale box by Kennedy (Kennedy 2011) showed that XiTRACK® can reduce track settlement by around 95-98% after 500,000 cycles with respect to conventional unbound ballast. This result was mainly attributed to a stiffening effect by between 55% and 65% of the ballast layer.

The third form is a thermoset polyurethane-resin foam (Figure 2.19c), which is synthesised by proportionally mixing a polyester or polyether polyol and an organic polyisocyanate in the presence of a catalyst (Keene et al. 2012). This foam, developed by Bayer Material Science in partnership with Uretek USA Inc., during injection flows and expands through ballast pores to form a bonded geocomposite. By increasing the density of the foam, the strength, hardness and resistance to fatigue increase (Keene et al. 2012). In this case, the curing is even faster (90% of maximum strength in 15 minutes), avoiding extended line closure. This technology, also called polyurethane stabilised ballast (PSB), exhibited the ability to sensibly reduce permanent deformation, ranging from 63% to 90% after 200,000 cycles, with respect to clean ballast (Keene et al. 2013). Similar results were obtained by Du Plooly et al. (du Plooy et al. 2017) investigating long-term performance (over 5,000,000 cycles) of PSB using a large scale ballast box. In this study, it was also found that PSB can lead to a significant decrease of the initial resilient modulus, which is associated with the foam expansion and consequent loss of some contact between ballast particles, which could lead to an important increase in rolling resistance and bending stress for the track superstructure (Hunt and Wood 2005, Sol-Sánchez, Pirozzolo, et al. 2016). Nonetheless, by reducing the optimal dosage of foam by 50% final values of resilient modulus comparable to unreinforced ballast were achieved, which was associated with a level of settlement that was still lower than the reference ballast (du Plooy et al. 2017).

Figure 2.19 – Polyurethane-based technologies: Elastrotrack® (a) (Dersch et al. 2011); XiTRACK® (b) (Kelly 2015); and Rigid polyurethane foam (c) (Keene et al. 2012).

Overall, these technologies could lead to economic and environmental benefits associated with the reduction in ballasted tracks maintenance, mainly related to the increase in longitudinal and lateral resistance of ballast bed. Indeed, despite the issues related to its relatively high initial cost, polyurethane stabilisation has been claimed to provide lifecycle cost benefits by a sensible reduction in routine maintenance costs (Kelly 2015).

In addition, polyurethane stabilisation can ensure a smooth transition between ballast track and ballastless track (Xiao et al. 2015) while conventional maintenance to correct geometry defects can be allowed by placing a top layer of untreated ballast between the polyurethane reinforced layer and the sleeper bottom (Woodward et al. 2007).

However, further studies should focus on its environmental impact, durability and long-term efficiency. In addition, it could be of interest to analyse ease with which it can be repaired during routine maintenance interventions, and replaced in renewal tasks.

2.6.2 Ballast bonding by resins

Apart from the bonding solutions using polyurethane (the most used bonding agent in ballast stabilisation), other materials with gluing properties are being developed in order to reduce polyurethane drawbacks while improving its effectiveness to protect and reduce ballast layer degradation.

Among these bonding solutions, the use of resins (Figure 2.20a) has been more widely applied in ballasted railway tracks with different purposes such as preventing the phenomenon of flying ballast in the high speed lines (Lakušic et al. 2010), mitigating the phenomenon of ballast creep on high speed lines (Laurans et al. 2016) or increasing the lateral resistance in small radius curves (Fischer et al. 2015). Nonetheless, bonding the ballast has found also important results in modifying track-bed mechanical properties depending on the layer thickness stabilised (Lakušic et al. 2010). This makes ballast bonding suitable for transitional areas such as joints on bridges, tunnels and level crossing, where a gradual stiffness variation is needed (Lakušic et al. 2010) while ballast settlement rate is reduced.

These resins for ballast bonding are typically made by proportionally mixing a base component with a hardener. Its dosage can vary, depending on the specific application, from 2 to 16 kg/m² and reach a penetration depth of 30 cm and its curing is relatively fast (30-180 minutes depending on the type of adhesive used). Experiments carried out at the Technical University of Budapest showed that by increasing the ballast stabilised volume a reduction of more than 50% in track-bed deflection (corresponding to increase stiffness) can be achieved by the stabilisation of the complete layer (Figure 2.20b) (Lakušic et al. 2010). This finding could imply also an increased resistance to settlement. However, relatively little research has yet been carried out on the effect of ballast bonding on permanent deformation. Nonetheless, other field experiences showed that after ballast bonding implementation an important reduction in maintenance (both for track geometry correction or ballast levelling) was observed (Lakušic et al. 2010, Fischer et al. 2015, Laurans et al. 2016).

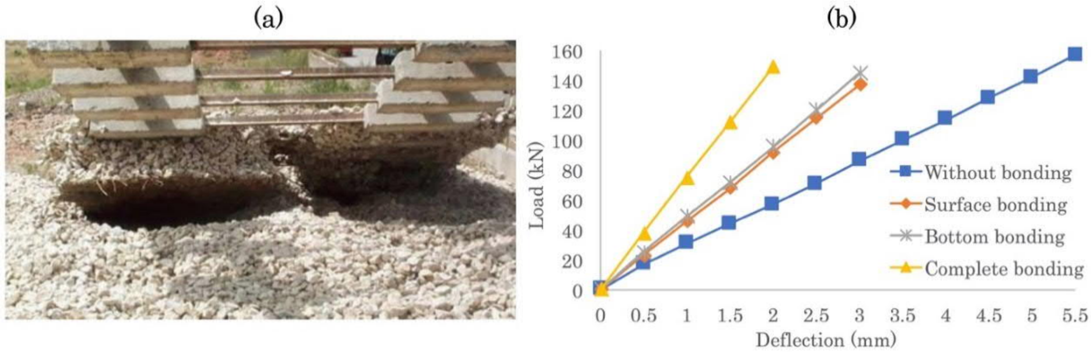

Figure 2.20 – Ballast after bonding on existing track (a); Influence of ballast bonding type on layer stiffness (b) (adapted from Lakušic et al. 2010).

This technology, by bonding stones only at the contact points, ensures water drainage through cavities in ballast. In addition, with respect to polyurethane-based stabilisers, resins are also claimed to have a lower sensitivity to humidity, characteristic that ensure longer resistance and applicability in different weather conditions (Gremmler 2016).

Also, ballast bonding is claimed to have no impact on subsequent tamping and levelling operations. However, following these maintenance operations, a new gluing would be required to restore a fully glued area (Laurans et al. 2016). Nonetheless, the relatively high cost (Laurans et al. 2016) of the technology may limit its applicability.

2.6.3 Other stabilisation technologies under development

The reduction of effectiveness of tamping on fouled ballasted tracks represents another important problem for many local railway lines with a restricted budget to maintain the degraded ballasted tracks. To cope with such an issue, specific technologies are being developed for stabilisation of fouled ballast, such as polyvinyl alcohol and cement grouts among others (Momoya et al. 2016).

The former technology consists of using a polymer aqueous solution (polyvinyl alcohol) to improve the ballast shear strength and thus resistance to permanent deformation (Nakamura et al. 2015, Momoya et al. 2016). This solution, which can be injected into the ballast layer during tamping, aims to extend ballast service life with a relatively low cost. In this regard, field trials applications showed that stabilised section exhibited lower growth of track irregularities over the first months of monitoring (Nakamura and Muramoto 2010, Furukawa 2016). In addition, full-scale laboratory tests showed a reduction of approximately 50% in rail elastic displacement, indicating a stiffening effect of this technology. Also, settlement after 600,000 cycles was half compared to untreated material (Nakamura et al. 2015).

A more invasive solution for fouled ballast stabilisation is the fine cement grout (Momoya et al. 2016). By filling the majority of voids and bonding the ballast to the sleeper, this method represents a radical change towards a ballastless track. As this latter track form, cement grout stabilised ballast inherits a better resistance to permanent deformation as well as major drawbacks such as the extremely difficult maintainability in case of geometry correction need, and the inability to drain water through the layer. Furthermore, despite the possibility to be applied to existing degraded ballast lines, its curing time is quite slow with respect to other stabilisation technologies, which implies a longer line downtime. Nonetheless, laboratory tests showed a significant reduction in ballast settlement (by approximately a factor of three) with respect to degraded ballast and thus an extension of ballast service life can be achieved (Momoya et al. 2016).

2.7 Bitumen emulsion for stabilisation purposes

Bitumen is one of the main components of asphalt mixtures used in road pavements from around 1900 (Thom, 2008) and more recently also in subballast of railroads. Its main advantages in comparison to other binding materials (such as cement, fly ash, and other hydraulically-bound materials) are the relatively low cost (residual product from refineries), and that, as asphalt mix for pavement surface, produce a better ride quality and reduce noise (Lacalle-Jiménez, 2017; Thom, 2008).

Bitumen is commonly used in hot mix asphalt (HMA), where it is mixed with dried preheated aggregate at approximately 170-185°C (Lacalle-Jiménez et al. 2017). Main drawbacks deriving from the use of this technology are related to the high energy consumption, relatively high carbon footprint, oxidative hardening of bitumen and more in general environmental degradation. In order to cope with these issues, recent decades have seen growing attention to more sustainable techniques such as warm and cold mixed, which need sensibly lower temperature while allowing recycling reclaimed asphalt planning (RAP) in plant or in situ. For cold mixes, no heating of the binder nor aggregate mixture is necessary, so that both mixing and laying can be carried out at ambient temperature (Yuliestyan et al. 2016).

For these mixes, one of the most used method is to emulsify bitumen in water. Bitumen emulsion consists of a dispersion of fine droplets of bitumen (liquid with a very high viscosity) in water. Generally, these droplets range between 1 to 30 µm in diameter and they are termed 'disperse phase' suspended in the 'continuous phase' of water. In order to produce a stable homogeneous mix of these two immiscible components, an emulsifier is required (Needham 1996). This stable mix can revert from discrete particles to continuous bitumen, a process termed 'breaking' during which droplets coalesce. This process occurs with different mechanisms depending on the emulsifier adopted (Needham 1996) when bitumen emulsion get in contact with aggregate. After coalescence process, the bitumen emulsion needs to fully cure or set for the binder to recover its original physical properties and resistance to water. Curing time is to a large extent dependent upon climatic conditions, being beneficial dry and hot conditions (Needham 1996, Ojum 2015).

There are different applications for bitumen emulsions in roads, depending on the setting characteristics, such as surface dressing, tack-coating, slurry seal, micro-surfacing, patch repair, crack sealing and grouting-penetration macadam among others (Needham 1996, Greening et al. 1999, Salomon 2006, Bocci et al. 2014, Goswami 2014, National Roads Authority (NRA) 2014). This last technique, which consists of pouring an emulsion grout into a single-size aggregate layer at defined rates in function on the thickness to be stabilised, is typically used to pave rural roads (Greening et al. 1999, Zoorob et al. 2002, Road Emulsion Associated Ltd (REAL) 2006).

This methodology reflects closely stabilisation techniques used for railway track-beds (described in previous sections), suggesting thus a possible alternative material to be used for ballast stabilisation.

Possible advantages would be the relatively low cost of the stabilising agent (approximately 500 €/t - Moreno-Martinez 2016), the possibility to use it at ambient temperature in any environmental condition and the large amount of research and studies carried out on bituminous materials for road applications, among others.

2.8 Discussion and conclusions

The literature reviewed within this project highlighted that ballasted track-bed is affected by relative high maintenance costs. These are mainly due to high rates of particle degradation and geometry variations (settlement) experienced under heavy traffic repeated loading. In this regard, typical loading conditions experiences by ballast under a 250 kN axle load have been employed in the laboratory studies reported in Chapters 3-7.

From the analysis of the different techniques and solutions for improving track quality and durability, Table 2.1 lists the main implication and functions of the design-based solutions, according to their effects on track performance, as well as the main properties to be adjusted to optimise their behaviour in different tracks.

It has been observed that the use of well-designed geogrids and bituminous sub-ballast could be appropriate to increase the shear strength of ballast layer as well as the sub-structure bearing capacity, which is required when the railway track section is on soft subgrade (for example, soft clay). As a direct consequence, it is possible to reduce sub-ballast layer thickness (around 30% with geogrids, and 50% with bituminous sub-ballast) without reducing bearing capacity while increasing the protection of sub-structure (particularly with bituminous sub-ballast, decreasing infiltration of water and vibrations) and reducing track settlement, which is more marked when using geogrids due to the higher confinement of the ballast layer (Powrie and Le Pen 2016). In addition, the use of these solutions allows for lower ballast degradation by limiting particle movement while reducing the frequency of maintenance interventions. Nonetheless, it should be taken into account that these solutions can lead to an increase in the initial costs, along with other environmental issues related to the consumption of raw materials.

The use of soft elastic elements, such as the conventionally used rail pad, USP, and UBM and innovative elements such as RBB, Neoballast and Ballastic, allows for reducing the breakage of ballast particles in reference to traditional tracks with only the stiff rail pad as the main elastic element. In this regard, UBM are considered to be adequate for reducing stress on ballast over rigid infrastructures (such as bridges, tunnels, etc.) while Neoballast and Ballastic are solutions designed to include rubber particles between ballast aggregates, protecting them from impacts and frictional wear.

However, it must also be taken into account that the use of very soft UBM and high quantity of rubber in Ballastic (higher than 10% over ballast volume) and in Neoballast, could lead to higher track settlement due to the increasing dynamic oscillation of ballast particles. Thus, to reduce track settlement, an appropriate design of these solutions is needed as well as specific studies for its optimization in reference to global track stiffness, since important deflections can occur. In addition, to limit track settlement, previous studies have found that the incorporation of soft rail pads, under sleeper pads and Resiliently Bound Ballast can lead to lower stress on ballast, and, in turn, lower plastic deformations.

Table 2.1 – Main effects of the design-based techniques to improve track quality and durability.

Solution	Increase in bearing capacity	Reduction in ballast degradation	Reduction in track settlement	Influence on global track stiffness	Main characteristic parameters
Soft rail pad	-	✓	✓	↓	Thickness and type of material
Soft USP	-	✓	✓	↓	Thickness and type of material
Soft UBM	↓	✓	?	↓	Thickness and type of material
RBB	-	✓	✓	↓	Proportion of components
Neoballast	-	✓	?	↓	Layer thickness and rubber properties
Ballastic	-	✓	?	↓	% rubber particles
Geogrids	✓	✓	✓	↑	Position into ballast and designing factors
Bituminous sub-ballast	✓	-	✓	↑	Thickness and designing factors

- Not widely known effect.
✓positive effect.
? Its effect depends on design factors and application.
↓ Decrease in global track stiffness
↑ Increase in global track stiffness

Table 2.2 summarises the controlling factors and the main implications of adopting the maintenance-based solutions analysed in this study. It can be observed that the aim common to all these techniques is the reduction of maintenance frequency as a consequence of a more durable geometry (settlement reduction). In this regard, polyurethane-based techniques, despite their relatively high initial cost (Woodward et al. 2007), appear to be the most effective in improving resistance to permanent deformations.

For the majority of these solutions, the reduction in settlement is associated with an increase in shear strength of the ballast, which also leads to track stiffening. Thus, these technologies are also suitable for railway spots where a gradual transition in stiffness is needed, achievable by varying the dosage and/or the penetration depth. Nonetheless, it is worth noting that increasing the stiffening of isolated sections could generate abrupt changes and lead to unwanted differential settlements.

Polyurethane stabilisation and the use of stoneblowing have all been shown to be capable of reducing the deterioration of ballast particles and thus the contamination of the ballast layer, thereby increasing its service life.

Common issues of the stabilisation technologies presented are the productivity during installation, the efficiency in maintainability of stabilised sections, the durability in performance and the end of life phase (particularly in terms of the recyclability of the stabiliser). In this regard, research should focus on these aspects and include them in life cycle analyses in order to effectively assess all the benefits and the impacts of each of these solutions when applied to exiting ballasted tracks.

Table 2.2 – Main effect of the maintenance-based techniques to improve track quality and durability.

Solution	Reduction in ballast degradation	Reduction in track settlement	Influence on global track stiffness	Main characteristic parameters
Stoneblowing	✓	✓	↑	Dosage of stones blown
Elastotrack	✓	✓	-	Stabilising agent rheology
XiTrack	-	✓	↑	Stabilising agent rheology
Polyurethan-resin foam	✓	✓	↓	Dosage
Ballast bonding with resins	-	✓	↑	Dosage
Polymer aqueous	-	✓	↑	Material properties
Cement grout	-	✓	↑	Material properties

- Not widely known effect.
✓positive effect.
? Its effect depends on design factors and application.
↓ Decrease in global track stiffness
↑ Increase in global track stiffness

In summary, in spite of the many advantages associated with ballasted railway tracks, phenomena such as settlement and particles breakage lead to the need for periodic maintenance interventions and renewal operations, which causes important economic and environmental costs that reduce the effectiveness of this type of infrastructure.

The inclusion of different types of elastic elements (conventional or innovative) to reduce permanent deformations and stress on ballast layer, joined to solutions to increase bearing capacity of track, are currently conceived as effective design-based technologies to prevent quick ballast layer degradation and loss in track geometrical quality. Among these alternatives, the following technologies/techniques, developed from elastic materials, can be highlighted:

- Soft conventional elastic elements such as rail pads (stiffness around 80-125 kN/mm) or under-sleeper pads (stiffness modulus close to 0.1-0.2 N/mm^3) allows for higher reduction in stress over ballast layer while higher damping capacity than stiff elements (more appropriate to reduce movements and vibrations of components), which results in lower settlement and particles breakage. However, very soft solutions could lead to excessive rail deflection (and then, higher rolling resistance, fatigue of some components, etc.).

- Soft under-ballast mats also reduce ballast degradation, but its application over subgrades with low bearing capacity causes important settlements associated to high dynamic movements.
- Elastic elements manufactured from waste materials (particularly waste tires) are being developed to improve track quality and durability while reducing economic and environmental costs, which could extend the application of them (particularly under-sleeper pads and under-ballast mats) and then, its benefits. Nonetheless, alternative waste polymers are to be studied with this aim.
- In addition, innovative elastic solutions made from waste crumb rubber such as Resiliently Bound Ballast, Neoballast® or Ballastic, have been found to effectively reduce track settlement and ballast breakage. Also, optimisation of track behaviour is possible by varying rubber particles properties and quantity. Nonetheless, further studies are required to analyse its long-term benefits.
- Geogrids are also considered as appropriate elastic components to decelerate ballasted track degradation due to the limitation of particles movements by increasing confinement. Grid aperture size has been found to be key factor (which should be higher than aggregate particle size, around 1.2-1.6 times) while its optimal realistic position is around 65 mm above the ballast-sublayer interface. Nevertheless, specific studies are to be carried out to define its optimal application depending on track properties while analysing its long-term performance and development of alternative materials to reduce costs associated to this solution.
- With the aim of increasing track bearing capacity and reducing excessive deflections associated with the use of soft elements, the inclusion of bituminous sub-ballast is increasingly becoming a solution to be

considered. This technique would reduce track settlement and ballast deterioration, together to higher protection for subgrade. Besides, to reduce drawbacks associated to bituminous materials, more environmentally friendly solutions are being developed (warm mix asphalt, inclusion of recycled materials, etc.). Nonetheless, more in-depth studies are required to mitigate the main concerns related to this solution such as environmental impact and durability.

On the other hand, due to the high number of existing railway lines, a main concern is to develop more efficient maintenance processes to maintain quality of current railway tracks. In this regard, conventional tamping presents a series of limitations associated to ballast memory and particles degradation due to the introduction and vibration of tines. Then, alternative processes are being developed:

- ‘High lifting’ tamping is claimed to improve track durability after maintenance due to a higher level of particles reorganisation, which could lead to a more stable layer. Nonetheless, this solution is not always available for limited headroom while problems such as higher irregularities can take place. Another alternative consists of a vibratory process to reduce post-process initial permanent deformations. Nonetheless, important limitations are still associated to tamping, which requires future research to improve its effectiveness.
- Stoneblowing appears to be a more effective process to reduce ballast settlement, and then, maintenance frequency, which would decrease particles degradation and ballast fouling. Nonetheless, attention should be paid to the fact that stoneblowing can lead to track stiffening and changes in track behaviour.
- Ballast stabilisation by using bonding materials such as polyurethane (the most used), resins or other stabilising materials, appears to effectively decelerate track settlement and particles degradation (reducing its movement and frictional contact) while optimising track performance by

varying the properties and dosage of bonding agents. However, due to high cost of the bonding agents, its application is limited to sections with difficulties for conventional maintenance (crosses, switches, etc.), which indicates the need for the development of more economic and durable solutions. Also, it is essential to analyse its long-term performance and the impact of ordinary maintenance processes on its durability.

Following these considerations, given the need for advance in the research of solutions which can extend ballasted track durability, the present research aims to propose and investigate the use of bitumen emulsion for ballast stabilisation. This solution would present a relatively low cost, the possibility to be applied at ambient temperature and the possibility of being applied during a maintenance operation in a similar fashion as the grout-penetrated macadam for road pavements.

Chapter 3 - Laboratory simulation of current maintenance operations

With the aim of improving current maintenance practices, the first part of this research focused on analysing the main factors influencing their effect on post-maintenance ballast layer behaviour. For this purpose, this chapter focused on a laboratory survey in which the main maintenance operations carried out to restore track-bed, namely tamping and stoneblowing, were simulated and their influence on track-bed behaviour was compared in a simplified and controlled manner.

3.1 Introduction

Maintenance operations used to restore track geometry such as tamping and stoneblowing have an important influence on post-maintenance track-bed behaviour, as highlighted in Section 2.5. In this regard, diverse laboratory and field experiences suggest that the use of stoneblowing could mitigate the main negative issues related to tamping (ballast memory and degradation) (Fair and Anderson 2003, McMichael and McNaughton 2003, Zaremsbki and Newman 2008, Tutumluer et al. 2015). However, some studies have showed that the stoneblower operation could also lead to a progressive increase in track stiffness and a reduction in its capacity to dissipate energy, due to progressive compaction of the ballast layer (Sol-Sánchez, Moreno-Navarro, et al. 2016b). This effect could eventually accelerate track degradation due to increased dynamic overloads (and lower damping capacity). This issue can be even more detrimental where adjacent sections are not similarly maintained, causing an abrupt change in stiffness (Dahlberg 2010). In this regard, more research is needed to give a better understanding of post-maintenance ballast behaviour and the factors influencing maintenance operation effectiveness.

In this context, the first part of this research focused on analysing the influence of tamping and stoneblowing on ballast's post-maintenance permanent deformation and mechanical behaviour. For this purpose, a ballast box has been used to simulate both field loading conditions and maintenance operations.

3.2 Materials

The box used for this study was a case-hardened steel box 200 mm wide, 460 mm long and 300 mm deep, which allowed for the introduction of an aluminium section 190 mm long, 148 mm wide, and 100 mm deep, simulating a sleeper, used to transmit the load to the ballast layer (Sol-Sánchez, Thom, Moreno-Navarro, Rubio-Gámez, et al. 2015). The thickness of the ballast layer was 200 mm under the sleeper. This box is a scaled (by a factor 2/3) version of that used by McDowell et al. (McDowell et al. 2005) and could be conceived as representing a section of ballast underneath the rail seat as shown in Figure 3.1.

This scale factor was necessary to allow the box to fit the hydraulic loading apparatus available in the laboratory. Being a comparative analysis, the use of a scale factor was a trade-off at this stage of the research in order to speed-up laboratory tests.

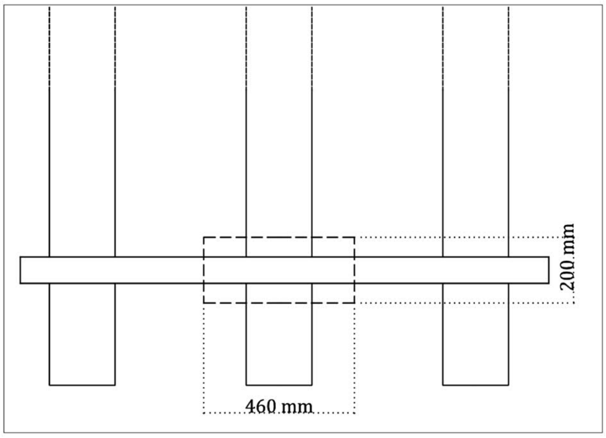

Figure 3.1 – Plan of rail and sleepers showing section represented by the box test.

A piece of synthetic rubber was used as a standard elastic mat beneath the ballast in order to generate realistic mechanical behaviour in the ballast. The mat was approximately 20 mm thick. Its static bearing modulus and its dynamic modulus at 5 Hz were obtained according to DBS 918 071-01 (Sol-Sánchez, Thom, Moreno-Navarro, Rubio-Gámez, et al. 2015); their values are 350 kPa/mm and 850 kPa/mm respectively. Four pieces of synthetic rubber, 3 mm thick, were placed on the sides of the box to simulate lateral continuity of field conditions. The visual appearance of a specimen inside the box before testing is shown in Figure 3.2.

Figure 3.2 – Specimen set-up before testing.

For this analysis two different materials were used. The first material (Ballast I) was a granite aggregate sourced from Cliffe Hill quarry in Leicestershire (UK), locally known as Markfieldite, containing principally microdiorite, an intrusive igneous material of superior uniformity, strength and durability (Whateley and Barrett 2009). The second material tested (Ballast II) was a granite aggregate sourced from Bardon Hill quarry also in Leicestershire (UK). Their physical properties are shown in Table 3.1 and Table 3.2, which indicate their compliance to UK Network Rail standards (BS EN 933-2 1996, RT/CE/C/006 2002, BS EN 1097-2 2010, BS EN 1097-1 2011, BS EN 933-1 2012, BS EN 933-3 2012, BS EN 1097-6 2013).

Table 3.1 - Mechanical and physical properties of Cliffe Hill quarry granite ballast (Laryea et al. 2014).

Property	Standard	Test result	Network specification
Los Angeles Abrasion (%)	EN 1097-2	14	≤20
Micro Deval (%)	EN 1097-1	6	≤7
Flakiness index (%)	EN 933-3	FI_{20}	≤35
Length (%)	RT/CE/S/006	$L_{RB}A$	$L_{RB}A$
Fine particle content (%)	EN 933-1	$G_{F}RB$ A	$G_{F}RB$ A
Fines content (%)	EN 933-2	f_{RB} A	f_{RB} A
Particle Density (Mg/m^3)	EN 1097-6	2.88	-

Table 3.2 - Mechanical and physical properties of Bardon Hill Quarry granite ballast (Aggregate Industries UK Ltd 2013).

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	FI_{25}	≤35
Length (%)	RT/CE/S/006	$L_{RB}A$	$L_{RB}A$
Fine particle content (%)	EN 933-1	$G_{F}RB$ A	$G_{F}RB$ A
Fines content (%)	EN 933-2	f_{RB} A	f_{RB} A
Particle Density (Mg/m^3)	EN 1097-6	2.77	-

Figure 3.3 shows the gradation of Ballast I specimens, which complies with BS EN 13450 (Gc RB A – Railway ballast size between 31.5 to 50 mm) (BS EN 13450:2013 2013).

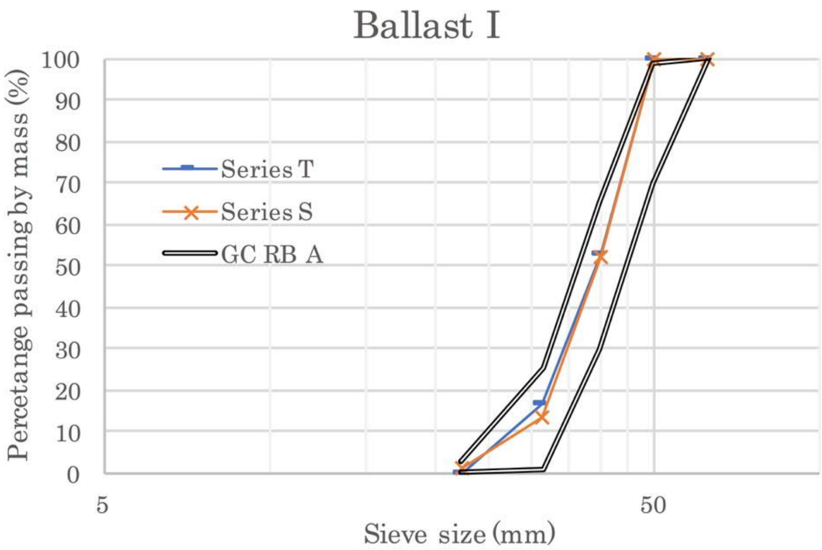

Figure 3.3 – Clean Ballast I gradations and EN 13450 Gc RB A limits (BS EN 13450:2013 2013).

In the case of Ballast II a lower maximum size (scaled using the same factor as for the box) was used in order to evaluate the influence of this factor on results (Figure 3.4). The gradation of clean Ballast II specimens, mostly within the G_c RB E specification (BS EN 13450:2013 2013), was markedly uniform to allow a wider range of gradations to be explored.

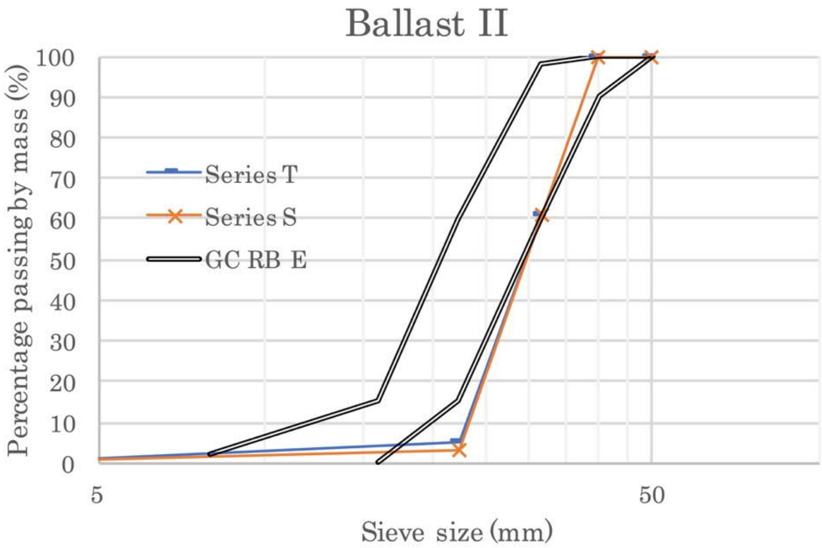

Figure 3.4 – Clean Ballast II gradations and EN 13450 Gc RB E limits (BS EN 13450:2013 2013).

To evaluate the influence of gradation on post-maintenance ballast performance further two gradations of Ballast II, corresponding to different levels of ballast degradation (moderately clean and fouled) (Ionescu 2004, Ebrahimi et al. 2015), were used (Figure 3.5).

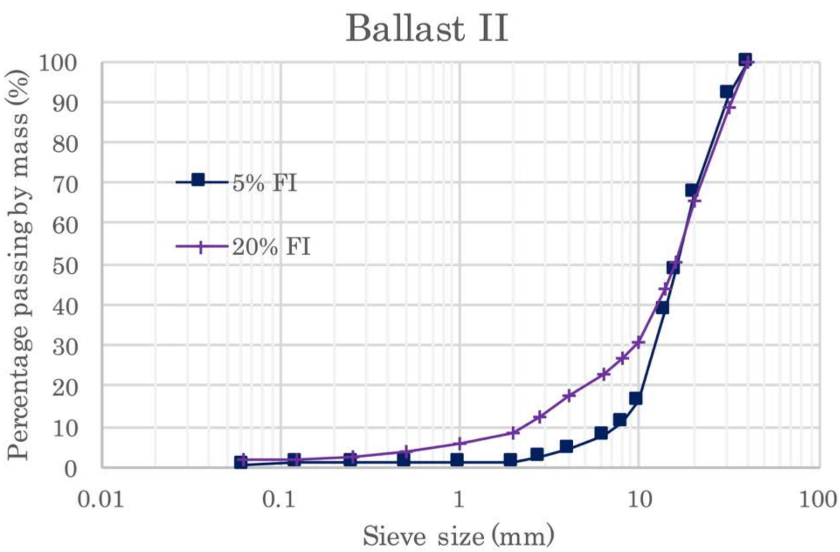

Figure 3.5 – Degraded Ballast II gradations: moderately clean (Fouling Index - FI 5%) and fouled (20% FI).

For this purpose, different sizes of aggregate have been combined in order to obtain the desired level of degradation. Only mineral fouling from breakage of particles was considered, being the major cause of fouling (Selig and Waters 1994).

For the stoneblowing process, aggregate from the same sources as the ballast was used to fill the gap between the sleeper and the ballast layer (Figure 3.6). Its particle size distribution is reported in Figure 3.7. It may be noted that the sizes ranged from 14 mm to 20 mm, necessary to avoid drainage and packing problems in field (Fair 2003).

Figure 3.6 – Stoneblower aggregate used.

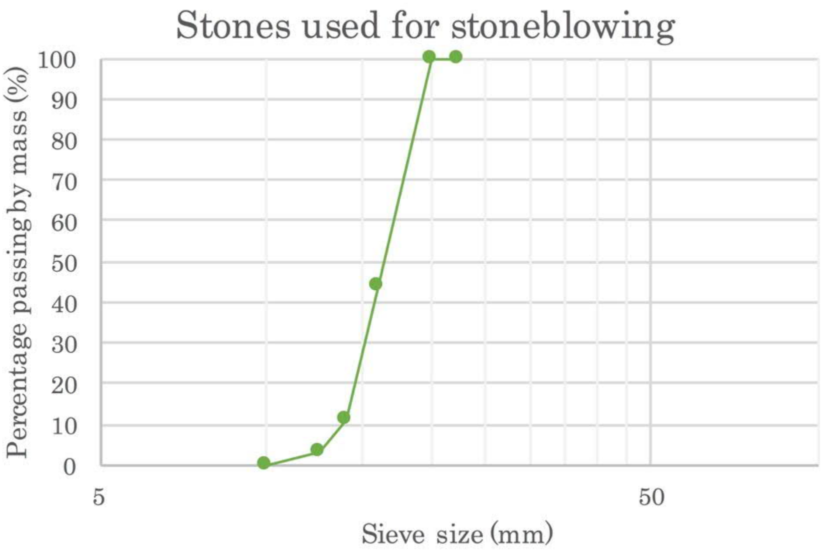

Figure 3.7 – Stoneblowing's stones gradation.

3.3 Method

In order to study the effect of the tamping and stoneblowing on post-maintenance ballast behaviour the study has been divided into two stages.

In the first stage two maintenance strategies, 'Series T' and 'Series S' were compared for the two different materials selected (Ballast I – clean and Ballast II – clean). Each series comprised 7 box tests, simulating train traffic. Following each test a maintenance operation was simulated in order to restore sleeper level to its initial value. In particular, Series T consisted of 5 tamping operations + 1 stoneblowing, while Series S consisted of 6 stoneblowing operations. This stage aimed at evaluating the influence of each simulated maintenance operation on post-maintenance behaviour of ballast from different sources.

In the second stage the same series of tests (Series T) was carried out on different gradations (Fouling Index, FI, from 0% to 20%) of the same ballast source (Ballast II) in order to evaluate the influence of gradation (i.e. fouling level) on ballast post-maintenance behaviour.

Table 3.3 summarises the work carried out. Each box test consisted of a sinusoidal pulse (Brown 1996) with a stress amplitude of 200 kPa, applied to specimens at a frequency of 3 Hz for 50,000 repetitions. The stresses achieved in the tests are comparable to those generally encountered in live railway (Anderson and Key 2000) (Section 2.2.2). Despite being relatively low, this number of cycles has been shown to be sufficient to obtain stable behaviour in the ballast layer (Indraratna et al. 2006), while fitting each box test into a reasonable period - it was not possible to continuously load overnight due to University regulations. Load and displacement were measured by means of a transducer integrated with the actuator.

Table 3.3 – Box test testing plan.

Variables	Material tested	Maintenance strategies	Test	Main parameters
Influence of maintenance operation on post-maintenance ballast behaviour				
-Material -Maintenance strategies	-Ballast I - Clean -Ballast II - Clean	Series T (7 tests): Initial (I1) Tamping 1 (T1) Tamping 2 (T2) Tamping 3 (T3) Tamping 4 (T4) Tamping 5 (T5) Stoneblowing (S) Series S (7 tests): Initial (I1) Stoneblowing 1 (S1) Stoneblowing 2 (S2) Stoneblowing 3 (S3) Stoneblowing 4 (S4) Stoneblowing 5 (S5) Stoneblowing 6 (S6)	Box test - Dynamic compression + simulated maintenance operations	-Plastic strain -Resilient modulus -Dissipated energy
Influence of gradation on post-maintenance ballast behaviour				
-Gradation	-Ballast II - Clean -Ballast II - FI 5% -Ballast II - FI 20%	Series T (7 tests): Initial (I1) Tamping 1 (T1) Tamping 2 (T2) Tamping 3 (T3) Tamping 4 (T4) Tamping 5 (T5) Stoneblowing (S)	Box test - Dynamic compression + simulated maintenance operations	-Plastic strain -Resilient modulus -Dissipated energy

The tamping operation was simulated by inserting a 2.5 cm wide chisel using a Kango hammer (Figure 3.8) into the ballast specimen (at approximately 15° to the vertical). The chisel was inserted 50 mm from the edge of the sleeper, applying vibration for around 2 seconds per side, the time necessary to re-arrange the stones below the sleeper (McDowell et al. 2005). Before this operation, the sleeper was lifted to the level occupied at the beginning of the test, to an accuracy of ±1.5 mm. This procedure was carried out in a similar manner as in other studies (Lim 2004, Aursudkij 2007).

Ballast samples bulk densities, at the beginning of each series, have been evaluated as reported in Table 3.1.

Table 3.4 – Bulk density for different ballast used.

Ballast I - clean	Ballast II - clean	Ballast II - moderately clean (FI 5%)	Ballast II - fouled (FI 20%)
(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)
1605.2	1507.8	1602.9	1697.0

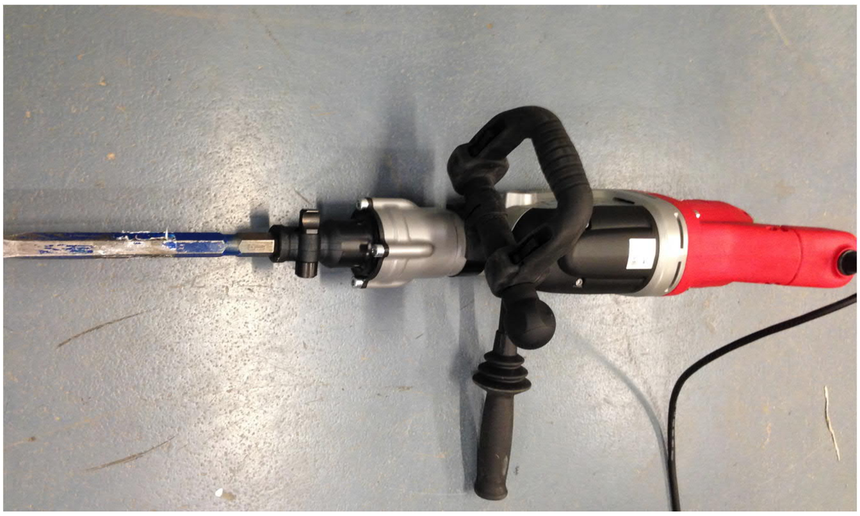

Figure 3.8 – Kango hammer used to simulate tamping process.

The stoneblowing process was simulated by lifting the sleeper, removing carefully the crib ballast taking care not to disturb the compacted ballast and adding the stoneblowing aggregate across whole of the exposed ballast surface (Anderson and Key 2000). The amount of stones was calculated based on the displacement that had occurred in the previous test, according to Tutumluer et al. (Tutumluer et al. 2015). The sleeper was then re-set at its original horizontal position, again with an accuracy of ±1.5 mm. Finally crib ballast was manually re-positioned on each side of the sleeper.

The main parameters evaluated were the plastic strain, the resilient modulus of the ballast layer and the energy dissipated per cycle.

With the aim of evaluating also the behaviour expected after initial compaction, from plastic strain values, it was decided to calculate the plastic strain rate (PSR) measured over the last 40,000 cycles, when the behaviour was relatively stable, according to Equation (3.1):

$$PSR = \frac{\Delta\varepsilon_S}{\Delta N_S} \tag{3.1}$$

where ΔN_s is the number of cycles and $\Delta\varepsilon_s$ is the change in plastic strain during the period considered.

For the same test range, also average values of the resilient modulus and the dissipated energy were calculated.

The resilient modulus M_r has been calculated for each cycle as the deviatoric stress $\Delta\sigma_v$ over the resilient (recoverable) average strain ε_r (calculated as vertical displacement over the original ballast depth), as in Equation (3.2):

$$M_r = \frac{\Delta\sigma_v}{\varepsilon_r} \tag{3.2}$$

The dissipated energy per cycle has been calculated from the hysteresis loop of the stress-strain diagram.

3.4 Results

3.4.1 Influence of maintenance operation on post-maintenance ballast behaviour

Figure 3.9 shows the curves of plastic strain (minimum displacement values per cycle over the ballast layer thickness) for each series (T and S). In the plots, maintenance operations are represented as 'spikes', restoring the sleeper level to the position occupied at the beginning.

It can be noted that ballast tamping was the least efficient maintenance operation, as after its application ballast quickly returned to its pre-maintenance position. This result can be related to the ballast memory phenomenon observed in the field after tamping (Selig and Waters 1994). In this regard, when a small lift takes place, tamping mainly dilates the compacted granular layer, providing a small degree of particle re-arrangement, so that relatively few load repetitions are sufficient to cause permanent deformations similar to those before maintenance.

In addition, it can be observed that the effectiveness of tamping became progressively reduced over the series, as after each tamping operation a lower number of cycles were necessary to obtain the same plastic strain. Also in terms of plastic strain rate (PSR), tamping had a lower efficiency than stoneblowing (Figure 3.10). These results correlate well with those obtained in other studies (Selig and Waters 1994, Aursudkij 2007).

In contrast, stoneblowing (carried out before the last test in Series T and all tests in Series S, as in Table 3.3) allowed for a more durable geometry as plastic strains following this maintenance operation were lower (up to three times) than those following tamping. In addition, from Figure 3.9 and Figure 3.11 it can be noted that stoneblowing progressively improved its effectiveness in terms of plastic strain and plastic strain rate (PSR). These results, in agreement with McMichael and McNaughton (McMichael and McNaughton 2003), indicates that the stoneblowing process could lead to an important increase in track geometry durability.

It can be also observed that for both ballasts in Series S the first stoneblowing operation carried out was less effective in terms of post-maintenance plastic strain and PSR, confirming that it is not efficient to use stoneblowing until the ballast has been compacted by traffic (Selig and Waters 1994). On the other hand, after 300,000 cycles, during which period the ballast progressively compacted under the load repetitions, plastic strain values following stoneblowing were the lowest, whatever the previous maintenance strategy. These results suggest the use of stoneblowing once the early stage of ballast life has passed.

It is important to notice that the material used had a low influence on results in terms of post-maintenance settlement and settlement rate, these values being similar for both Ballast I and II.

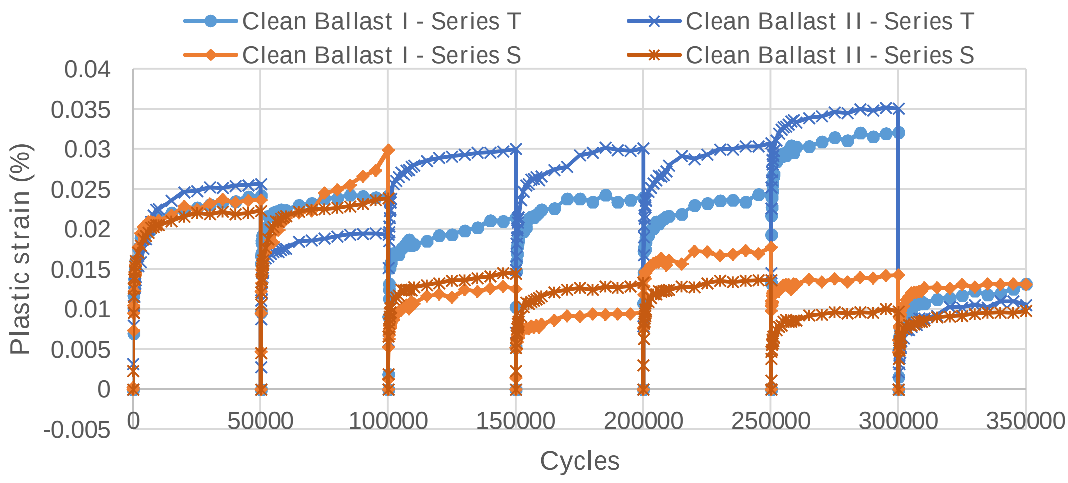

Figure 3.9 – Influence of maintenance operation on the plastic strain for clean Ballast I and II.

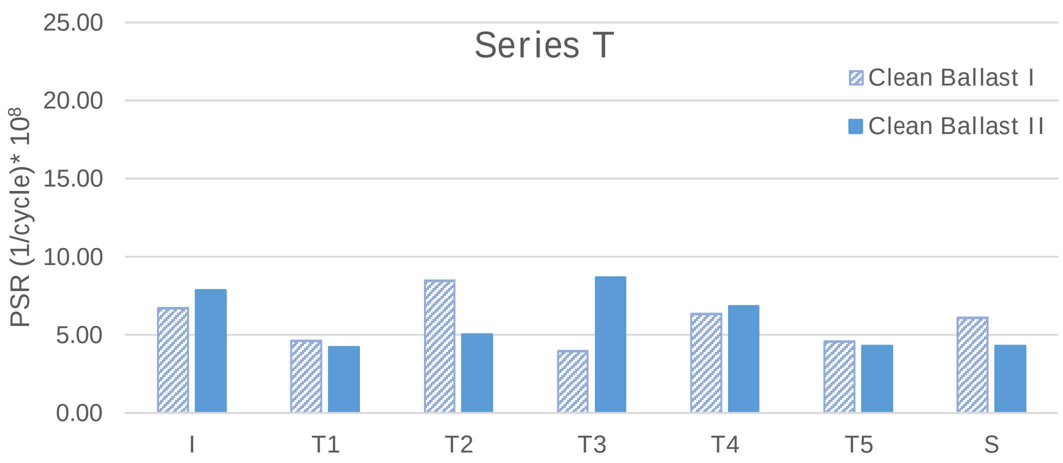

Figure 3.10 – Plastic strain rate (PSR) over Series T for clean Ballast I and II.

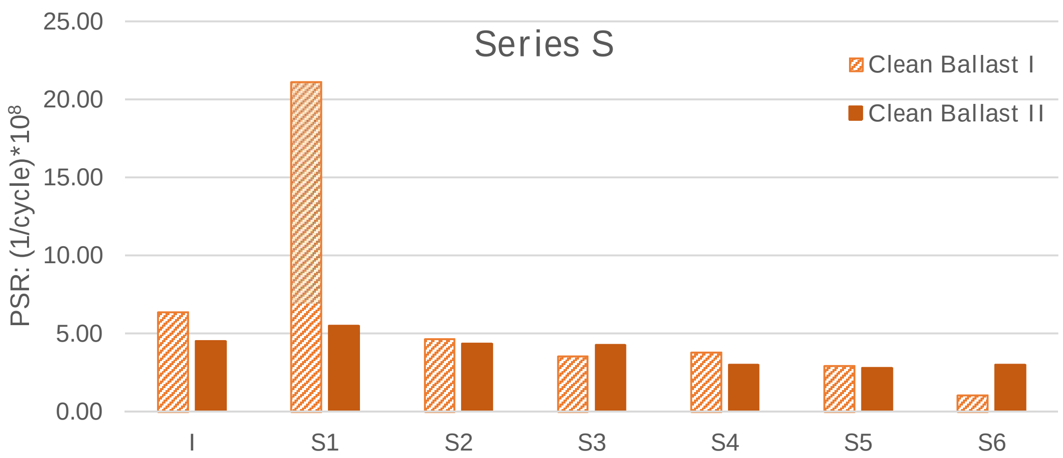

Figure 3.11 – Plastic strain rate (PSR) over Series S for clean Ballast I and II.

The effect of tamping and stoneblowing on ballast resilient properties is shown in Figure 3.12 and Figure 3.13 for series T and S, respectively. It can be observed that there was no clear correlation between tamping application and stiffness or dissipated energy variations. In the case of Ballast I, in fact, after an initial stiffening (from T1 to T3), resilient modulus decreased to its initial value (from T3 to T5). For Ballast II the resilient modulus maintained an approximately constant value over Series T.

On the other hand, a slight increase in ballast layer stiffness and a reduction in its capacity to dissipate energy was observed after each stoneblowing application, confirming the findings of Sol-Sanchez et al. (Sol-Sánchez, Moreno-Navarro, et al. 2016b). This phenomenon, which can accelerate track-bed degradation (Dahlberg 2010), is associated to the progressive compaction of the ballast layer, not disturbed by this type of maintenance.

It has to be observed that Ballast I in series T had higher values of stiffness and lower values of dissipated energy compared to the other series. This fact could have been attributed to the different to slightly different material gradation (and properties) as well as the intrinsic variability in specimen preparation, which in this case could have resulted in a stiffer layer from the beginning of the series.

In this regard, Series S showed that it was not the material source that induced the stiffer behaviour.

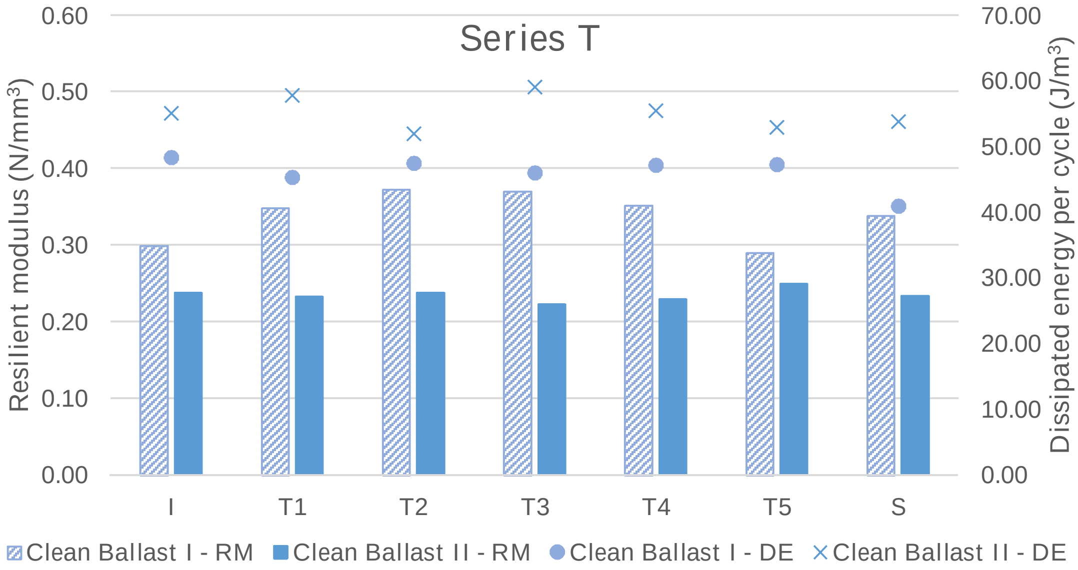

Figure 3.12 – Resilient modulus and dissipated energy average values over Series T for clean Ballast I and II.

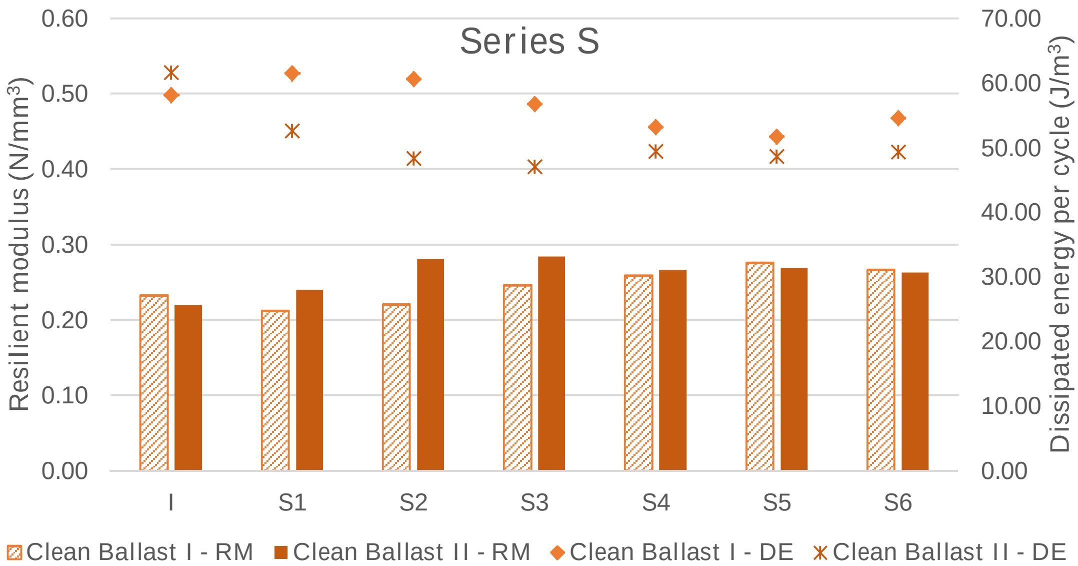

Figure 3.13 – Resilient modulus and dissipated energy average values over Series S for clean Ballast I and II.

3.4.2 Influence of gradation on post-maintenance ballast behaviour

With the aim of evaluating the effect of different levels of ballast degradation (fouling level) on tamping and stoneblowing effectiveness Series T was carried out also for two other gradations of Ballast II. In this stage, only one material source was tested as in the previous stage this factor had a negligible influence on results. In addition, only series T, which includes both tamping and stoneblowing simulations, has been carried out to compare different gradations as the maintenance strategy analysis was already the object of the previous stage.

Figure 3.14 and Figure 3.15 show the evolution of plastic strain and PSR, respectively, for the two levels of fouling considered in relation to clean ballast from the same source (Ballast II). From the initial tests (prior to any maintenance), when the level of compaction under the load repetition was the lowest, it can be observed how increasing the level of fouling led to higher permanent deformation. This result is in agreement with other studies carried out on fouled ballast (Ionescu 2004, Ebrahimi et al. 2015).

However, for both degraded specimens, over the following tests a progressive reduction (lower for higher FI) in plastic strain, took place. This fact is mainly attributed to progressive compaction that, in dry conditions, increased ballast shear strength and thus its resistance to permanent deformation (Lim 2004). In this regard, a study carried out by Indraratna et al. (Indraratna, Khabbaz, Salim, et al. 2004) showed that passing from a very uniform to a moderate gradation can be beneficial in terms of axial strain as well as particle breakage. Nonetheless, fouled specimens exhibited overall higher values of PSR, indicating a worse behaviour in the long-term compared to clean ballast.

As regards the influence of maintenance operations, also in this case it is possible to observe a substantial improvement after stoneblowing. However, it should be noted that for fouled ballast (FI 20%) the final plastic strain was approximately 65% higher than for the other two gradations.

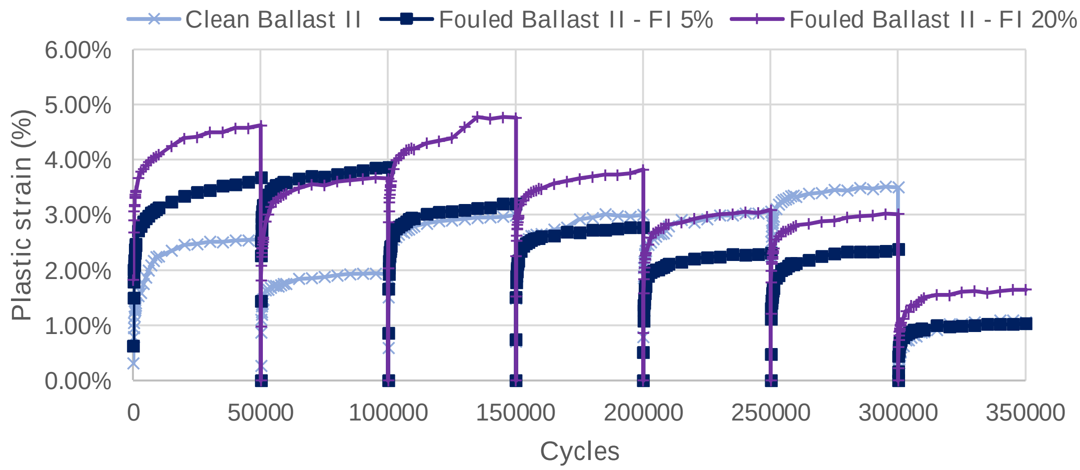

Figure 3.14 – Influence of gradation (fouling level) on the plastic strain over Series T.

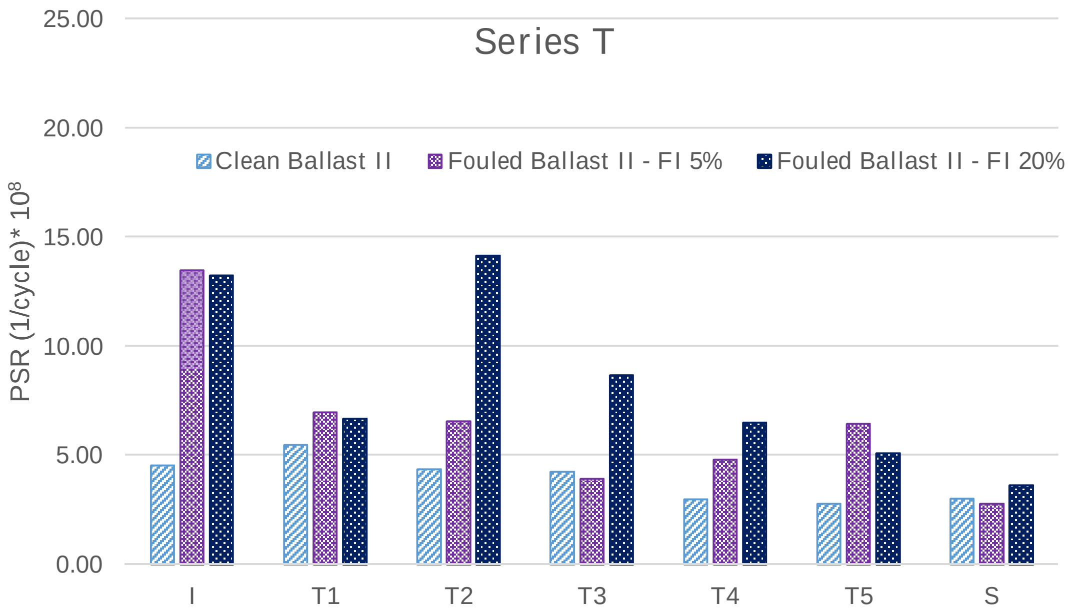

Figure 3.15 – Plastic strain rate (PSR) over Series T for different gradations of Ballast II.

From Figure 3.16 it can be observed that the progressive improvement in the resistance to permanent deformation was associated with a stiffening process and reduced ability to dissipate energy. This process was slightly more marked for the higher level of fouling and, as highlighted previously, under dynamic overloads this could speed-up track-bed degradation.

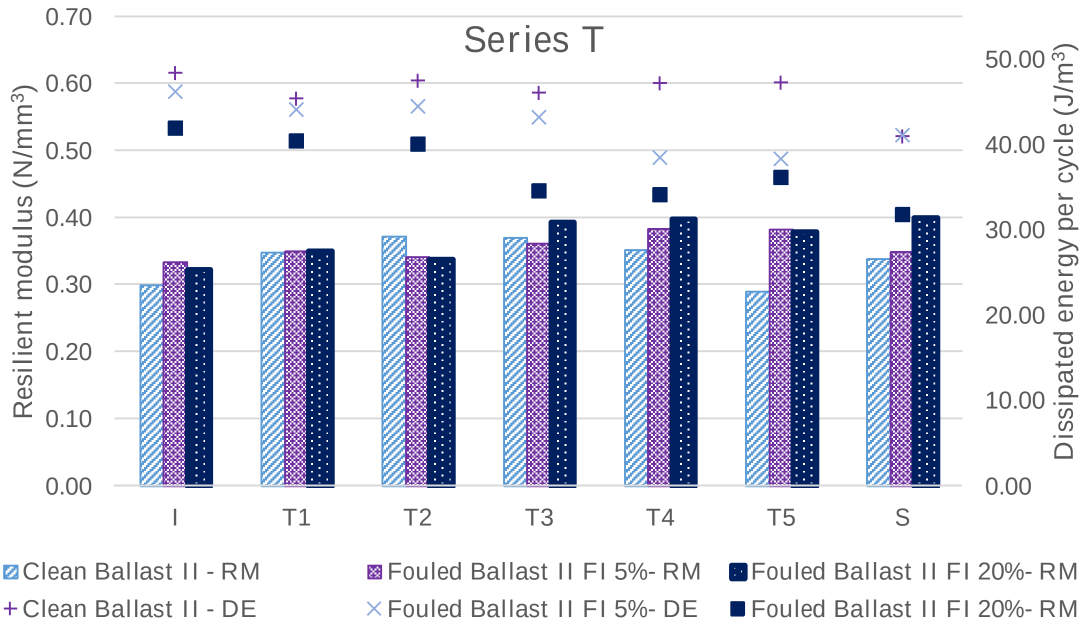

Figure 3.16 – Resilient modulus and dissipated energy average values over Series T for different gradations of Ballast II.

3.5 Concluding remarks

During this first stage of the research a ballast box was used to simulate and compare, in a simplified and controlled manner, the effectiveness of current maintenance operations on ballast resistance to permanent deformation and resilient behaviour. The results obtained led to the following conclusions:

- Tamping is less effective than stoneblowing in terms of plastic strain (higher initial settlement) and also PSR. In addition, the effectiveness of tamping appears to progressively decrease after each intervention.
- In this regard, results indicate that the use of stoneblowing could potentially increase maintenance intervals up to 3 times.
- However, stoneblowing has been found not to be efficient until the ballast has been compacted by traffic. Therefore, maintenance by stoneblowing would be more appropriate after the early stage of ballast service life.
- Furthermore, for both materials and different gradations it was noted that the progressive improvement in the resistance to permanent deformation was also associated with a stiffening process and reduced ability to

dissipate energy, which, in the presence of high dynamic overloads, can accelerate trackbed degradation.

- The tests carried out confirmed that the use of a broader gradation can be beneficial in terms of vertical permanent deformation. However, the excessive fine particle can also reduce the effectiveness of maintenance operations.

From this first part of the research it was concluded that stoneblowing can represent better way to maintain trackbed. Nevertheless, some limitations and issues associated with its use together with its use limited to few countries push research to investigate alternative solutions that can reduce the overall need for maintenance of ballasted track-bed.

Chapter 4 - Potential of bitumen emulsion for ballast stabilisation

In this chapter the viability of using bitumen stabilised ballast (BSB) in order to reduce the need for maintenance associated with ballast settlement and degradation is analysed.

4.1 Introduction

Despite its worldwide spread, traditional ballasted track still presents considerable problems of settlement and particle degradation, which lead to high maintenance costs and low durability. In this regard, in recent years, to mitigate these issues mainly related to the unbound nature of ballast, several solutions have been proposed to reinforce or stabilize aggregate by means of polymers or resins. In this context, the use of bitumen emulsion for ballast stabilisation is proposed in this research study as a relatively economic solution to extend ballast service life.

In this research stage, the feasibility of ballast stabilisation by bitumen emulsion (BE) is evaluated by considering: (i) the influence of dosage, (ii) the influence of curing time, (iii) the influence of stress level, and (iv) the influence of ballast gradation on the effectiveness of the stabilisation method and on BSB mechanical behaviour.

4.2 Materials

4.2.1 Ballast

From the previous section, it was seen that both types of ballast exhibited a similar behaviour. Therefore, in this phase it was decided to continue only with one type of aggregate (Ballast II from Section 3.2). This material was selected because of the higher availability of different particle sizes.

In this part of the study scaled tests and scaled ballast gradation were used. Despite not being completely representative of full scale ballast, the use of scaled ballast for this part of the study offered an attractive and economical means to evaluate the potential of unbound material stabilisation by bitumen emulsion (Ajayi et al. 2014). In this regard, according to Marachi et al. (Marachi et al. 1969) if the ratio between the sample diameter and the maximum particle is larger than 6, the specimen size should not influence the test results.

From the previous stage, two gradations of Ballast II were selected to be scaled down: clean and moderately clean (FI 5%) ballast gradations. Ballast II with 20% FI was excluded because its scaled gradation would have resulted in too many fines for the application of bitumen emulsion.

Therefore, for the specific tests to be carried out, in order to have a maximum particle size smaller than 1/6th the diameter of the sample, both clean and moderately clean ballast were scaled using the parallel gradation method (Sevi 2008). Since the specimen was to be 150 mm deep with a diameter of 150 mm, curves were shifted horizontally in order to have a maximum particle size lower than 25 mm, as shown in Figure 4.1.

According to various fouling index definitions related to the lower limit of standard gradations (Anbazhagan et al. 2012, BS EN 13450:2013 2013) both parallel-graded materials should be considered contaminated (fouled). However, for convenience, in this chapter, the original gradations are named ‘Clean ballast-0’ and ‘Moderately clean ballast-0’ while the corresponding scaled ones are

'Clean ballast' and 'Fouled ballast', respectively. To obtain the scaled gradations, different nominal sizes were combined: 20 mm, 14 mm, 10 mm and 6 mm.

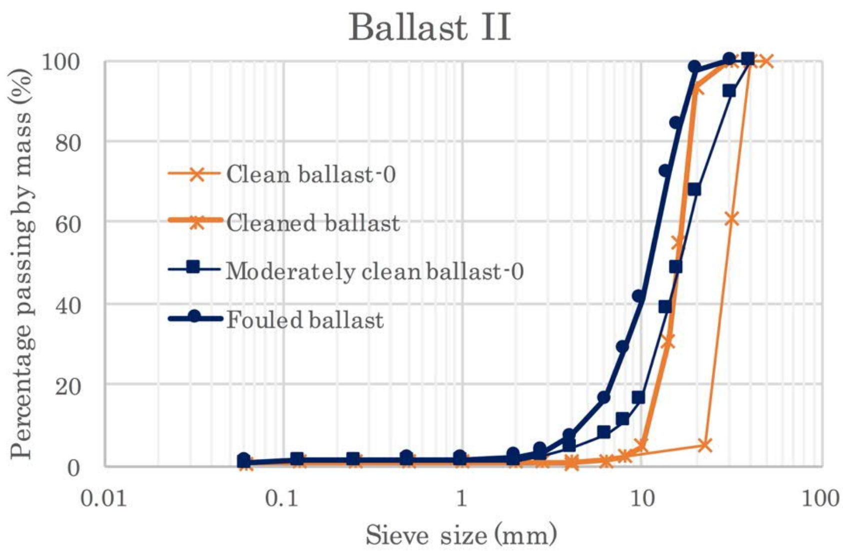

Figure 4.1 – Parallel gradation curves of clean and fouled ballast.

4.2.2 Bitumen emulsion A

The bitumen emulsion used for stabilising the ballast, termed BE (A), was a cationic emulsion with affinity to a wide range of mineral aggregates that promotes adhesion of bitumen to a wide range of aggregate materials (Nassar et al. 2016). This BE is effective for use in all weather conditions (Ojum 2015). The main properties of the emulsion are reported in Table 4.1.

Based on previous studies, an optimum content of 2% by weight of pre-wetting water was used to lubricate the aggregate and activate the surface charges on aggregate particles before the BE was added (Ojum 2015).

Table 4.1 – Main physical and rheological properties of bitumen emulsion A.

Property	Value
Appearance	Black to dark brawn liquid
Breaking Behaviour [s]	> 170
Softening Point [°C]	52
Viscosity - Efflux time 2 mm - 40°C [s]	15-70
Desirable particle surface electric charge	Positive
Bitumen content [%]	60
Penetration [dmm]	47
Density [g/cm³]	1.016

4.2.3 Bitumen Stabilised Ballast (BSB)

To stabilise ballast before testing the following procedure has been used. Once aggregate has been placed and compacted inside a specific mould, the calculated amount of bitumen emulsion was poured uniformly over the ballast at ambient temperature. During this phase, BE started gluing contact point between particles while flowing through the pores within the ballast along the paths of least resistance.

4.3 Methods

With the aim of assessing the feasibility of using bitumen emulsion as a stabiliser agent, the methodology summarised in Table 4.2 has been used.

Table 4.2 – Methodology used to assess BSB viability.

Variables	Material tested	Test	Main parameters
Influence of BE dosage, ballast gradation and field conditions on BSB behaviour			
-Dosage (2%, 3%) -Gradation -Compaction method (M, K) -Stress level (200, 300 kPa)	-Clean ballast -C-BSB (A) -Fouled ballast -F-BSB (A)	-Precision Unbound Material Analyser (PUMA)	-Plastic strain -Resilient modulus -Dissipated energy
Effect of ballast gradation and BE dosage on stabilisation process			
-Dosage (2%, 3%) -Gradation	-C-BSB (A) -F-BSB (A)	-Flowability test	-Quantity of BE lost

4.3.1 The Precision Unbound Material Analyser (PUMA)

In order to assess the feasibility and main factors affecting BSB technology, a relatively simple test (the PUMA) has been used for comparison purposes. This test, similar to both the Springbox (Edwards et al. 2005) and K-Mould tests (Semmelink 1991), was designed to simulate the stress conditions that granular materials experience in pavement and railway substructures by automatically increasing lateral confinement on the sample as the vertical load increases (Thom et al., 2013). Thus, for this stage it was used in order to assess the viability of the proposed technology while analysing the influence of BE dosage, ballast gradation and field conditions on BSB behaviour.

4.3.1.1 PUMA test planning

To investigate the influence of the main variables affecting BSB performance the laboratory plan of this second stage of research was divided into two parts: (i) and (ii).

The first part (i) focused on the analysis of the influence that the percentage of bitumen emulsion used for stabilisation, the ballast gradation and the compaction method have on BSB performance. The type of emulsion (BE A) and the percentages (2% and 3% by weight) were chosen according to typical bitumen stabilised materials used in pavements (Collings et al. 2009, Nassar et al. 2016). Clean ballast and Fouled ballast gradations from Figure 4.1 were used. Since ballast behaviour depends also upon its level of compaction (Fischer et al. 2015), two different methods were used. In the first method (M) samples were compacted by manual vibration of the mould, carried out after each third of material was poured into the mould; in the second method (K) the specimen was compacted by a vibrating hammer (Figure 4.2) through a plate for approximately 60 seconds, until no noticeable movement of particles was observed (Huang et al. 2009).

Figure 4.2 – Vibrating hammer used for compaction.

These two methods were considered to be simulative of the situations where a dynamic track stabiliser (DTS) is used or not used after construction or routine maintenance. Bulk densities achieved using these two compaction methods are reported in Table 4.3.

Table 4.3 – Bulk density achieved after compaction methods used for both clean and fouled ballast.

Clean (M) (kg/m^3)	Clean (K) (kg/m^3)	Fouled (M) (kg/m^3)	Fouled (K) (kg/m^3)
1660.3	1697.7	1949.5	2015.8

For this part of the investigation, Clean BSB (C-BSB) and Fouled BSB (F-BSB) configurations were compared to reference Clean and Fouled ballast.

In the second part (ii) the influence of stress level on BSB performance was assessed by increasing the maximum contact stress applied from 200 kPa to 300 kPa. In this way the effect of higher loads (freight lines) or dynamic overloads due to high-speed trains or rail/wheel imperfections were simulated (Indraratna et al. 2011, Keene et al. 2012). Since the other variables were explored in the previous part, higher load tests were carried out only for Fouled ballast with 3% BE (K).

It was considered interesting to know also the effect of water on ballast in a PUMA test, so unbound specimens have been tested for both dry and wet conditions, ballast in wet condition being considered to be more critical (Selig and Waters 1994).

The PUMA testing plan is summarised in Figure 4.3.

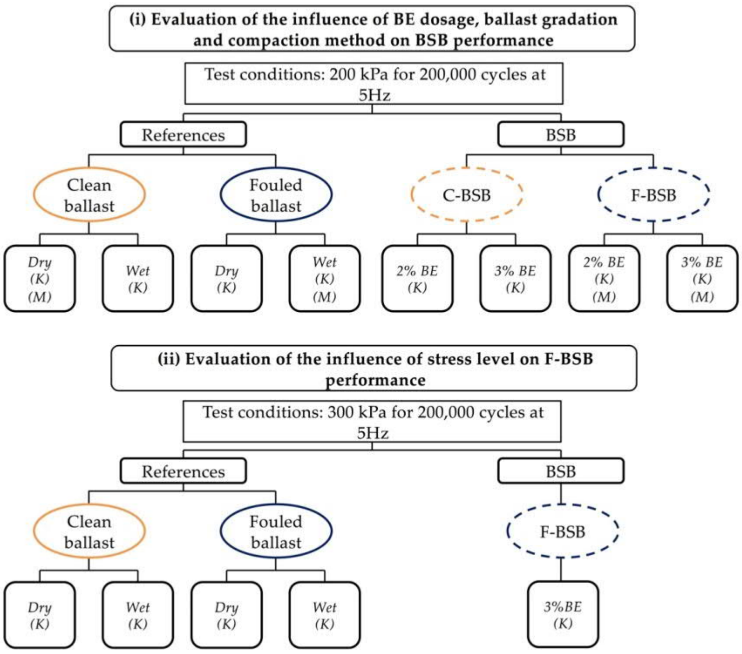

Figure 4.3 – PUMA testing plan.

4.3.1.2 PUMA Equipment

The test apparatus consists of eight steel curved wall segments which form a quasi-cylindrical chamber. Between wall sections steel T-sections run the full height of the cylinder to prevent material from escaping between the wall sections when a load is applied (Winters 2009) (Figure 4.4). Steel walls are confined within a rubber-lined steel band which provides the possibility of wall movement under load, simulating the elasticity of surrounding material in-situ (Thom et al., 2013) (Figure 4.4).

The lateral stress, whose initial value can be set at the beginning of the test, progressively accumulates under the repeated vertical loading (typically between 0 and 50 kPa), again simulating the in-situ condition.

Figure 4.4 – Components of the PUMA frame.

The specimen is compacted inside the mould and then loaded on its top surface by a circular platen. Its inner diameter is 150 mm and the height is 150 mm.

The specimen is loaded using the Nottingham Universal (NU) loading frame, as shown in Figure 4.5, which is a piece of equipment commonly available in UK materials testing laboratories and widely used for the testing of asphalt samples.

Figure 4.5 – PUMA frame and loading apparatus (Thom et al. 2013).

The NU equipment is used to apply the desired repeated loading (measured by a load cell) to the sample and to record vertical and lateral displacements and stresses.

Vertical displacements are measured by means of a pair of Linear Variable Differential Transformers (LVDTs), while a strain gauge on the rubber-lined steel band allows for measurement of lateral strain (Thom et al., 2013). This last measure is directly proportional to the stress in the rubber-lined steel band and therefore to the horizontal stress (σ_h), as in Equation (4.1):

$$\sigma_h = \frac{\varepsilon_b \cdot E_s \cdot t_s \cdot h_b}{r_s \cdot h_s} \tag{4.1}$$

where,

ε_b (m/m) is the measured band strain;

E_s (Pa) is the modulus of the steel (200 GPa);

t_s (mm) is the thickness of the steel (0.28 mm);

h_b (mm) is the height of the band (50 mm);

r_s (mm) is the inner radius of the specimen (75 mm);

h_s (mm) is the height of specimen (150 mm);

Thus, while only vertical stress is controlled, vertical and horizontal stress and strain are all monitored during the test.

4.3.1.3 Test set-up

After sieving operations, ballast samples were poured into the PUMA mould and compacted. In the case of wet tests or before bitumen stabilisation, the aggregate was previously wetted in order to obtain a moisture content (MC) of 2% by weight (Ojum 2015).

Ballast stabilisation of BSB specimens was carried out as described in Section 4.2.3. Following this operation, specimens were cured for 72 h at 40°C, conditions which simulated long-term curing (Ojum 2015).

Figure 4.6 shows the appearance of BSB before and after the emulsion had broken. It can be noted that it appears similar to an open graded asphalt mix, although in this case no mixing was carried out.

Figure 4.6 – Visual appearance of the BSB before and after testing.

Once the set-up of the specimens was concluded they were tested using the NU loading frame at a controlled temperature of 20°C.

The tests were conducted by applying a sinusoidal pulse (Brown 1996) as a 5 Hz haversine, bell-shaped loading pulse with peaks (200 kPa for part (i) and 300 kPa for part (ii) of the study) and rest loads (11.7 kPa) (Ebrahimi et al. 2010) for

200,000 repetitions. This frequency is commonly used in laboratory dynamic tests simulating railway traffic loading (Momoya et al. 2016). A constant initial confining pressure of 10 kPa was applied to all the specimens as representative of the in-situ confining pressure due to self-weight of ballast (Aursudkij et al. 2009). These loading conditions, even if they are not fully simulative of real track, were considered adequate to reach a stable behaviour, according to similar tests carried out for granular materials (Indraratna et al. 2006, Keene et al. 2012, Bach and Veit 2013).

Data were recorded during each cycle for the first 100 repetitions, each 10 cycles from cycle 100 to 1000 and then every 1000 cycles thereafter.

The main parameters analysed were the plastic strain, the resilient modulus and the dissipated energy per cycle.

4.3.2 Flowability test

One of the most important factors influencing the stabilisation process is the viscosity of the BE, since BE should be able to penetrate the aggregates, ‘gluing’ the contact points, but should not drain through the layer. The viscosity should therefore be an optimum to allow penetration to the bottom of the layer while minimising the percentage of material that reaches the interface with underlying materials.

The main variables involved in the stabilisation process are: the bitumen content in the emulsion (the higher the bitumen content the more viscous the BE); the dosage; and the breaking behaviour (Lesueur 2015).

In this regard, a specific test, similar to the determination of penetration power of bituminous emulsion (BS EN 12849, 2009), was set-up to evaluate the ability of the BE to penetrate a specific aggregate mix.

For this purpose, the same ballast gradations (Clean and Fouled) and BE dosages (2% and 3% by weight) as for PUMA tests (Section 4.3.1) were used for the flowability test.

The test apparatus consisted of a transparent tube with an inner diameter of 120 mm and height of 240 mm having in the base a porous metal plate with a pore size of 1 mm, as shown in Figure 4.7. The use of a transparent tube allowed observation of bitumen emulsion flow during material stabilisation.

Figure 4.7 – Flowability test apparatus and specimen set up.

The test consisted of pouring the calculated amount of BE into a cylindrical aggregate volume with a height of 150 mm within 20-30 s at room temperature, approximately 20°C.

The test duration was 1200 s, during which the process was recorded photographically in order follow the flow of BE over the test. The emulsion that drained through the layer was collected at the bottom of the apparatus so that the percentage of material lost could be evaluated.

4.4 Results

4.4.1 PUMA test results

4.4.1.1 Influence of the compaction method and BE dosage on clean and fouled ballast performance

Figure 4.8 and Figure 4.9 report results obtained from the PUMA test in terms of final plastic strain and plastic strain rate, calculated as in section 3.3, for Clean and Fouled ballast, respectively.

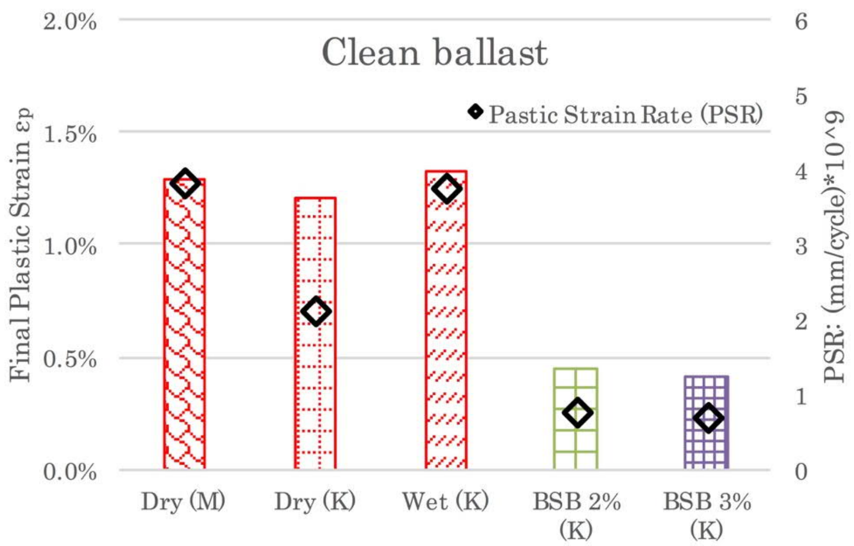

Figure 4.8 – Final plastic strain and PSR for clean ballast (reference material) and C-BSB specimens.

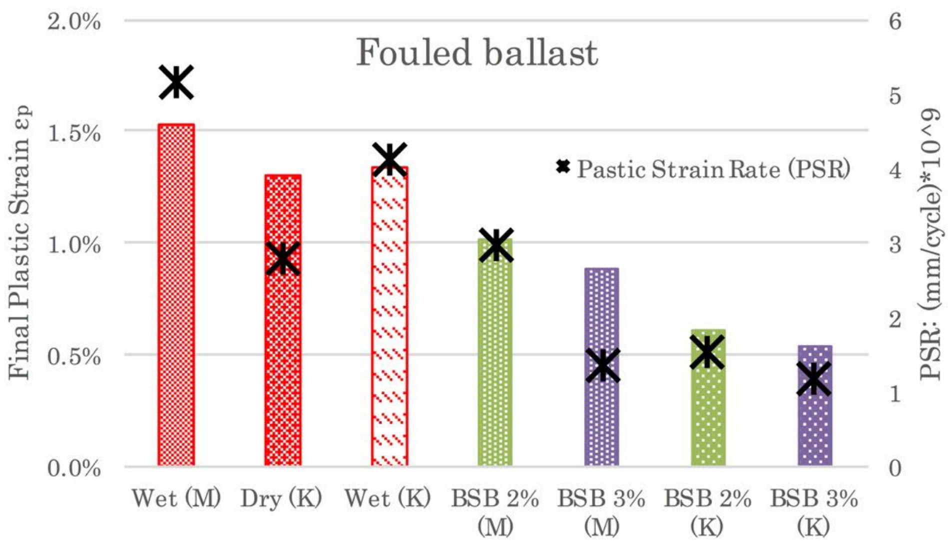

Figure 4.9 – Final plastic strain and PSR for fouled ballast (reference material) and F-BSB specimens.

It can be observed that overall stabilised specimens presented lower plastic deformations and deformation rates (long-term projections) than reference materials. This confirmed that this stabilisation technique could represent a possible solution to reduce maintenance frequency due to geometry degradation of ballasted track-bed.

Comparing both plots, the influence of gradation on plastic deformations can be highlighted. In particular, stabilised and unbound fouled specimens exhibited overall a lower resistance to permanent deformation than their clean counterparts. These results confirm the important role of gradation (or fouling level) on the material’s resistance to permanent deformation (Ionescu 2004, Keene et al. 2012, Ebrahimi et al. 2015). Nonetheless, it is worth noting that both parallel-graded materials used in this phase should be considered degraded (fouled) with respect to clean field ballast, as discussed in Section 4.2.

In this context, as shown by other studies (Indraratna et al. 2011, Momoya et al. 2016), depending on fouling level and type of material, the presence of water can have an important influence on ballast settlement. In this regard, the additional tests carried out in this phase indicated that, for these gradations, a small increase in moisture content produced a small increase in plastic strain.

From Figure 4.8 and Figure 4.9 it is also possible to evaluate the influence of the compaction method on vertical plastic deformation. All specimens compacted by Kango hammer (K) resisted permanent deformation better, confirming the importance of this factor on in-track behaviour (Fischer et al. 2015). Nonetheless, this difference was greater for fouled ballast than clean ballast, which ties in with the findings of Thom and Brown (Thom and Brown 1988) in relation to shear strength of materials with different uniformity coefficients. The underlying reason may be that single-sized materials require less compaction effort to achieve their maximum density.

The influence of dosage on permanent deformation was also non-negligible. In this sense, for all fouled BSB specimens increasing from 2% to 3% BE gave a decrease in both permanent deformation and deformation rate. This effect was less evident in the case of clean BSB and this 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.

From data recorded during the test the resilient modulus and dissipated energy per cycle have also been calculated as described in Section 3.3.

Figure 4.10 shows the evolution of resilient modulus over the dynamic test for two configurations (bound and unbound) of clean ballast in order to highlight their different behaviours over the test. Figure 4.11 and Figure 4.12 synthesise results in terms of both resilient modulus and dissipated energy, as average values over the last 40,000 cycles, when the behaviour was more stable, for clean and fouled ballast, respectively.

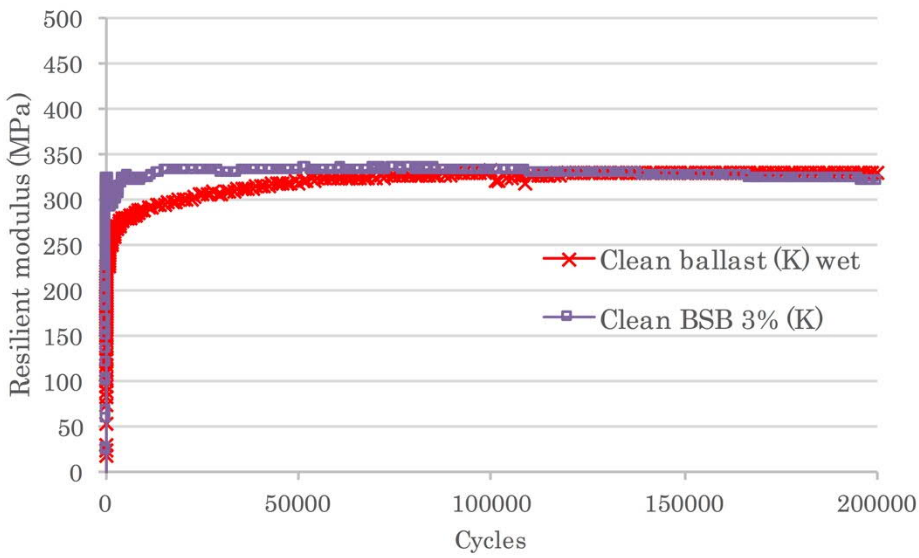

Figure 4.10 – Resilient modulus over the cyclic compression testing for two representative cases of clean ballast.

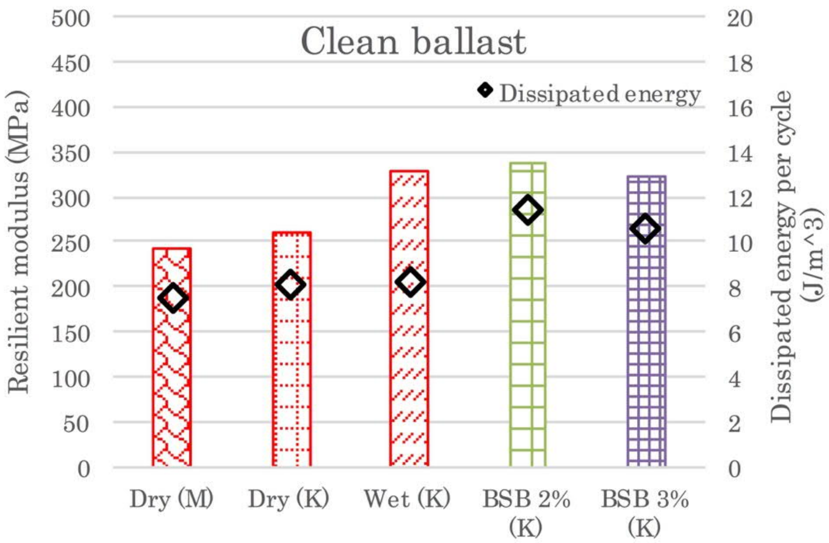

Figure 4.11 – Average resilient modulus over the cyclic compression testing and dissipated energy per cycle for clean ballast.

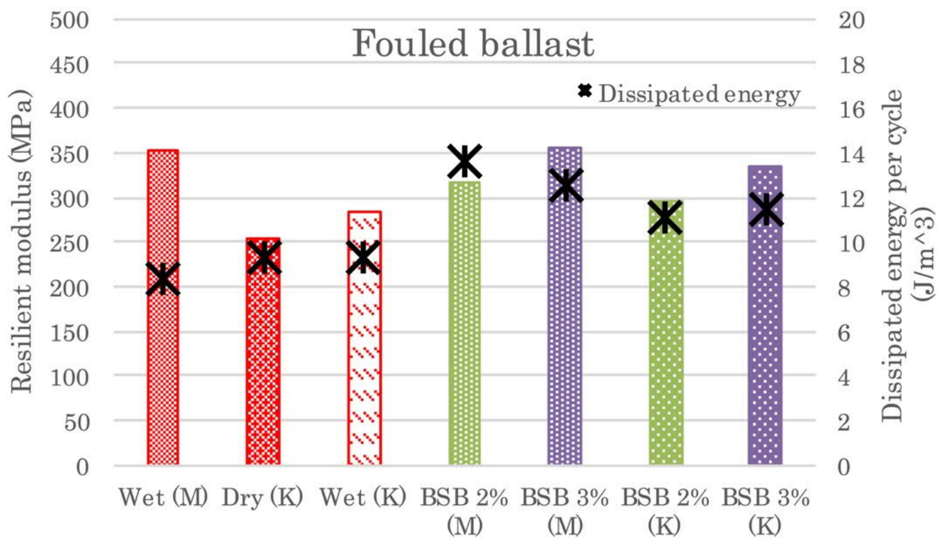

Figure 4.12 – Average resilient modulus over the cyclic compression testing and dissipated energy per cycle for fouled ballast.

From Figure 4.10 it can be observed that the unbound ballast, after the first 10,000 cycles characterized by plastic hardening, exhibited slightly but steadily increasing values of resilient modulus, as can be expected from granular materials (Lim 2004). On the other hand, BSB resilient modulus, after a first stage during which it was approximately constant, started to decrease slightly. This BSB behaviour mirrors closely the fatigue experienced in cyclic tests by bituminous materials.

From Figure 4.11 and Figure 4.12 it can be noted that overall, for this specific test and these conditions, the stabilisation process corresponded to an increase in resilient modulus. However, no clear correlation could be established between bitumen emulsion dosage and stiffness: in the case of fouled ballast, BSB specimens with 3% BE had slightly higher stiffness values than those with 2%, regardless of the compaction method. A different behaviour was observed for clean ballast. Clean BSB specimens exhibited a higher stiffness with lower dosage - a result probably associated again with the maximum quantity of bitumen emulsion that could be retained within a nearly single-sized material.

At the same time, bitumen stabilisation also provided an important increase in energy dissipation. This increase was approximately 35% and 40% with respect to the fouled and clean ballast reference materials, respectively. In this regard, the viscoelastic behaviour of bitumen added to the material very desirable hysteretic damping properties, which, unlike with the use of elastic elements, are not associated with a decrease in the global stiffness (Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2015, Sol-Sánchez, Thom, Moreno-Navarro, Rubio-Gámez, et al. 2015, Sol-Sánchez, Moreno-Navarro, et al. 2016a). This is to be expected since the presence of bitumen induces energy loss due to viscous effects, in addition to the frictional energy losses taking place due to inter-particle slip within ballast (Su 2005, Goncu 2012).

This ability of bitumen stabilisation to vary the mechanical behaviour of track-bed could be useful to improve track durability and performance. In this regard, as mentioned before, low levels of stiffness could increase flexural deformation and consequently the bending moment of the rail (and thus its stresses) as well as trackbed settlement (Goncu 2012, Sol-Sánchez, Thom, Moreno-Navarro, Rubio-Gámez, et al. 2015, Sol-Sánchez, Pirozzolo, et al. 2016). On the other hand, increasing the stiffness can lead to higher dynamic forces transmitted by trains that, if not adequately damped, necessarily leading to the deterioration of all components of the track (Lopez Pita et al. 2004, López-Pita 2010). In this regard, increasing the energy dissipation could be appropriate for damping dynamic overloads, reducing trackbed and ground vibrations and therefore maintenance costs (Su 2005). Nonetheless, it has also to be considered that excessively flexible tracks (high deflection values) can lead to substantial increases in rolling resistance and thus service costs (Lopez Pita et al. 2004).

4.4.1.2 Influence of stress level on BSB behaviour

Figure 4.13 shows results obtained from PUMA tests carried out under higher stress level (300 kPa) in terms of plastic strain and PSR (long-term behaviour). As could be expected, all specimens tested exhibited higher permanent deformation than those obtained for 200 kPa. Deformational behaviour reflected that observed in the previous tests, as, for the same test conditions, fouled specimens presented higher plastic strains and PSRs than clean ones.

As for the previous stress level, the addition of water reduced resistance to permanent deformation in terms of final plastic strain (especially for fouled ballast) and, in particular, in terms of PSR (values more than double than those of dry tests).

Also for this stress level, bitumen stabilisation improved the resistance to permanent deformation (approximately 50% reduction in final plastic strain). These results are in line with those obtained by other stabilisation techniques (Woodward et al. 2007, Kennedy et al. 2009, Keene et al. 2012).

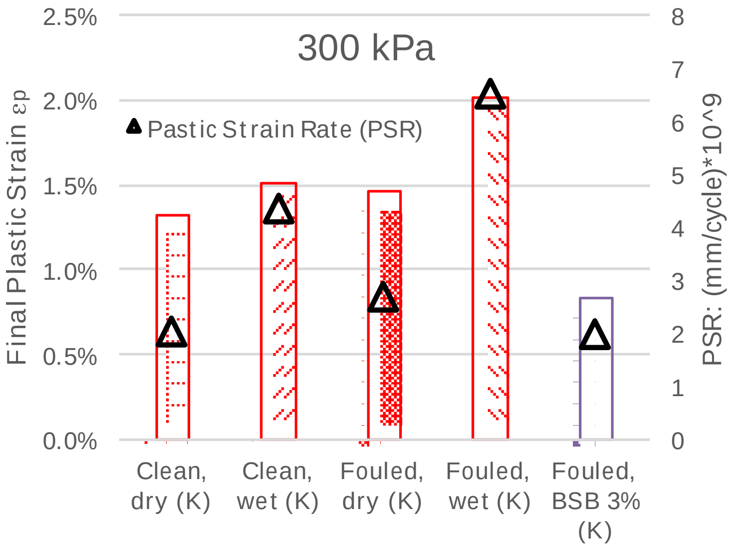

Figure 4.13 – Final plastic strain and PSR under high stress level (300 kPa).

Figure 4.14 reports the values of resilient modulus and energy dissipation of specimens tested under high stress level. Also for these test conditions bitumen stabilisation had a stiffening effect on ballast, approximately the same increase (20%) as for the previous level of stress. It is worth noting the non-linearity in the behaviour of both unbound and stabilised ballast, which is in agreement with results obtained by other studies on granular and stabilised materials (Aursudkij 2007, Keene et al. 2012). Indeed, it can be observed that values of resilient modulus obtained at 300 kPa are higher than those obtained at lower stress, all other conditions being the same.

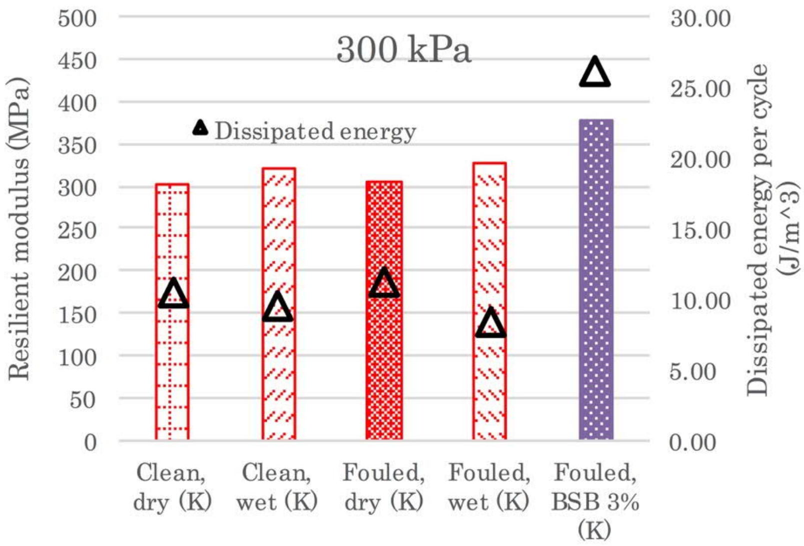

Figure 4.14 – Average resilient modulus and dissipated energy per cycle under high stress level (300 kPa).

Regarding energy dissipation, a major variation was observed. If, under an ordinary stress level, BSB showed the potential to dissipate approximately 40% more energy than the reference material, when the level of stress was increased this value grew to 150%. In this regard, the increase in dissipated energy per cycle is due to the viscoelastic behaviour provided by the bitumen addition rather than a more flexible behaviour (which would lead to higher operational costs), as can be observed from Figure 4.15. In this sense, BSB can be considered potentially more effective for severe conditions of loading.

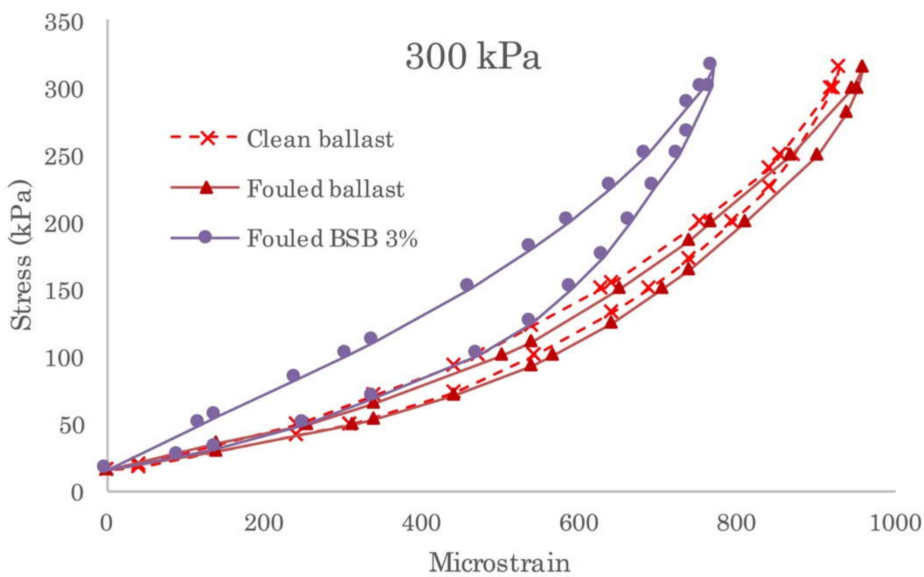

Figure 4.15 – Stress-strain hysteretic loops for different specimens at high stress level (300 kPa).

This result correlates well with results obtained by Sol-Sanchez et al. (Sol-Sánchez, Pirozzolo, et al. 2016), who compared mechanical behaviour of track-bed sections with granular or bituminous sub-ballast.

It is worth mentioning that overall values of plastic strains and resilient modulus obtained from this test are in line with those obtained in other studies on ballast behaviour using triaxial tests (Keene et al. 2012, Merheb et al. 2014). This indicates that the PUMA test can be considered as an alternative to conventional laboratory tests to simulate ballast behaviour under cyclic loading.

4.4.2 Flowability test results

Results of previous tests carried out during this phase showed that no clear correlation could be established between BE dosage and any parameter evaluated (stiffness and energy dissipation), especially for the clean ballast gradation. In addition, during the stabilisation process it was observed that a sizeable part of the BE drained through the specimen. In this regard, in order to quantify the amount of material lost during the stabilisation process, this specific test was set up.

Results obtained for clean and fouled ballast (with BE A) are shown in Figure 4.16.

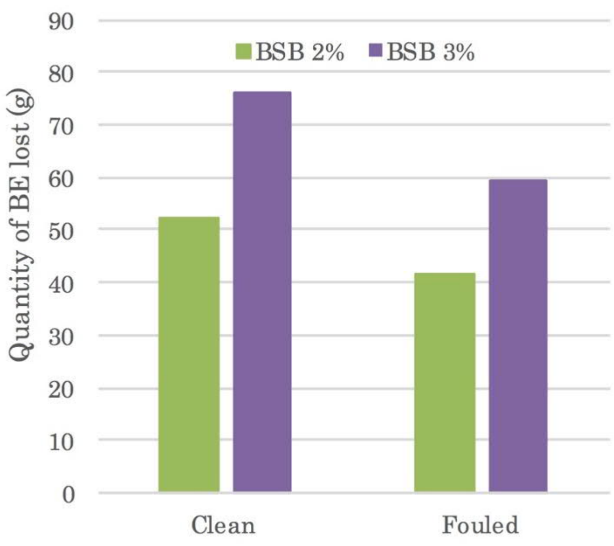

Figure 4.16 – Flowability test results for emulsion A.

It can be noted that a significant amount of BE was lost (more than 40% of that poured) for all configurations. In this regard, an important step to further develop this technology was the optimisation of BE properties in order to avoid this type of inefficiency.

As expected, a higher amount of BE was lost for more uniform gradation (clean ballast). Thus, depending on the BE used, an optimum dosage should be selected to minimise the material lost while maximising the improvement in performance of the stabilised volume.

4.5 Conclusions

This part of the research focused on establishing the potential of using bitumen emulsion, poured at ambient temperature onto a ballast layer, as a stabilisation method for clean and fouled ballast. This technology aims to improve ballast resistance to permanent deformation through a relatively economic and easy to apply method.

This procedure was simulated at model-scale in the laboratory using a practical test suited to both unbound and stabilised materials (PUMA), investigating its feasibility and the major factors affecting its effectiveness. At the same time, flowability tests were carried out to evaluate the efficiency of the stabilisation process itself for the materials used in this preliminary analysis.

The results obtained led to the following conclusions:

- At ordinary stress levels, the use of bitumen emulsion as a stabilisation agent led to a significant decrease in ballast permanent deformation and deformation rate, greater when the dosage was increased. This suggested a good potential for this technology to improve both the short-term and the long-term in-field ballast deformational behaviour to reduce maintenance frequency.
- A non-negligible influence on results was given by the compaction method used: in particular, results indicated better and more stable behaviour when compaction by vibrating hammer was used. Therefore, for higher stress levels and for the optimisation method described in the next chapter only this compaction method was used.
- BSB specimens exhibited a relatively small increase in stiffness, which, in the case of fouled ballast, was related to the amount of BE poured (the higher the stiffer). Clean BSB specimens, however, exhibited a higher stiffness with lower dosage. These results were associated with fact that the maximum quantity of bitumen emulsion that could be retained within a nearly single-sized material had already been reached. This aspect will be further investigated in the next chapter.
- Tests carried out on BSB specimens 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 potentially affect rolling resistance) but to the changed mechanical behaviour of BSB. BSB viscoelastic properties could be highly desirable to dampen dynamic overloads.

- Overall, by modifying both the stiffness and damping characteristics of the ballast layer, BSB can effectively reduce deterioration and associated maintenance costs.
- Nonetheless, despite the improvement to performance, a high inefficiency was observed when using this BE in the stabilisation process (shown by the flowability test). Thus, the next stage focuses on the optimisation of bitumen emulsion properties for ballast stabilisation.

Chapter 5 - BSB: bitumen emulsion properties optimisation

The second stage of the technology development focused on the optimisation of bitumen emulsion characteristics to effectively stabilise ballast. This chapter describes the optimisation method followed and the laboratory programme carried out to achieve this.

5.1 Introduction

The previous stage showed the potential for bitumen stabilisation to improve ballast resistance to permanent deformation and modify its mechanical behaviour. However, properties of bitumen emulsion A in terms of solid content and breaking behaviour, caused a significant part of the material to be lost by drainage. Therefore, this part of the research was aimed to further develop bitumen stabilisation by optimising bitumen emulsion characteristics in relation to bitumen type, proportion, breaking behaviour and dosage, in terms of their influence on flowability through the ballast layer and on BSB performance (for both clean and fouled ballast).

For this purpose, the same configurations tested in the previous stage have been used with different types of bitumen emulsion. In this regard, the philosophy of all model-scale testing on bitumen stabilised ballast was on the one hand to investigate the viability of this technology and on the other hand to analyse the various parameters affecting BSB performance as well as the stabilisation process itself.

The following sections describe the materials used, the method adopted to optimise the technology and results of laboratory tests.

5.2 Materials

5.2.1 Ballast

In order to compare results obtained at this stage with previous ones, the ballast used was the same as in Chapter 4. Due to the dimensions of the test apparatus, the same scaled (approximately one third of standard EN 13450 G_C RB A ballast, in case of clean ballast) gradations were used.

5.2.2 Bitumen emulsions

As stated previously, several variables are involved in the stabilisation process and BSB behaviour. Among others the most relevant are the solid content in the emulsion, the dosage, and the breaking behaviour (Lesueur 2015).

Therefore, for this part of the study, two more bitumen emulsions (B and C) were selected to be compared with previous (A) (Table 5.1). Since this is a new application for bitumen emulsion a wide range of possibilities, in terms of BE characteristics, was explored: different viscosities (depending on solid content); use of neat or modified bitumen; different breaking behaviour; and different types of bitumen.

Bitumen emulsions B and C, both of which were polymer modified, were selected for their quick breaking, high viscosity and suitability for this new application (Lesueur 2015). All of them are cationic emulsions with affinity to a wide range of mineral aggregates and promote adhesion of bitumen to ballast particles.

Table 5.1 - Physical and rheological properties of bitumen emulsions (B and C) used.

Property	Standard	A (previous stage)	B	C
Particle surface electric charge	-	Positive	Positive	Positive
Binder content (%)	EN 1428 or EN 1431	60	67	70
Breaking behaviour (s)	EN 13075-1	> 170	< 110	< 110
Bitumen type	-	Neat	Styrene-Butadiene-Styrene polymer modified	Styrene-Butadiene-Styrene polymer modified
Penetration (dmm)	EN 1426	47	160-220	45
Softening point (°C)	EN 1427	52	40	70

5.3 Methods

5.3.1 Test planning

As stated in previous sections, bitumen emulsion dosage and properties, as well as the aggregate gradation used, can affect the stabilisation efficiency and could also influence BSB mechanical behaviour. Thus, with the aim of evaluating the influence of such variables on the application method and on the main parameters affecting in-field ballast performance, flowability and PUMA tests have been carried out for more BSB configurations (using B and C bitumen emulsions). These configurations are then compared with those of first stage, as summarised in Table 5.2.

Table 5.2 – Testing plan of second stage.

Variables	Material tested	Properties tested	Test	Main parameters
-Dosage -BE Viscosity -BE breaking behaviour -Ballast gradation	-Clean BSB (A) -Clean BSB (B) -Clean BSB (C) -Fouled BSB (A) -Fouled BSB (B) -Fouled BSB (C)	-Flowability of BE	-Flowability test	-Penetration time Quantity of BE lost Flowability Index
-Dosage -Bitumen type -Ballast gradation	-Clean ballast -Clean BSB (A) -Clean BSB (B) -Clean BSB (C) -Fouled ballast -Fouled BSB (A) -Fouled BSB (B) -Fouled BSB (C)	-BSB mechanical behaviour	-Confined compression test (PUMA)	-Plastic strain -Plastic strain rate -Resilient Modulus -Dissipated Energy per cycle

The flowability test, necessary to evaluate the quantity of BE effectively stabilising the ballast specimen, was carried out under the same conditions as in Section 4.3.2, but with the bitumen emulsions B and C.

In order to assess efficiency of the different configurations analysed, two key parameters were measured: (i) the penetration time, i.e. the time for the emulsion to completely penetrate into the aggregates, expressed in seconds; and (ii) the % BE lost, i.e. the percentage of emulsion that had drained through the ballast by the end of the test.

These parameters were combined to calculate a flowability index, necessary for the optimisation method used (see Section 5.3.2), as in Equation (5.1):

$$flowability\ Index = (100 - \%BE\ lost) \cdot (test\ duration - penetration\ time) \tag{5.1}$$

This index increases as %BE lost and penetration time decrease, giving information about the ability of the BE to quickly penetrate the aggregate layer and to start breaking.

To evaluate the mechanical behaviour of the new BSB configurations, the PUMA test has been used. Test conditions were the same as those described in Section

4.3.1.3: cyclic compression as a 5Hz haversine, bell-shaped loading pulse with peaks (200 kPa) and rest loads (11.7 kPa) for 200,000 cycles. The only change was that vibrating hammer compaction (K) has been used because it provided a more stable behaviour while the influence of compaction method has already been investigated in Chapter 4.

From this test, plastic strain, resilient modulus and energy dissipation were evaluated.

5.3.2 Optimisation method

In order to assess and compare different BSB configurations many responses associated with measured parameters need to be taken into account. A method that allows these different properties to be optimised across the different configurations analysed had to be established at this stage. For this purpose an optimisation method was used that introduces desirability functions (DFs) that transform the parameters into desirability in the range (0-1), where 0 values are unacceptable and 1 means the most desirable properties (Chomicz-kowalska and Maciejewski 2015). Two types of DF were proposed by Derringer & Suich (Derringer and Suich 1980): the first type defines a range of acceptability, using lower and upper limits and a target value; the second type is defined using only the lower and upper limits. Four parameters were considered for this optimisation method: (i) flowability index; (ii) plastic strain; (iii) resilient modulus; and (iv) dissipated energy.

A range of acceptable values, given by lower and upper limits, or a single boundary value that should not be exceeded, were specified. These limits were established according to information obtained from other studies referred to below. It is acknowledged that much further work is required before these limits can be considered robust, but they illustrate the use of the optimisation technique. Flowability index ranged from 0 to 1200 (the total test duration expressed in seconds). Plastic strain ranged from 0% to 3.2% (limit for maintenance according to Federal Railroad Administration) (Keene et al. 2012). For the resilient modulus, the optimum value was 375 MPa while lower and upper limits were 62.5 MPa and 625 MPa related to very soft and very stiff layers, respectively (Sussmann et al. 2001, Lopez Pita et al. 2004, Hunt and Wood 2005). Finally dissipated energy ranged from 0 J/m^3 to 20J/m^3 (Su 2005, Ferreira and Teixeira 2011, Jung et al. 2014). Almost all these limits and optimum values are related to particular field studies and are here correlated to responses obtained from specific laboratory tests. Thus, caution should be exercised in interpreting these limits too literally. The purpose of using them is to support the optimisation of the variables considered here.

The desirability functions used in this phase are presented in Figure 5.1.

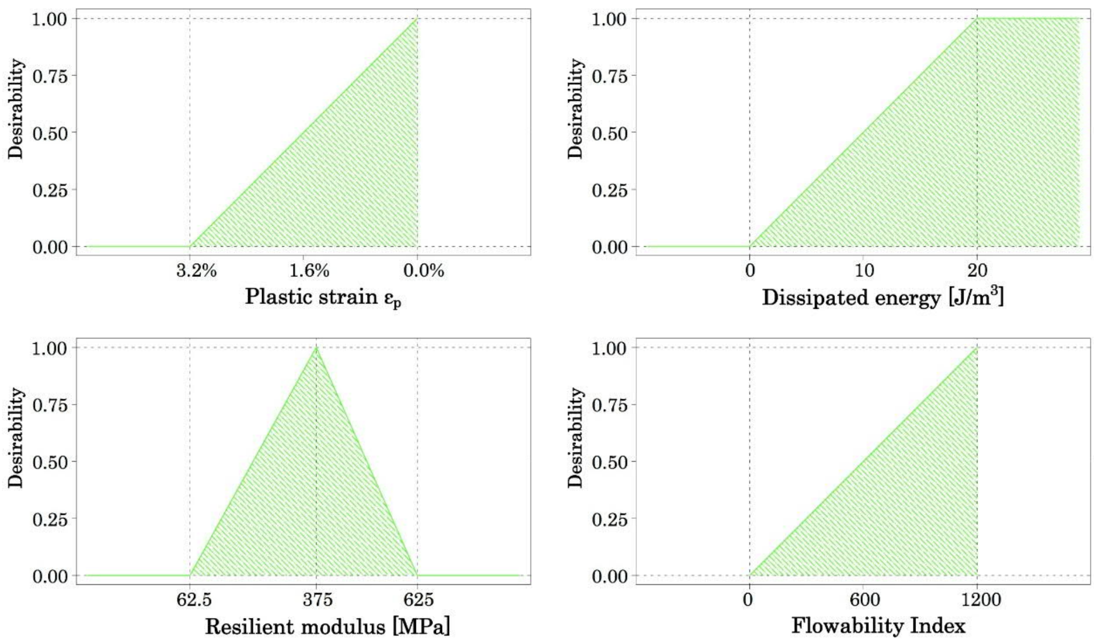

Figure 5.1 – Derringer's desirability functions for the selected BSB properties.

5.4 Results and discussion

5.4.1 Influence of gradation and BE on flowability

Table 5.3 shows results of the flowability tests, indicating penetration time, quantity and percentage of BE lost, and flowability index as determined by Equation (5.1).

Table 5.3 - Flowability test results.

Gradation	Clean						Fouled					
BE	A		B		C		A		B		C	
Dosage	2%	3%	2%	3%	2%	3%	2%	3%	2%	3%	2%	3%
Penetration time (sec)	16	15	180	134	55	77	52	22	210	98	155	135
BE lost (g)	52.4	76.3	2.5	20.3	2	2.7	41	59.6	1	10.6	0.5	0.8
BE lost (%)	81.9	79.5	3.9	21.1	3.1	2.8	64.7	62.0	1.6	11.0	0.8	0.8
Flowability index	215	243	980	841	1109	1092	406	447	975	981	1037	1056

It can be observed that viscosity and breaking behaviour played the most important roles: passing from low binder content (60%) and slow setting (A) to high binder content (70%) and fast setting (C) (with an intermediate situation for B) the percentage of material lost dropped drastically.

As discussed in Section 4.4.2, gradation also had an important influence on the final amount of BE lost for emulsions B and C: in the case of fouled ballast gradation there was a 20-75% (depending on the BE) reduction in material lost with respect to clean specimens.

Depending on the gradation and the BE used, also the dosage can significantly influence the percentage of BE retained from the specimen. This can be observed especially for BE B where an increase from 2% to 3% BE led to an approximately tenfold increase in material lost. In this regard, it can be asserted that in case of BE A the maximum amount of BE that could be retained by the ballast specimen was lower than 2%, whereas in case of BE C, because of its viscosity and breaking behaviour, BE was mostly kept by the aggregate even when increasing its dosage.

Results show that, among the configurations analysed, BE C had the best scores in terms of flowability index.

It is worth noting that all these variables are related to each other. Depending on the gradation (field ballast degradation level) an optimum type of BE (in terms of viscosity and breaking behaviour) and dosage can be used to achieve the desired penetration depth. At the same time, it is important to observe that this analysis focused on minimising the amount of BE lost, since it represents a waste, not working as stabiliser. However, depending on gradation and BE, a higher dosage could improve BSB performance while having a relatively low increase on BE lost (as shown in the next Section).

Thus, for each combination BE/gradation an acceptable level of efficiency (considering both BE lost and the performance of BSB) could be established by extending these types of test (flowability and PUMA) to a wider range of configurations.

5.4.2 Influence of BE properties on ballast behaviour

Figure 5.2 and Figure 5.3 show the plastic strain after 200,000 repetitions in the PUMA test for the new BSB configurations in comparison with BSB A and reference clean and fouled ballast.

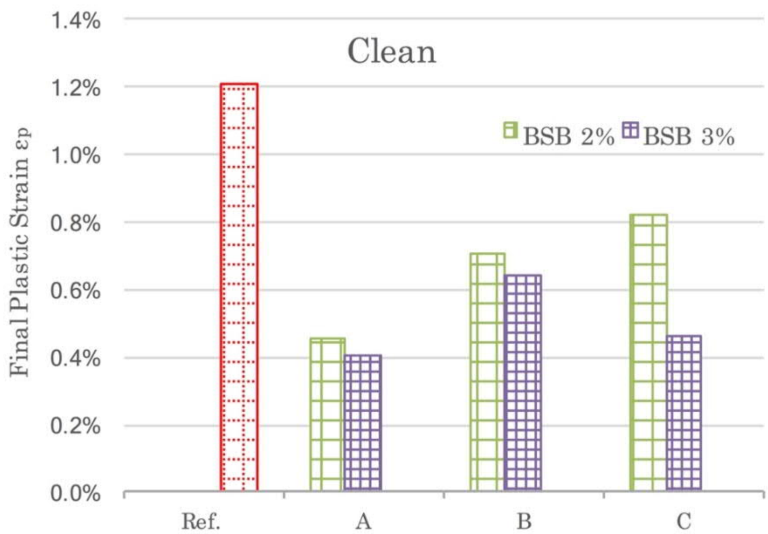

Figure 5.2 – Final plastic strain after 200,000 repetitions in the PUMA test for clean ballast.

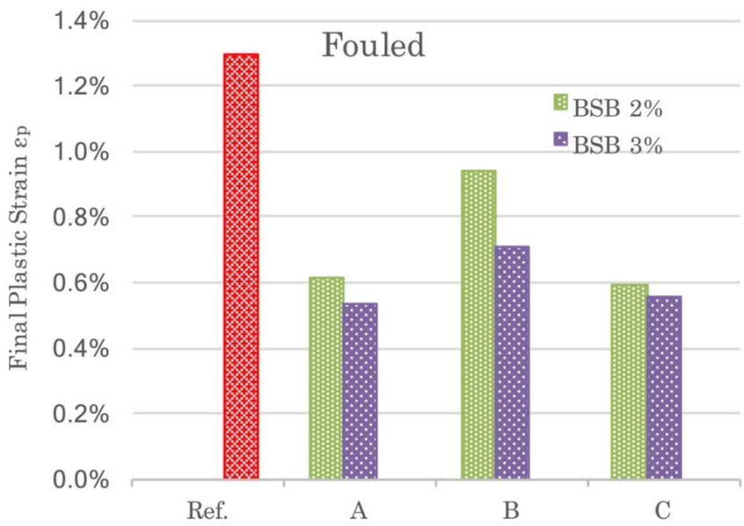

Figure 5.3 – Final plastic strain after 200,000 repetitions in the PUMA test for fouled ballast.

In agreement with results previously obtained for BE A, Figure 5.2 and Figure 5.3 indicate an overall improvement in resistance to permanent deformation for stabilised specimens compared to the unbound reference materials. The same trend was observed with regard to the influence of gradation: in almost every case clean ballast specimens exhibited a lower plastic strain than their fouled counterparts, results in agreement with Keene et al. (Keene et al. 2012). In addition, the influence of dosage of BE agrees with previous results: increasing % BE (and thus the volume of ballast stabilised) led to a lower final plastic strain.

Apart from supporting previous findings, these tests allowed evaluation of the effect of different types of BE on BSB performance. In this regard, it can be observed that the type of bitumen plays an important role: almost all BSB specimens with harder bitumen (A and C) exhibited lower plastic strain than those with softer bitumen (B).

With the aim of analysing the influence of BE on long-term ballast behaviour, Table 5.4 shows plastic strain rate (PSR) values calculated as in Section 3.3. It can be noted that, for both gradations, stabilised specimens had lower values of PSR than the reference materials. Also for this parameter gradation had an important influence - PSR values for clean ballast being lower than those for fouled ballast. This indicates that bitumen stabilisation effectiveness could decrease with increasing levels of ballast degradation.

Nonetheless, overall results obtained in terms of plastic strain and PSR confirm the potential of this technology to improve track-bed resistance to geometry degradation and consequently increase the intervals between maintenance operations for geometry corrections.

Table 5.4 - Influence of BE stabilisation on long-term behaviour (PSR) of clean and fouled ballast.

PSR: (mm/cycle)*10^9													
Clean							Fouled						
	A		B		C			A		B		C	
Ref.	BSB 2%	BSB 3%	BSB 2%	BSB 3%	BSB 2%	BSB 3%	Ref.	BSB 2%	BSB 3%	BSB 2%	BSB 3%	BSB 2%	BSB 3%
2.12	0.75	0.70	1.20	1.43	0.94	1.81	3.79	1.53	1.16	1.99	1.63	1.12	2.67

Figure 5.4 and Figure 5.5 illustrate PUMA results in terms of resilient modulus and dissipated energy per cycle, calculated as in Section 3.3, for clean and fouled ballast, respectively.

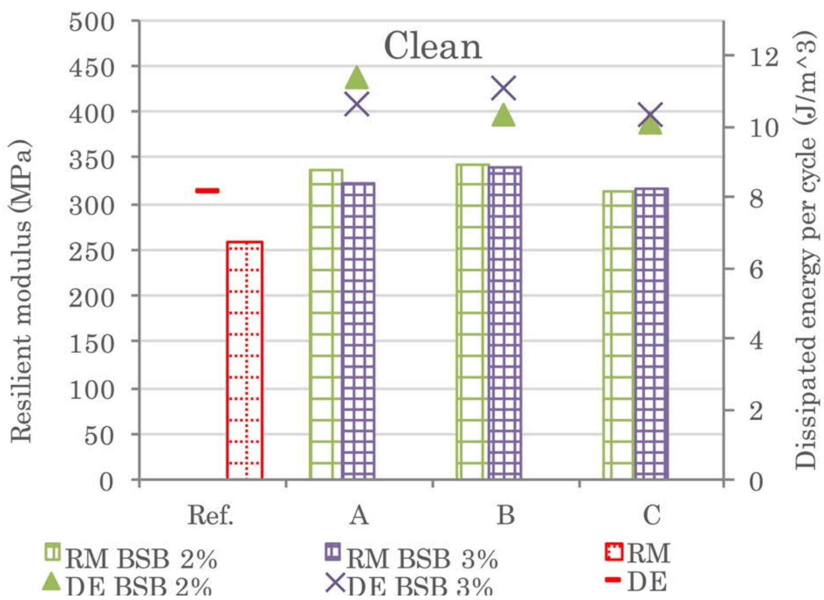

Figure 5.4 – Influence of stabilisation on resilient modulus (RM) and dissipated energy per cycle (DE) for clean ballast.

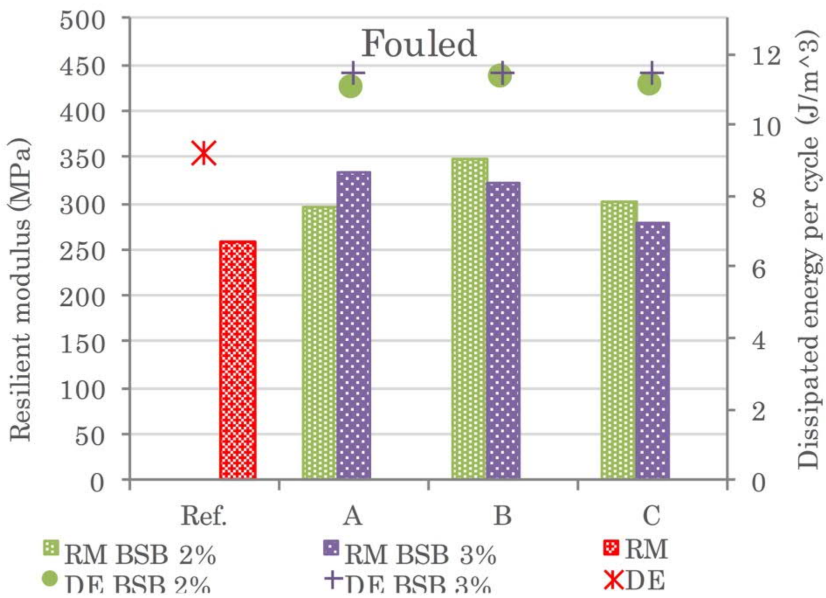

Figure 5.5 – Influence of stabilisation on resilient modulus (RM) and dissipated energy per cycle (DE) for fouled ballast.

It can be observed that, for these test conditions, overall bitumen stabilisation provided a stiffening of the specimen together with an increased capability for energy dissipation, due to the presence of a viscoelastic component, confirming what was obtained for BE A.

Despite the wider range of BE, with different properties, the relation between dosage and stiffness (see Section 4.4) still appears case-sensitive: in the case of clean ballast it seems that % BE does not significantly influence this parameter; for fouled specimens, however, BSB with B and C bitumen emulsions presented lower stiffness for higher % BE, in contrast with BE A.

In the case of energy dissipation, dosage had a clearer influence: with the exception of 2 % BSB (A), a small increase in bitumen content (BE from 2% to 3%) corresponded for the rest of BSB specimens to a small increase in dissipated energy, which correlates with the increased viscous component in the mix.

Ballast gradation had a clear influence on BSB behaviour: fouled specimens presented lower stiffness and higher ability to dissipate energy, even if by a relatively small margin, than their clean counterparts.

Following the analysis reported in Figure 4.10, it was interesting to understand the influence of BE type on the resilient modulus evolution over the PUMA test. For this purpose, Figure 5.6 plots the resilient modulus for clean BSB configurations with the same dosage (3%). It can be observed that BSB configurations using emulsions B and C did not exhibit a decrease in resilient modulus as observed for BSB (A), maintaining an almost constant value after the first 50,000 cycles (similar to the reference material). This behaviour could be attributed to the presence of polymers which, as for asphalt mixtures used in pavements, guarantee a more stable and durable behaviour over time (Airey 2004, Moreno-Navarro et al. 2015).

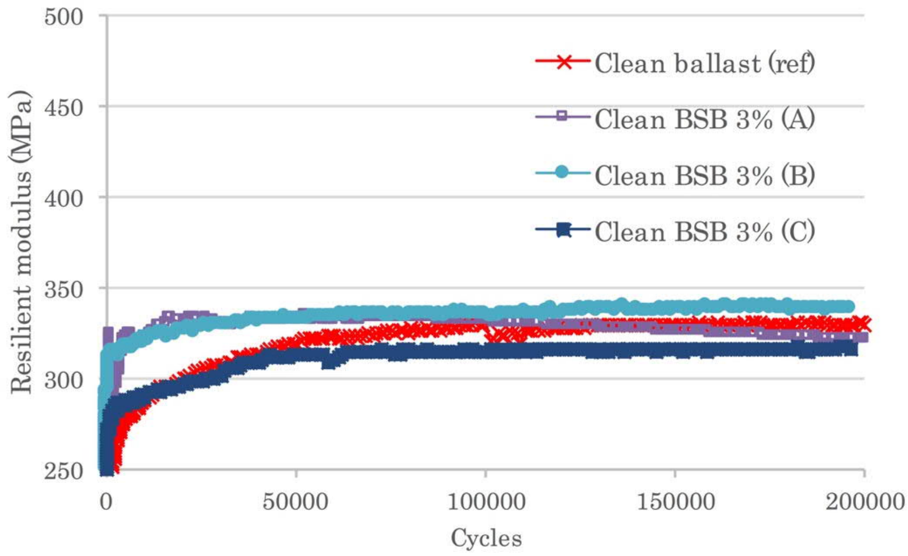

Figure 5.6 – Resilient modulus over the cyclic compression testing for all BSB 3% cases of clean ballast.

In general, as discussed in the previous chapter, these results indicate that bitumen stabilisation of ballast could represent also a relatively economic solution to reduce track component deterioration: it can provide a slight increase in ballast stiffness while increasing also the damping properties of the layer (Hunt and Wood 2005, Sol-Sánchez, Moreno-Navarro, and Rubio-Gamez 2015). Nevertheless, it is worth noting that these results may be partly a function of the scale adopted, since at this scale a higher number (compared to full-scale) of contact points is activated by bitumen stabilisation.

5.4.3 Desirability of the different BSB configurations

In the previous sections the potential benefits of stabilising ballast with bitumen emulsion have been highlighted. This section will provide a comparison of the BSB configurations analysed in this study using the optimisation method illustrated in Section 5.3.2. This method was carried out based on the data obtained from flowability and confined compression tests. The evaluated parameters, namely flowability index, plastic strain, resilient modulus and dissipated energy are indexes of the efficiency of the stabilisation method, of the ballast layer resistance to geometry change and of ballast mechanical behaviour.

Table 5.5 presents results in terms of desirability values obtained using Derringer's desirability functions with parameters analysed during flowability and PUMA tests. By using the geometrical mean (Equation 5.2) the corresponding desirability index (DI) is obtained for each configuration:

$$DI = \sqrt[4]{DV_{FI} \cdot DV_{PS} \cdot DV_{RM} \cdot DV_{DE}} \tag{5.2}$$

where the subscripts stand for flowability index, plastic strain, resilient modulus and dissipated energy, respectively. It can be noted that, in this case, equal unitary weight was assigned to all parameters. However, these factors, could have different importance from Rail Authorities' perspective – aspect that could be further exploited in future studies.

Table 5.5 - Detailed desirability values (DV) of flowability index, plastic strain, resilient modulus, dissipated energy and resulting desirability index for all BSB configurations.

Gradation	Clean						Fouled					
BE	A		B		C		A		B		C	
Dosage	2%	3%	2%	3%	2%	3%	2%	3%	2%	3%	2%	3%
Flowability index	0.18	0.20	0.82	0.70	0.92	0.91	0.34	0.37	0.81	0.82	0.86	0.88
Plastic strain	0.86	0.87	0.78	0.80	0.74	0.85	0.81	0.83	0.71	0.78	0.82	0.83
Resilient modulus	0.88	0.85	0.89	0.87	0.79	0.80	0.77	0.90	0.91	0.84	0.76	0.68
Dissipated energy	0.58	0.53	0.52	0.55	0.51	0.52	0.55	0.57	0.57	0.57	0.55	0.58
Desirability index	0.53	0.53	0.74	0.72	0.72	0.75	0.58	0.63	0.74	0.74	0.74	0.73

Figure 5.7 summarises these values for clean and fouled BSB.

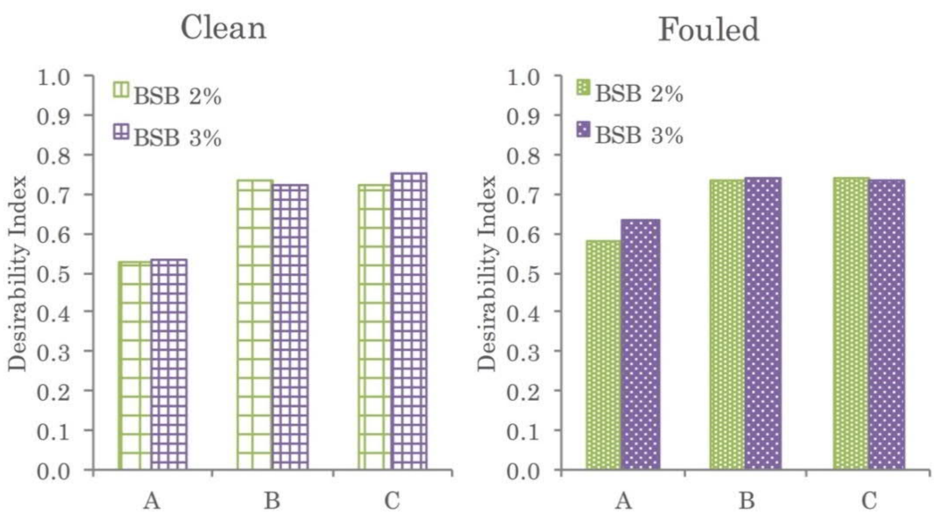

Figure 5.7 – Desirability index results of (a) clean and (b) fouled stabilised specimens as a function of BE dosage and type.

In can be observed that the best scores, ranging from 0.72 to 0.75, were obtained by bitumen emulsions B and C, regardless of the gradation considered. BE A, in contrast, reached noticeably lower values, especially in the case of clean ballast. In this regard, despite the general improvements in terms of mechanical properties of BSB, BE characteristics negatively influenced its flowability through the ballast, allowing a high quantity of material to be lost during stabilisation. This parameter, which in this study was considered equally important to those related to performance, had a decisive impact on the optimisation process.

5.5 Conclusions

During this second stage, the research focused on the optimisation of the stabilisation process. Different configurations in terms of type of bitumen emulsion, dosage, bitumen properties and ballast gradation have been compared, using an optimisation method, in terms of mechanical performance and efficiency of BE application. From the analysis carried out, the following conclusions can be drawn:

- Results obtained in this phase using different types of BE, overall, confirmed those obtained in the previous phase: bitumen stabilisation improved ballast properties in terms of plastic strain and plastic strain rate (long-term behaviour), indicating the potential of this technology for reducing the need for maintenance due to geometry degradation in field applications.
- At the same time, it was observed that overall bitumen stabilisation provided a stiffening of the specimen together with an increased capability for energy dissipation, due to the presence of a viscoelastic component, confirming findings with the first BE. This suggested that BSB could also be employed to modify track-bed mechanical behaviour and reduce noise and vibrations. However, it has to be considered that at this scale a higher number (compared to full-scale) of contact points is activated by bitumen stabilisation.
- These tests highlighted that ballast gradation is also an important factor to take into account. Overall clean specimens exhibited better deformational behaviour than fouled ones. At the same time, fouled specimens presented lower stiffness and higher ability to dissipate energy, even if by a relatively small margin, than their clean counterparts. As regards the stabilisation process, moving from clean to fouled ballast leads to a significant increase in stabilisation efficiency. Nevertheless, it is worth remarking that, in this phase, model-scale was used and the level of

contamination (or fouling index) of clean ballast may be different from a typical full-scale clean ballast.

- The type of emulsion and its dosage seemed to play an important role in BSB properties: increasing the % BE provided a better resistance to permanent deformation and changed the mechanical properties of BSB; increasing the viscosity of bitumen emulsion decreased the percentage of material lost, thereby providing improved stabilisation efficiency. This indicates that, depending on the field condition (ballast gradation) and ballast depth to be stabilised, a specific BE could be designed to obtain the desired results in terms of BSB behaviour and stabilisation efficiency.
- With regard to bitumen properties, results showed that the use of harder bitumen for BSB can improve the resistance to permanent deformation while polymer modification can provide a more stable behaviour over time (constant stiffness values).
- The optimisation method used, by combining all the above-mentioned factors and comparing all BSB configurations analysed at model-scale, indicates that bitumen emulsions similar in properties to B and C appear to be the most desirable for bitumen stabilisation of ballasted tracks.

Results obtained in this phase provide important guidance on the influence of the factors analysed on the proposed technology. However, to understand to what extent BSB could represent a solution to improve sustainability and performance of ballasted track-beds full-scale tests were necessary. For this purpose, the next laboratory investigation focused on the simulation of in-field BSB application, response to traffic loading and maintainability.

Chapter 6 - Full-scale ballast box: bitumen stabilisation to improve current maintenance operations and newly constructed track-beds

In the previous stages of this research ballast stabilisation by bitumen emulsion has been proposed as a solution to extend service life of existing ballasted track-beds. The feasibility of this technology and the main factors affecting its performance have been evaluated at model-scale in Chapter 4 and Chapter 5, respectively. This chapter focuses on the application of such a technology to existing ballasted tracks during maintenance operations or to newly constructed track-beds.

6.1 Introduction

As described in Chapter 2, one of the main issues associated with the unbound nature of ballast is the settlement of the track-bed (particularly when it is not uniform along the track). This phenomenon consists of an initial major compaction after construction or maintenance and then a steady consolidation due to particle slippage and degradation (aggregate breakage and abrasive wear), the rate of which determines also track-bed durability. Fine material progressively produced by abrasion is, in fact, the main contribution (around 70%) (Huang et al. 2009) to ballast void contamination (fouling phenomenon), which can compromise the ability of ballast to fulfil its essential functions.

In order to restore track geometry and guarantee adequate levels of safety and ride comfort, frequent maintenance interventions are required during the service life of the track. In this regard, tamping is the most common technique to correct geometry defects, the vibrating action of the tines allowing for the dilatation of the granular layer to restore the original position of the track. However, this operation also represents one of the main causes of ballast particle degradation (Pires and Dumont 2015) due to its aggressiveness during the introduction and vibration of the tines. Furthermore, as shown by several studies (Selig and Waters 1994, Anderson and Fair 2008) and verified during the first stage of this research (Chapter 3), this process leads to the loosening of the already compacted ballast layer, which rapidly returns the track to its pre-maintenance position (ballast memory).

Stoneblowing, as an alternative maintenance technique, aims to overcome issues related to tamping by blowing a calculated amount of smaller size stones under each sleeper without disturbing the already dense ballast, which is supposed to allow for a more effective solution in the long term for track geometry correction (McMichael and McNaughton, 2003;Tutumluer et al., 2015; Sol-Sánchez et al., 2016). However, in agreement with other studies (Sol-Sánchez, Moreno-Navarro, et al. 2016b, Sol-Sánchez et al. 2017), in Chapter 3 it was shown how this process can lead to track-bed stiffening and a consequent reduced damping capacity, which is one of the important functions of the ballast layer.

In this context, ballast stabilisation by bitumen emulsion has been investigated during this research as an effective technique which could increase ballast service life by reducing the need for maintenance (and thus lifecycle costs). The concept behind this solution, was to investigate a relatively cheap technology to be applied during a maintenance operation. Thus, tamping and stoneblowing maintenance processes would represent also an opportunity to apply the proposed technique (BSB) on in-service railway tracks. This type of application would limit the costs required for longer traffic disruptions necessary for other stabilising technologies (Woodward et al. 2012) while enabling its eligibility for existing ballasted tracks with relatively simple machinery (implementation of a BE injection system to current tamper/stoneblower).

For this purpose, the main aim of this part of the research was evaluating how this technology could effectively be applied to existing ballasted tracks during maintenance operations widely used all around the world. Various scenarios were analysed (clean or fouled ballast, corresponding to the early life and a degraded state, respectively) in order to evaluate the effect of BSB at different stages of the service life of ballasted track.

During this research stage, also bitumen stabilisation of newly constructed track-beds (not yet needing for maintenance) has been evaluated as a solution to extend ballast service life by reducing settlement and thus frequency of future maintenance.

This type of test follows those carried out in model-scale and full-scale PUMA, providing test conditions closer to those experienced in real track.

This laboratory investigation was carried out at the University of Granada in cooperation with Labic research group (during a Secondment planned within the SUP&R ITN project), using two full-scale ballast boxes (I and II) designed to simulate in-situ traffic loading and maintenance operations.

6.2 Materials

The analysis of BSB effectiveness during maintenance was carried out using a ballast box (I) 440 mm wide, 750 mm long and 500 mm deep. Boundary conditions were created by using four wooden panels, 3 cm thick, reinforced by a steel frame. Perpendicular to the length of the box, a piece of concrete sleeper whose base dimensions were 250 mm and 357 mm and a rail type UIC-54 250 mm long fastened to the sleeper by a fastening type VM and a rubber rail pad (7 mm thick with a static stiffness near 125 kN/mm, manufactured from end-of-life tires - Sol-Sánchez et al., 2014b, 2015b) were used to transmit the load to the ballast layer, as in Figure 6.1a (Sol-Sánchez, Moreno-Navarro, et al. 2016b, Sol-Sánchez, Pirozzolo, et al. 2016). This box (I) provided a means to run a full-scale test which was easy to set-up, manageable in size while requiring a relatively small quantity of material.

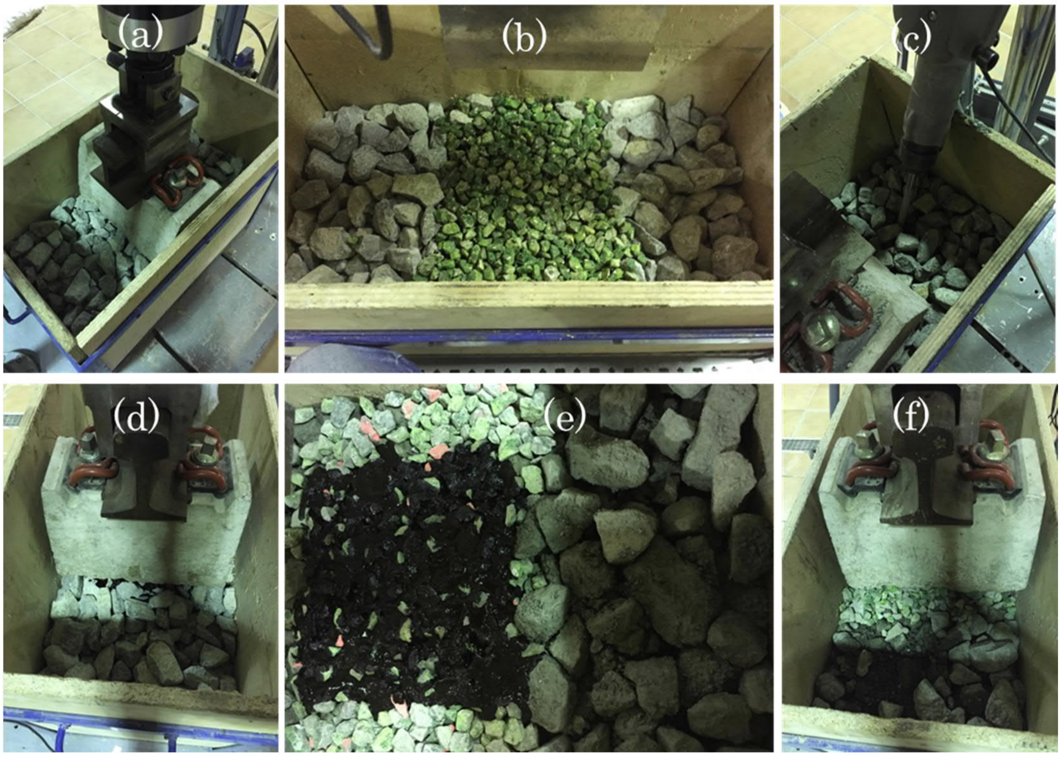

Figure 6.1 – a) Specimen set up in the ballast box I; (b) stoneblowing; (c) tamping; (d,e) simulation and bitumen stabilisation; (f) fouled ballast after stoneblowing.

A larger full-scale ballast box (II) was used to evaluate the effectiveness of BE stabilisation of newly constructed track-beds. This box had a base area of 1000 mm by 1000 mm and a height of 400 mm (Sol-Sánchez, Moreno-Navarro, and Rubio-Gámez 2014a). Analogous to the other box, wooden walls were used to simulate the continuity of field conditions. To transmit the load to the ballast a sleeper section 940 mm long and 250 mm wide was used. The same rail type, fastening and rail pad as for the smaller box were used. The visual appearance of the box filled with ballast before testing is shown in Figure 6.2.

Figure 6.2 – Visual appearance of specimen set up in the ballast box (II).

Following commonly used track-bed design methodologies, a ballast layer 300 mm deep under the sleeper was used, a normal thickness to allow the use of automated track maintenance by tamping (Nelder et al. 2008).

The tests were carried out by placing the ballast directly on the steel base of the laboratory box to be consistent with other tests carried out at model-scale and full-scale. In this way, only ballast behaviour was investigated.

The ballast used in this study was ophite aggregate sourced from Cerro Sillado quarry in Cogollos de Guadix, Spain. Table 6.1 shows the main physical and mechanical properties of the ballast, which indicate that the granular material is appropriate for its application as ballast in railway tracks, according to BS EN 13450 (2013).

Table 6.1 - Mechanical and physical properties of Cerro Sillado ophite ballast (after Sol-Sánchez et al. 2016).

Property	Standard	Test result	Network specification
Los Angeles Abrasion (%)	EN 1097-2	5	≤12
Flakiness index (%)	EN 933-3	6	≤15
Fine particle content (%)	EN 933-1	0.08	0.6
Fines content (%)	EN 933-2	0.03	0.5
Particle Density (Mg/m^3)	EN 1097-6	3.24	-

Two ballast gradations, ‘clean’ and ‘fouled’ ballast, were formulated by combining ophite aggregate of different sizes. In particular, the clean ballast is compliant with European standards G_c RB A (BS EN 13450:2013 2013), whereas the fouled ballast approximated to real fouled ballast measured after the degradation of ballast particles due to traffic and maintenance interventions in real railway tracks (Ionescu 2004, Ebrahimi et al. 2015). As shown in Figure 6.3, the fouled ballast gradation curve used in this study represents an intermediate gradation compared to the examples considered from real track experience, simulating a moderate level of ballast degradation. Water was added to the fouled ballast in order to achieve a moisture content of 3% (Ebrahimi et al. 2015).

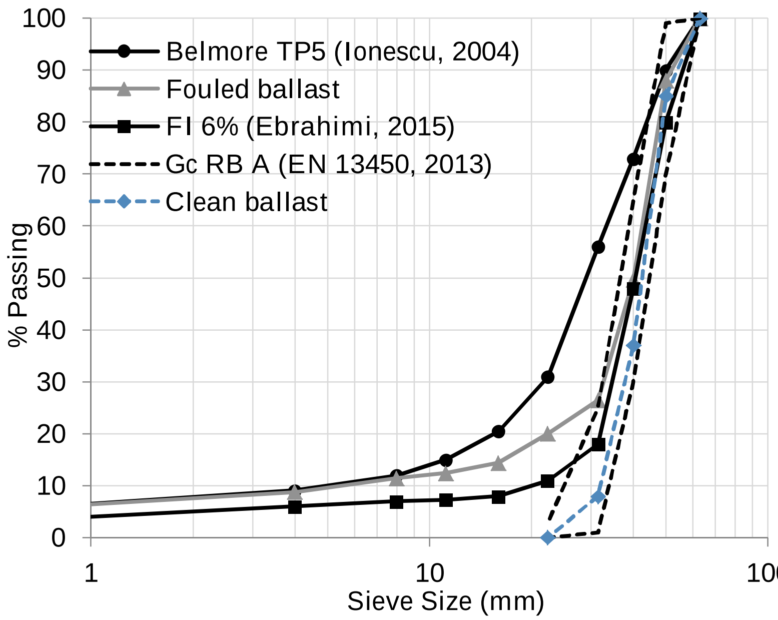

Figure 6.3 – Particle size distribution of clean ballast and fouled ballast used for full-scale ballast box.

Following the optimisation study carried out in Chapter 5, bitumen emulsions B and C, because of their viscosity and quick breaking behaviour were selected as stabilising agents for full-scale tests.

Tamping and stoneblowing operations were simulated as described in Chapter 3. Stoneblowing stones employed to restore the original position of the sleeper-rail system were sized between 14 and 20 mm (same gradation as in Figure 3.7), recommended on actual track to avoid any possible drainage problem (Fair and Anderson 2003). These stones were marked with a different colour (Figure 6.1b) to distinguish them from clean and fouled ballast particles.

A pneumatic hammer with a chisel 5 cm wide was used to simulate the tamping process (D'Angelo et al. 2015, Sol-Sánchez, Moreno-Navarro, et al. 2016b) (Figure 6.1c).

In order to avoid the intrusion of ballast particles under the sleeper during the maintenance interventions carried out in the laboratory, the part of the ballast section studied corresponds to the ballast layer under the sleeper, without considering the ballast cribs. This same configuration was used in previous studies conducted using the same equipment (Sol-Sánchez, Moreno-Navarro, and Rubio-Gámez 2014a, Sol-Sánchez, Moreno-Navarro, et al. 2016b).

6.3 Methods

After having selected from Chapter 5 the types of bitumen emulsion which provided the most efficient stabilisation process while exhibiting similar performance under traffic loading, the first step was to validate flowability results at full scale and select only one BE for the subsequent dynamic tests.

Once this operation was completed, the main objectives of full-scale dynamic tests were: to evaluate effectiveness of bitumen stabilisation of ballast when applied during a maintenance operation to correct track geometry at different stages of ballast service life; and when applied to newly constructed track-bed (without need for geometry correction). It is worth highlighting that in both scenarios the lifecycle benefits provided by BSB would be related to the reduction in future maintenance frequency and ballast degradation.

Furthermore, additional tests were carried out: to understand the influence of water application for ophite aggregate fouled ballast; and to study the future maintainability of BSB.

For these purposes, the laboratory testing carried out is summarised in Table 6.2.

Table 6.2 – Testing plan for full-scale ballast box investigation.

Variables	Material tested	Properties tested	Test	Main parameters
Influence of BE properties on full-scale stabilisation efficiency				
-BE type	-BE B -BE C	-Flowability of BE	-Flowability test	-Quantity of BE lost
Influence of BE stabilisation when applied during maintenance operations				
-Ballast gradation -Maintenance strategies	-Clean ballast -Clean BSB (C) -Fouled ballast -Fouled BSB (C)	-BSB mechanical behaviour	-Ballast Box (I) test	-Settlement -Resilient Modulus -Dissipated Energy per cycle -Ballast degradation
Influence of water application for ophite aggregate fouled ballast				
-Maintenance strategies -Timing of water application	-Fouled ballast	-Wet fouled ballast mechanical behaviour	-Ballast Box (I) test (Test IDs: F1, F2, F3, and F4)	-Settlement -Resilient Modulus -Dissipated Energy per cycle
BSB maintainability				
-Maintenance operation used for future geometry correction	-Clean BSB (C)	-BSB mechanical behaviour	-Ballast Box (I) test	-Settlement -Resilient Modulus -Dissipated Energy per cycle
Effectiveness of BE stabilisation for newly constructed track-beds				
-BE application	-Clean ballast -Clean BSB (C)	-BSB mechanical behaviour	-Ballast Box (II) test	-Settlement -Resilient Modulus -Dissipated Energy per cycle -Ballast degradation -Stress dissipation

In detail, initially a full-scale flowability test was carried out to define the type of bitumen emulsion to be used in subsequent tests, proving as well the suitability of the dosage selected in previous studies for application in BSB. In this regard, a dosage of 1.44% by weight was used. This quantity corresponded to the 3% used in model-scale in proportion with the average specific surface of aggregate. It is worth noting that, after setting, around 1.52% of total volume (3.7% of void structure for a clean ballast) is taken up by the bitumen, which still allows drainage through the ballast layer, as for similar stabilisation techniques (Woodward et al. 2009, Lakušic et al. 2010).

For both BEs (B and C), the calculated amount of BE was poured over a 300 mm deep ballast layer after stoneblowing (which added a layer of stones with higher potential to retain BE). The device used for this test was a steel permeameter 300 mm wide, 300 mm long and 500 mm deep, having a glassy wall that allowed inspection during the test, as in Figure 6.4.

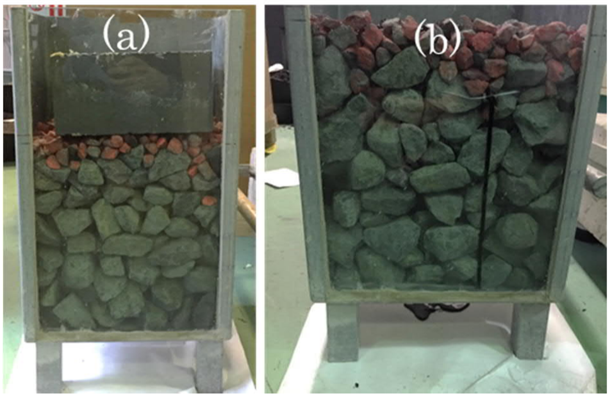

Figure 6.4 – Visual appearance of permeameter after stoneblowing (a) and after bitumen emulsion stabilisation (b).

Once the ballast was poured, stoneblowing was simulated in order to recover 15 mm of permanent deformation. Afterwards, the BE was poured uniformly over the surface within 15-20 seconds. After 1200 s (when the process could be considered complete – Chapter 4) the ballast was removed and the amount of bitumen collected at the bottom was considered as BE loss (which should be minimised in order to maximise the stabilisation efficiency while not to contaminating the granular sub-layers). Based on this test, the BE type to be used for dynamic load tests was chosen. The best BE was used also after tamping to evaluate also the influence of the maintenance operation used.

Having selected the most appropriate type and proven the optimal dosage of BE, the second objective was to evaluate the influence of bitumen stabilisation of ballast applied during a maintenance operation on post-maintenance ballast performance. To achieve this, four series of dynamic tests, including tamping and stoneblowing simulations (with and without stabilisation with BE), were carried out in a ballast box (I), comparing the results for the different solutions in terms of mechanical performance. In order to understand the most appropriate stage, in terms of ballast service life, at which to apply this technology, these series of tests were carried out for both clean and fouled ballast (wet). Each series comprised repeated loading and maintenance operations.

To simulate both traffic and maintenance interventions a period of 200,000 load repetitions was considered. During this period, in order to restore original geometry, the selected maintenance task was carried out for the first time at cycle 50,000, when the settlement had reached approximately 15 mm, and thereafter each time the settlement was close to this value (Sol-Sánchez, Moreno-Navarro, et al. 2016b).

The load amplitude was equivalent to 250 kPa under the sleeper applied at a frequency of 4 Hz - characteristics deemed appropriate to simulate field conditions (Indraratna et al. 2006, Sol-Sánchez, Moreno-Navarro, et al. 2016b).

The stabilisation process was carried out immediately after tamping or stoneblowing by pouring uniformly, at room temperature (approximately 20°C), the calculated amount of BE over the ballast/sleeper contact area. Thus, different from previous tests carried out on BSB, in this case only ballast volume underlying the sleeper area was stabilised. Even if this could limit the performance offered by an all-BSB section, this choice was taken in order to reproduce in the laboratory a feasible way to readily implement this technology in existing tracks. After a curing time of approximately three hours (quick setting BE), the dynamic test was resumed.

The parameters evaluated during the dynamic ballast box test were: the vertical settlement (to analyse the effectiveness of BSB on reducing the geometrical track degradation, which is one of the main issues in ballasted tracks); the vertical stiffness and the dissipated energy per cycle (to determine the mechanical behaviour of each solution, and its effect on track response under train passage); in addition, to assess the influence of each maintenance strategy considered on ballast degradation, in the case of clean specimens, ballast gradation was measured before and after each series.

To better understand the influence of water on this type of fouled ballast, additional tests were carried out for fouled ballast only, differing mainly for the timing of water addition. Synthetic 20 mm rainfalls (corresponding approximately to the average of one-week period in UK) (World Bank Group 2017) were simulated by pouring three litres of water evenly on each side of the sleeper. This operation was repeated at different stages of tests F1 and F2 as indicated in Figure 6.14, to evaluate the effect of the first and following wetting episodes of fouled ballast. The same synthetic rainfall was simulated at the beginning of test F3 and F4, while for this latter (F4) a continuous wetting over the test was applied (Figure 6.14).

Furthermore, in order to evaluate in the laboratory the future maintainability of BSB, while assessing the effectiveness of BE stabilisation when coupled with maintenance operations for clean ballast, it was decided to simulate also two possible future methods to maintain BSB: stoneblowing and tamping. In the case of tamping, since the vibrating action of tines could damage existing cohesive links between particles, it was decided conservatively to apply a second BE stabilisation after geometry was restored. Nevertheless, these tests represented only a preliminary study on maintainability of BSB, leaving specific investigations to future studies.

For all these tests the smaller ballast box (I) was used to optimise time and resources available. For the following phase, consisting of a lower number of tests, the larger ballast box (II), was used since it was possible to simulate more closely in-situ conditions.

In order to evaluate the potential of bitumen stabilisation as reinforcement for newly constructed tracks the same dynamic test was carried out using the ballast box (II). In this case, clean ballast was stabilised immediately after sample preparation and tested after curing. Results obtained were compared with unbound ballast used as the control case.

For all box tests, ballast sample compaction was carried out by applying 100 cycles as conditioning.

The parameters evaluated were: settlement, stiffness, energy dissipation and ballast degradation. This last parameter was assessed by comparing the total amount of particles passing 31.5 mm and 4 mm sieves. In addition, for ballast box (II), a loading cell was placed underneath ballast layer (covered with a 20 mm thick layer of sand and a layer of geotextile to avoid interpenetration) to assess the potential impact of the use of ballast stabilisation on stress distribution (Sol-Sánchez, Pirozzolo, Moreno-Navarro, and Rubio-Gamez 2015). This cell was previously calibrated by the Labic (University of Granada), which provided the spreadsheet to convert each reading into pressure measurement. Readings were taken right after the initial phase (cycle 20,000) and along the last 10,000 cycles.

6.4 Results

6.4.1 Influence of BE properties on full-scale stabilisation efficiency

Results of the full-scale flowability test in terms of bitumen emulsion lost are reported in Table 6.3. This parameter represents the quantity of material ‘lost’ (not working) during the stabilisation process and indicates the efficiency of the process. It can be observed that, for the same maintenance operation (stoneblowing), BE C provided the best results in terms of material lost (5 times lower), which was attributed to the higher viscosity (higher bitumen content in the emulsion) compared to BE B. These results indicate that BE C leads to better ballast stabilisation since less material percolates to the bottom of the ballast layer, giving a more homogeneous material composed of BE and ballast particles. This emulsion would also reduce the amount filtrating to granular sub-layers, which would avoid the contamination of such layers. For this reason, BE C was chosen as the stabiliser for further tests.

At the same time, it is worth noting how the gradation of the granular layer can influence the ability of the bitumen emulsion to penetrate between particles for ballast stabilisation. It is seen that, after the stoneblowing simulation (which consisted of adding a layer of smaller stones, with higher specific surface area), the amount of BE lost was almost three times lower than that measured after tamping (which consists of dilating the granular layer, obtaining a higher volume and/or size of air voids between ballast particles while no small particles with higher specific surface are included). Therefore, the amount of BE employed during track maintenance will be conditioned to the type of technique employed to restore the original position of the railway track, which requires previous studies to select the optimal dosage of BE to be used. Nonetheless, in this study the BE C dosage was the same for both processes in order to obtain a comparative analysis between the effectiveness of BSB after each maintenance technique.

Table 6.3 – Full-scale flowability test results.

	Stoneblowing + BE C	Tamping + BE C	Stoneblowing + BE B
BE lost (g)	9.1	26.3	46.9

6.4.2 Effectiveness of BE stabilisation when applied during maintenance operations

Figure 6.5 shows the evolution of settlement of the ballast layer recorded during the dynamic tests. The spikes in the graph are due to the simulated maintenance operations carried out (conventional stoneblowing and tamping and the same techniques combined with the inclusion of BE for ballast stabilisation), when level of settlement had reached approximately 15 mm, to recover initial geometry. After each maintenance operation, the settlement values start again from zero although the level could only be set by the simulated maintenance to an accuracy of ±1.5 mm. Nonetheless, this type of plot allowed for a clear comparison between the different series analysed (D’Angelo et al. 2015).

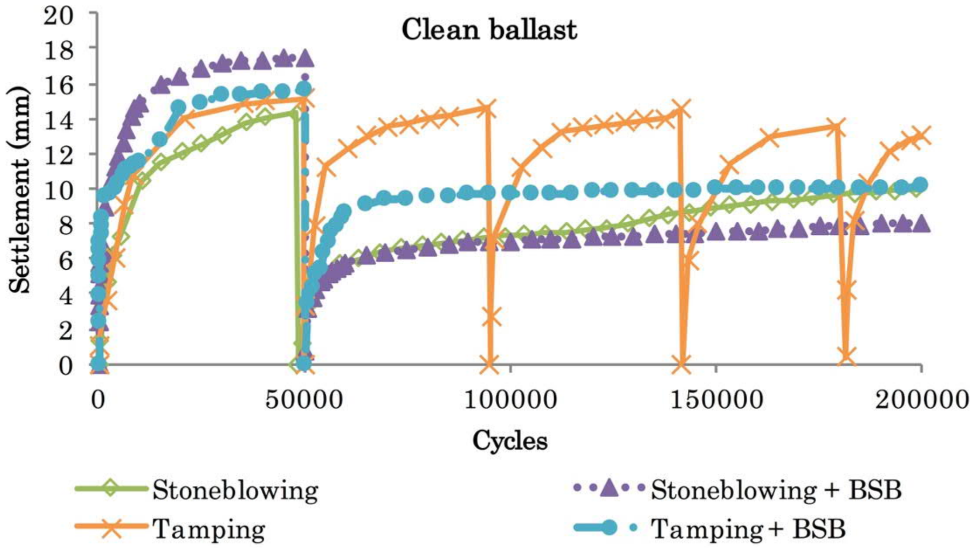

Figure 6.5 – Influence of BE stabilisation on settlement when applied during tamping and stoneblowing for clean ballast.

With the aim of evaluating also the long-term behaviour, the Settlement Rate per Load Cycle (SRLC) was evaluated according to Equation (6.1):

$$SRLC = \frac{\Delta S_S}{\Delta N_S} \tag{6.1}$$

where ΔN_S is the number of cycles and ΔS_S is the settlement variation during the stable range considered.

Figure 6.6 shows the SRLC calculated over the last 40,000 cycles (long-term) but also in the 40,000 cycles following the first maintenance operation (short-term). This second parameter was calculated in order to compare all series (for the tamping series without BSB the long-term SRLC could not be evaluated).

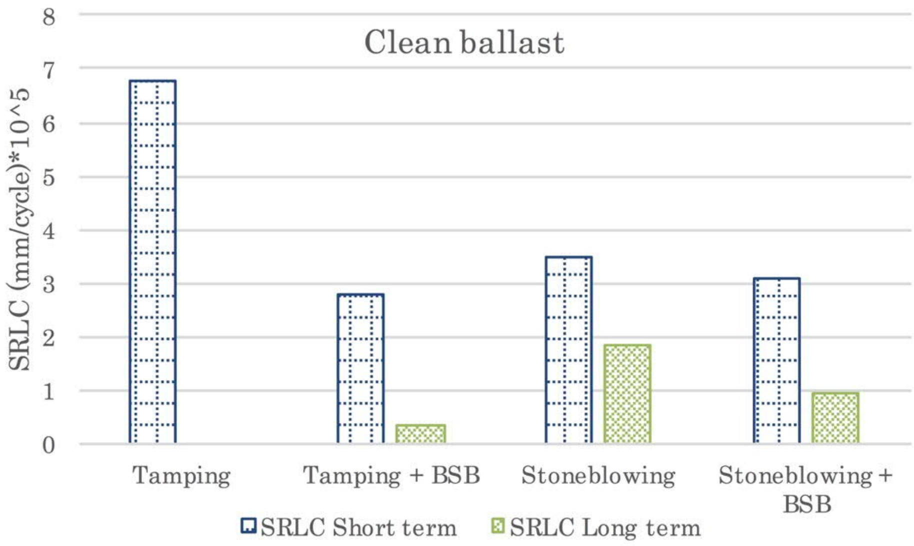

Figure 6.6 – Short and long term SRLC for different maintenance strategies analysed for clean ballast.

Overall, it can be observed from the first 50,000 cycles and following each tamping series that results in terms of settlement here obtained are similar to those of other laboratory studies on railway ballast (Indraratna, Khabbaz, and Salim 2004, Ionescu 2004, Aursudkij 2007, Kennedy 2011), with an initial phase characterised by ballast densification (quick settlement) followed by a more stable phase where settlement increases almost linearly with the number of loads applied (Dahlberg 2004).

Both tamping series exhibited higher settlement values than those with stoneblowing. When only tamping was carried out, its vibrating action, by loosening the compacted layer, led to a quick re-compaction and thus the need for more maintenance interventions. This phenomenon became quicker after each maintenance operation, confirming that tamping progressively reduces in effectiveness over time (Section 3.4) (Selig and Waters 1994, McMichael and McNaughton 2003, Aursudkij 2007). However, the addition of bitumen emulsion provided a better resistance to permanent deformation so that, after an initial lower re-compaction, no further maintenance intervention was needed for the traffic window considered. This improvement is even more evident when the settlement rate per load cycle (SRLC), is analysed in the short (60,000-100,000 cycles) and long term (160,000-200,000 cycles) (Figure 6.6).

On the other hand, both stoneblowing series exhibited a lower final settlement, due presumably to a lower post-maintenance re-compaction (Anderson and Key 2000), presenting apparently lower BE effectiveness since the stoneblowing process already allows for a more stable track behaviour (Section 3.4) (Anderson and Key 2000, D'Angelo et al. 2015, Tutumluer et al. 2015, Sol-Sánchez, Moreno-Navarro, et al. 2016b). Nevertheless, despite the decrease in BE influence after this maintenance technique, results indicate that the stabilisation process contributed to increased performance, especially in the long-term where the SRLC value for stoneblowing alone was double that for stoneblowing with BSB. This finding will be further exploited in Chapter 7. The addition of bitumen stabilisation, thus, could be beneficial if the improved long-term performance (and consequent reduced maintenance frequency) could balance the additional costs needed.

According to these results, it can be asserted that bitumen stabilisation can improve track-bed post-maintenance performance when applied in the early stages of service life of the infrastructure, especially in the case of tamping, where effectiveness of the maintenance task was increased by a factor of approximately four. This could result in an important reduction in the economic and environmental impact associated with railway track maintenance.

For these 4 different maintenance strategies analysed, Figure 6.7 and Figure 6.8 show the evolution of stiffness and energy dissipation, respectively, for clean ballast.

Resilient modulus values were calculated as stress amplitude over the resilient deformation per cycle while the dissipated energy was given by as the hysteresis loop (strain-stress diagram) per cycle, as described in Section 3.3 .

Confirming results from Section 3.4, from Figure 6.7 it can be observed that stoneblowing can induce a stiffening of the track. This phenomenon could lead to abrupt changes in reference to adjacent sections where this maintenance process is not carried out, which could result in differential settlement (Sol-Sánchez, Moreno-Navarro, et al. 2016b). In this case, BE stabilisation appeared to mitigate this phenomenon.

On the other hand, repeated tamping interventions provided abrupt changes in stiffness and dissipated energy just after the maintenance process. In this regard, stabilisation provided an increasingly stable behaviour over the test which is very desirable to avoid differential settlement (Sussmann et al. 2001).

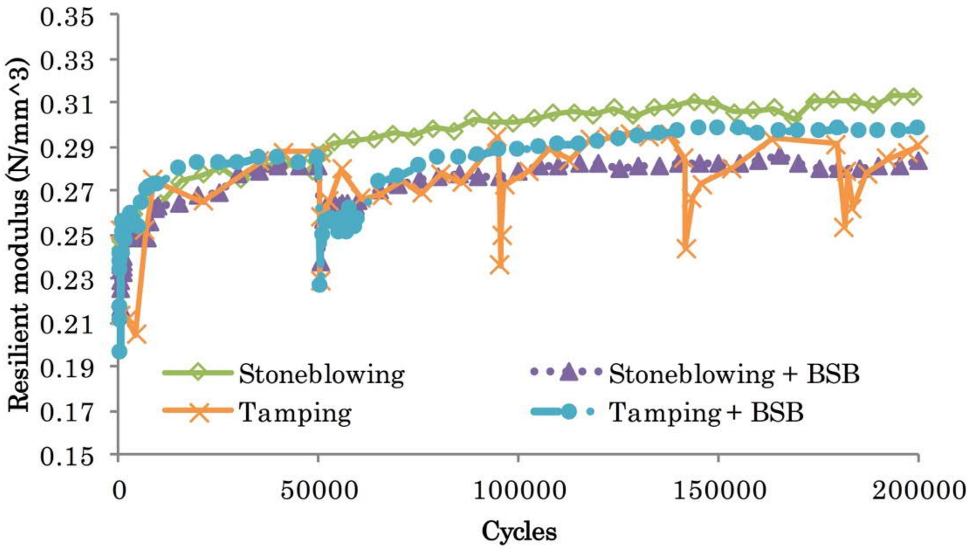

Figure 6.7 – Influence of maintenance and BE stabilisation on stiffness evolution for clean ballast.

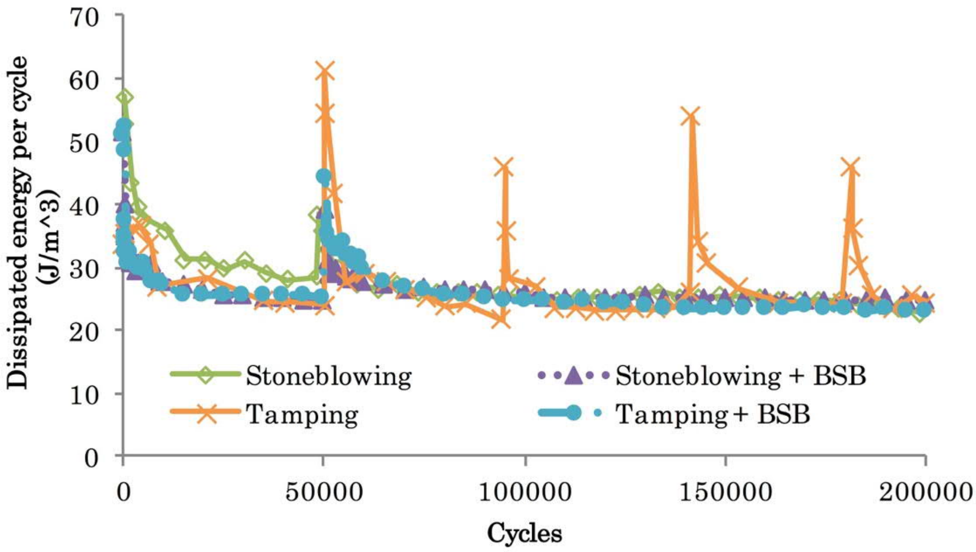

Figure 6.8 – Influence of maintenance and BE stabilisation on the evolution of dissipated energy per cycle for clean ballast.

In order to assess the influence of the maintenance operations considered on ballast durability, particle degradation was also measured and the results are reported in Figure 6.9. This parameter is important for clean ballast in order to know the particle deterioration rate, and the consequent reduction in service life resulting from mineral contamination. The degradation was measured as the variations in percentage of particles with size lower than 31.5 mm (inferior limit for European Standard) (BS EN 13450:2013 2013) and 4 mm (used for Fouling Index calculation) (Selig and Waters 1994), obtained from gradations before (8% passing through the 31.5 mm sieve and 0% through the 4 mm sieve – see Figure 6.3) and after box tests.

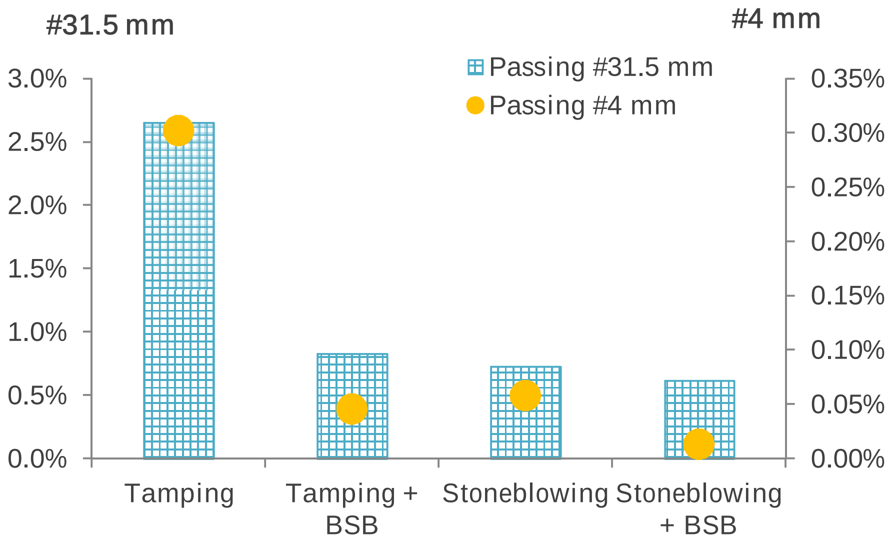

Figure 6.9 – Influence of maintenance and BE stabilisation on track-bed durability: increase in the percentage of particles with size lower than 31.5 mm and 4 mm.

It can be seen that the series with tamping only was the one that most degraded ballast particles due to the higher number of repetitions of the operation itself (which included a pneumatic hammer to simulate the aggressiveness of tine activity during tamping maintenance) as well as the re-compaction from a loose state after each operation (slips between particles generating fines). In this regard, bitumen stabilisation, while reducing settlement and hence the number of interventions, provided a higher shear strength due to the cohesion component which reduced the abrasion between particles and therefore production of fines, as can be noted from both BSB series. Bitumen stabilisation, therefore, appears to be an effective method to increase ballast layer durability after tamping as seen in other shear-resistance reinforcing techniques (Indraratna and Salim, 2003; Dersch et al., 2010; S. Fischer et al., 2015).

Nonetheless, it must be recognised that the effectiveness of BE to reduce ballast degradation is lower in the case of stoneblowing since this technique already gives an important decrease in particle breakage and wear (Sol-Sánchez, Moreno-Navarro, et al. 2016b) in comparison with tamping, as a result of the lower number of operations required to restore track geometry and the fact that less ballast re-compaction and particle movement occurs since the granular layer is not disturbed during the maintenance process.

In order to understand how level of ballast degradation can affect the effectiveness of BSB, the four maintenance strategies analysed for clean ballast have been repeated for fouled ballast.

Figure 6.10 and Figure 6.11 show settlement and SRLC values, respectively, in the case of fouled ballast.

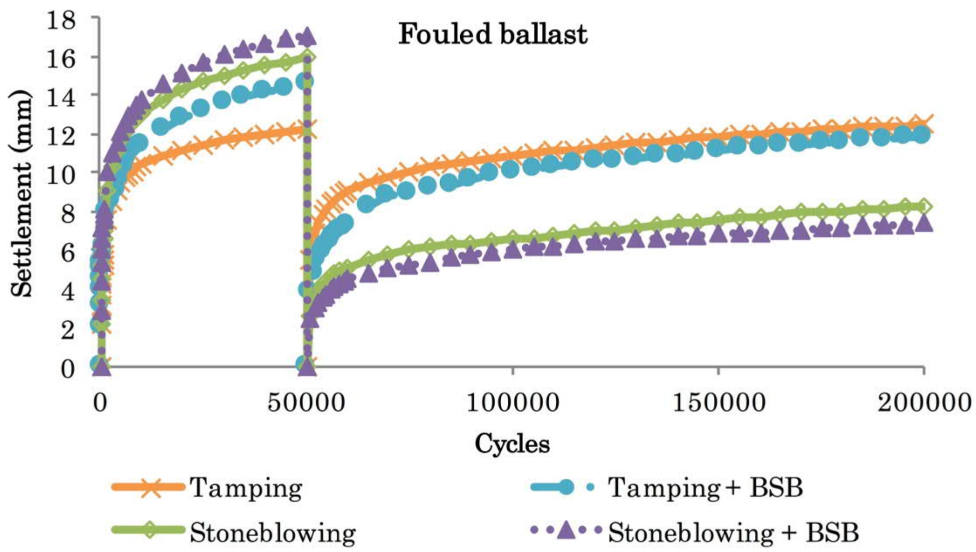

Figure 6.10 – Influence of BE stabilisation on settlement when applied during tamping and stoneblowing for fouled ballast.

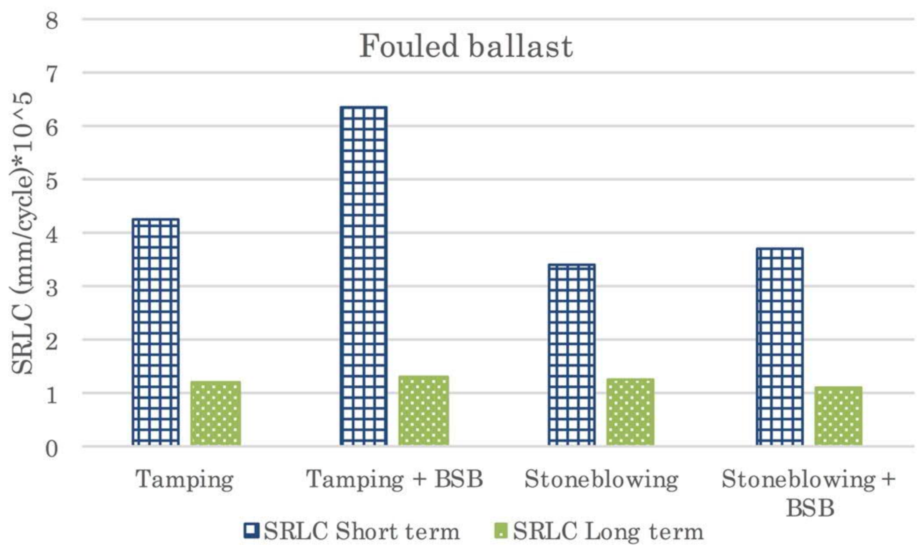

Figure 6.11 – Sort and long term SRLC for different maintenance strategies analysed for fouled ballast.

It can be noted that overall all fouled series exhibited permanent deformations lower than those of clean ballast. This could be associated with the reduction in air voids volume due to a broader gradation. In this regard, several studies have shown how the use of a less uniform gradations can reduce permanent deformation. An example is given by Ionescu et al. (Ionescu et al. 2016) study, in which desert sand contamination of ballast was investigated. Nonetheless, when air voids are sensibly reduced (fouled ballast) the presence of water by increasing the pore pressure can reduce shear resistance of layer and, thus, result in important plastic deformations.

In this case, specimens were pre-wetted so that it was expected to obtain similar results to those of Sections 4.4, where fouled wet specimens exhibited higher plastic strains. However, the box results apparently contradict previous results obtained with the PUMA as well as other studies on wet fouled ballast (Tutumluer et al. 2008, Ebrahimi et al. 2010, 2012). A possible reason was identified in the apparent cementation of ballast observed after the test. This could be the result of an additional adhesion offered by the negative pore pressure of water (present in relatively small amount after drying). Nevertheless, to better understand this phenomenon related to the material used for this stage of research, additional tests investigating the influence of water on ophite fouled ballast were carried out and results are discussed in Section 6.4.3.

In this specific case the influence of BE stabilisation on fouled ballast permanent deformation was very low for both the stoneblowing and tamping series: reductions of 5-10% are observed for the final settlement, whereas no significant differences are noted in the long-term deformation rate. This result could be related again to the already better resistance to permanent deformation offered by a low-voids material (and the adhesion offered by the) which also sensibly reduced the ability of BE to homogenously stabilise the ballast layer due to the reduced permeability. In this regard, when samples were removed at the end of the test, it was found that the bitumen emulsion was able to penetrate only partially (few centimetres) the ballast layer.

In Figure 6.12 and Figure 6.13, the mechanical performance in terms of stiffness and energy dissipation for the fouled ballast series are reported.

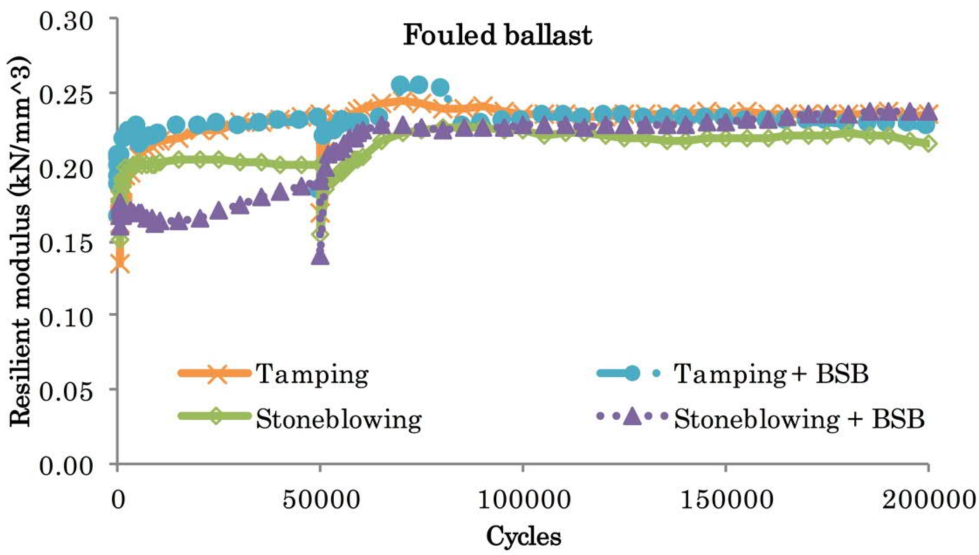

Figure 6.12 – Influence of maintenance and BE stabilisation on stiffness evolution for fouled ballast.

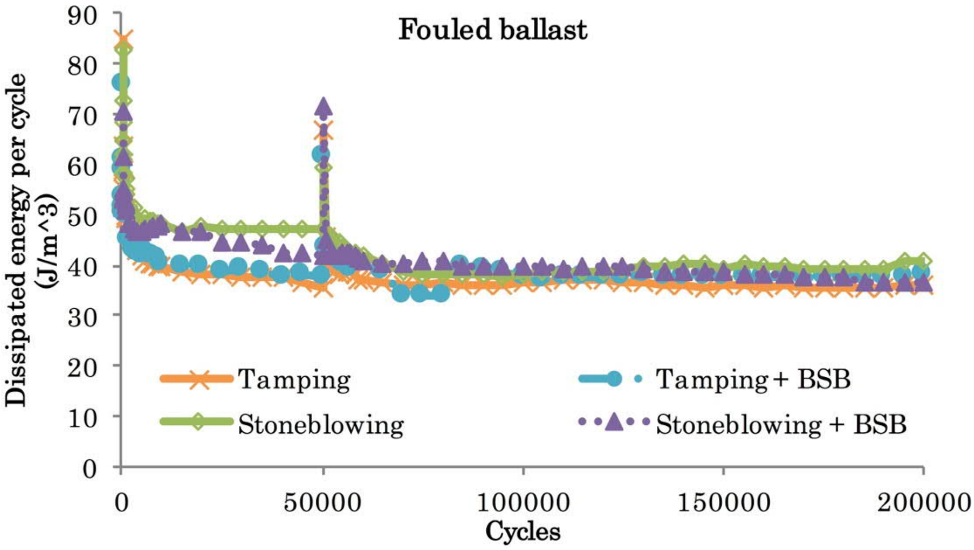

Figure 6.13 – Influence of maintenance and BE stabilisation on the evolution of dissipated energy per cycle for fouled ballast.

It can be noted that all four scenarios present very similar mechanical performance, especially looking at the last part of the test, where the behaviour is more stable. In this regard, results confirm that, at this stage of ballast life, mechanical behaviour was mostly influenced by the material composition (including the presence of water) itself rather than by the maintenance strategy applied.

In this context, also BE stabilisation did not provide any significant variations in mechanical performance, due to the same considerations as per the deformational behaviour.

6.4.3 Influence of water application for ophite aggregate fouled ballast

To better understand the influence of water on this type of fouled ballast, additional tests were carried out for fouled ballast only, differing mainly in the timing of water addition.

Figure 6.14 plots the values of settlement for four different scenarios in which water has been applied to fouled ballast at different times over the dynamic test.

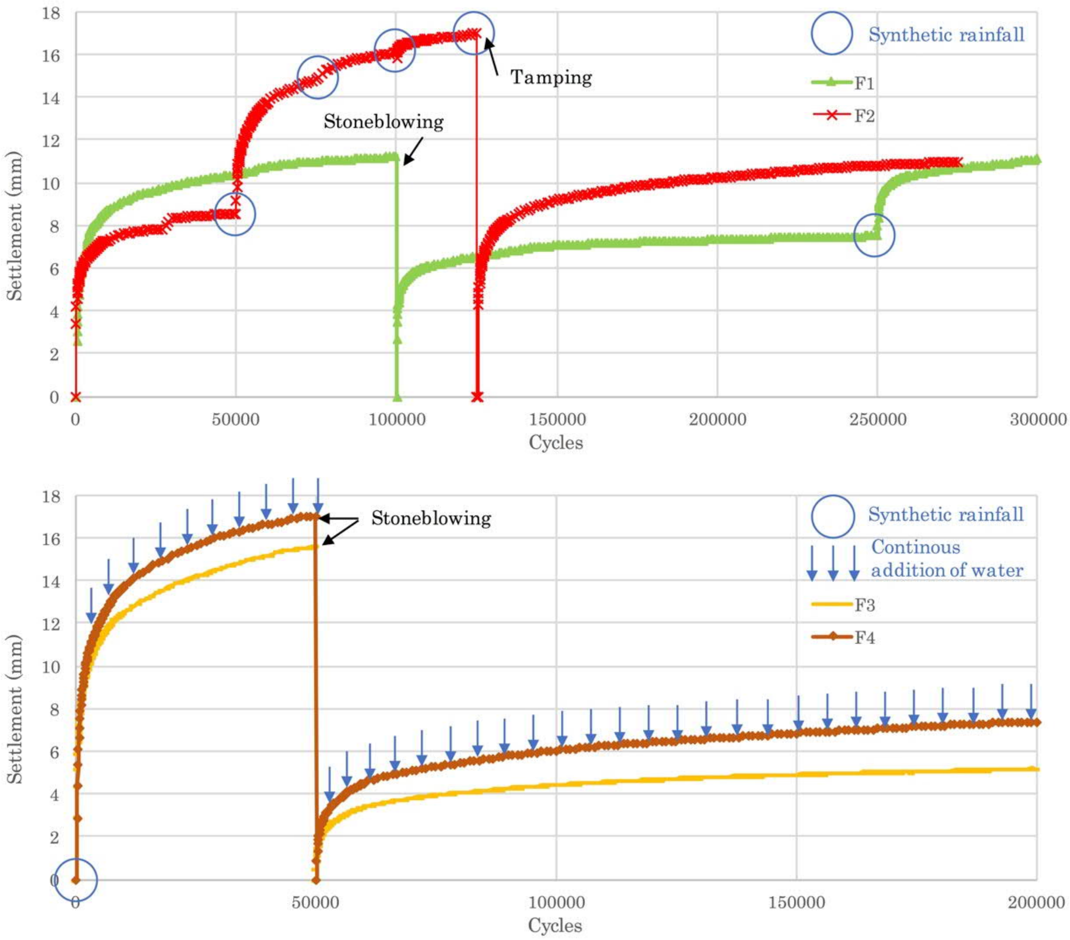

Figure 6.14 – Influence of water application on settlement for fouled ballast used in this study.

It can be noted how dry fouled ballast (first 50,000 of F1 and F2 tests) exhibited lower settlement than wet ballast, in agreement with results obtained for model-scale (Section 4.4.1).

Synthetic rainfall events, indicated in the graph by blue circles, were also followed by an increase in settlement values. This increase was abrupt for the first synthetic rainfall (cycle 250,000 for test F1, cycle 50,000 for test F2 and cycle 0 for tests F3 and F4), and less pronounced in the following applications (cycles 75,000, 100,000 and 125,000 in test F2 and all of the test F4). These results are in agreement with similar studies conducted on fouled ballast (Ebrahimi and Keene 2011, Momoya et al. 2016).

By relating these results with those of the previous Section (6.4.2), it can be confirmed that an initial addition of water followed by drying and cyclic loading (which led to increased adhesion), could actually improve the long-term resistance to permanent deformation (in reference to dry material). This can be seen by comparing tests F1 (initially dry) and F3 (initial rainfall event), which resulted in a lower settlement after maintenance (long term period; after drying). This can also confirm the reason why in this case bitumen stabilisation did not have a significant influence on results.

For the same tests, resilient modulus and dissipated energy per cycle are reported in Figure 6.15 and Figure 6.16, respectively.

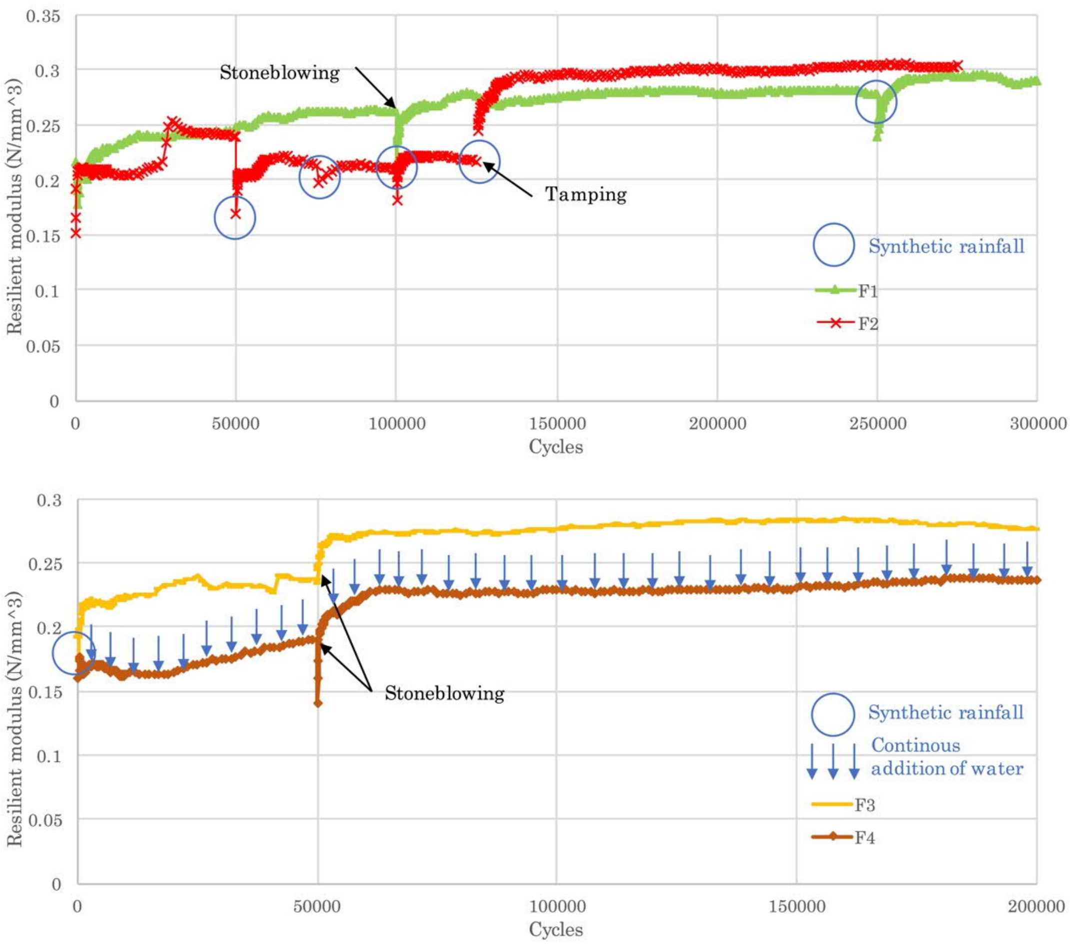

Figure 6.15 – Influence of water application on resilient modulus for fouled ballast used in this study.

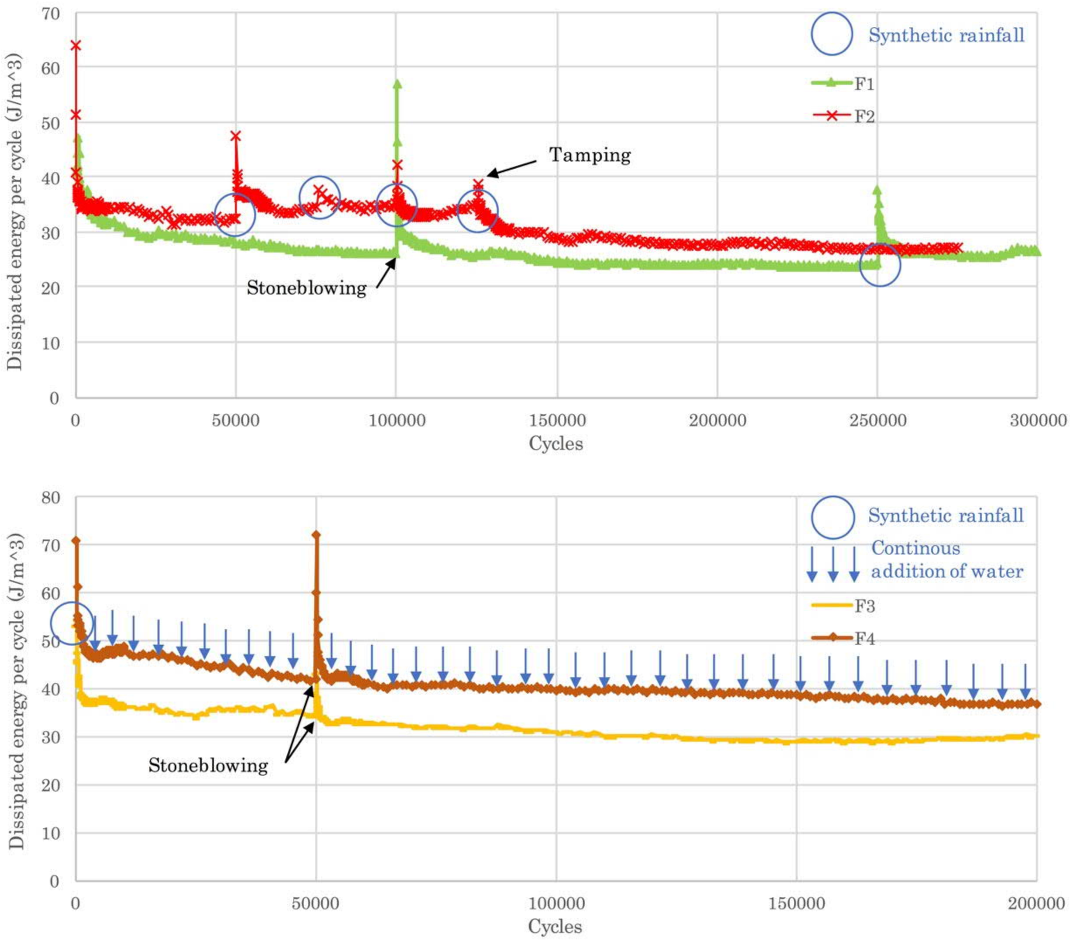

Figure 6.16 – Influence of water application on resilient modulus for fouled ballast used in this study.

It can be noted that water application corresponded to a sudden variation in both these parameters. In particular, stiffness had an abrupt fall during the water application while increasing again after this process. This variation matches the increases in permanent deformation shown in Figure 6.14.

The behaviour in terms of energy dissipation (Figure 6.16,) mirrors that described for stiffness: abrupt increases of dissipated energy per cycle followed the applications of water while these values started to decrease during the drying process.

6.4.4 BSB maintainability

In order to assess the maintainability of a section stabilised with BE, after the series tamping + BSB for clean ballast (following 2 repetitions of the same series) both tamping + BSB and stoneblowing maintenance operations were simulated.

The results of these tests in terms of settlement are plotted in Figure 6.17.

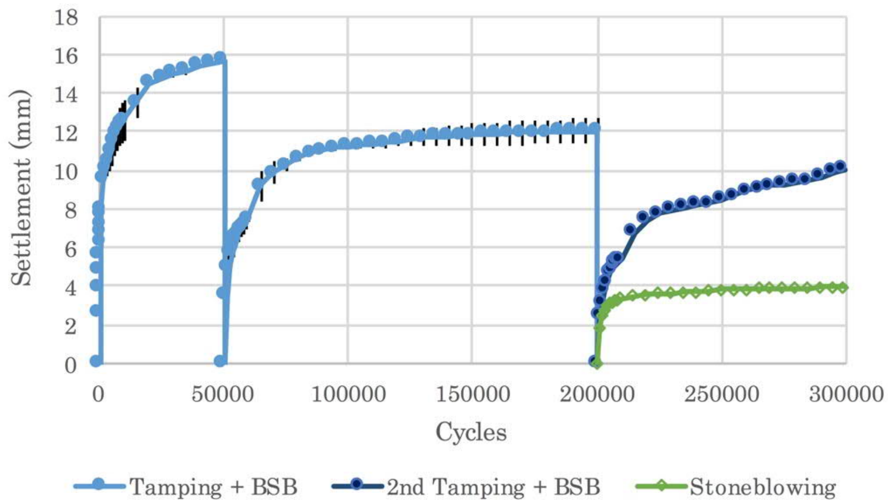

Figure 6.17 – Influence of future maintenance operations on settlement of existing BSB track-beds.

It can be noted that applying a stoneblowing operation to maintain BSB resulted in an additional small settlement of the ballast layer. It is worth noting that this settlement was almost half those obtained after the stoneblowing application at 50,000 cycles in Figure 6.5. In this case, in fact, the final settlement is mostly due to the initial compaction of stoneblowing stones, while the long-term settlement rate reflects pre-maintenance BSB behaviour. In this regard, this operation, which does not disturb the already compacted and stabilised layer, represents the ideal maintenance process for future geometry correction of BSB track-beds.

For the scenario including a second tamping coupled with BE stabilisation, it can be observed that after the second maintenance process, ballast exhibited approximately the same value of settlement as after the first operation. This indicates that the repetition of this alternative maintenance technique in the field could potentially maintain its effectiveness. It can therefore represent a feasible solution to increase conventional maintenance performance in countries where only tamping is available.

For both scenarios, average values for the last 40,000 cycles (from 260,000 to 300,000) of stiffness and dissipated energy have been compared with those of BSB before the second maintenance operations (baseline – from 160,000 to 200,000). These results are shown in Figure 6.18.

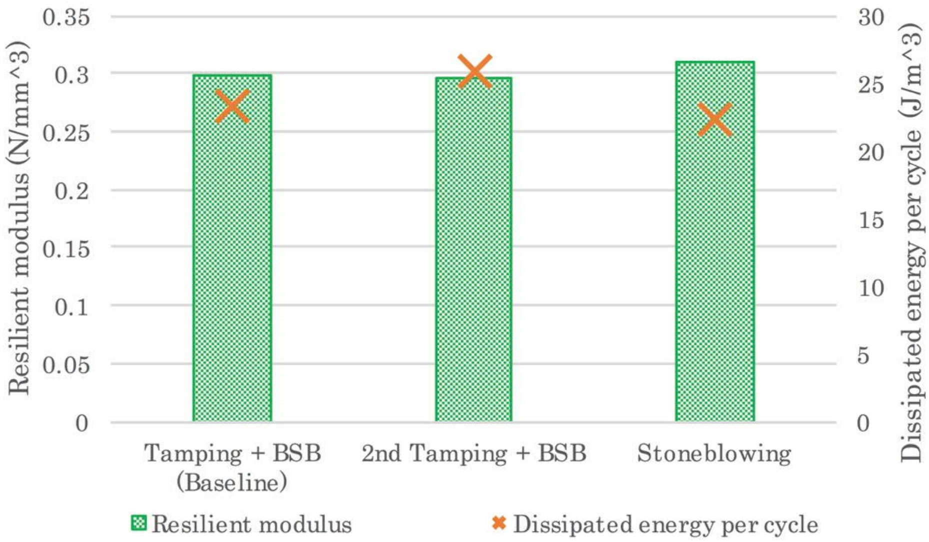

Figure 6.18 – Influence of future maintenance operations on mechanical behaviour of existing BSB track-beds.

It can be noted that overall the mechanical properties of BSB were little influenced by either maintenance processes. Nonetheless, a slight stiffening effect could be noted after the stoneblowing application, which correlates with results shown in previous sections.

At the same time, looking at tamping series, it is possible to observe a low increase in energy dissipation which correlates well with the second application of BE (as explained in Section 4.4.1).

6.4.5 Effectiveness of BE stabilisation for newly constructed track-beds

In order to compare results obtained from the two ballast boxes, the stoneblowing series (with and without BE stabilisation) carried out with the smaller box (I) have been repeated using the larger ballast box (II). Results in terms of settlement, reported in Figure 6.19, show that both tests mirror those obtained with the smaller box (I), indicating that results obtained with the two boxes are comparable with each other.

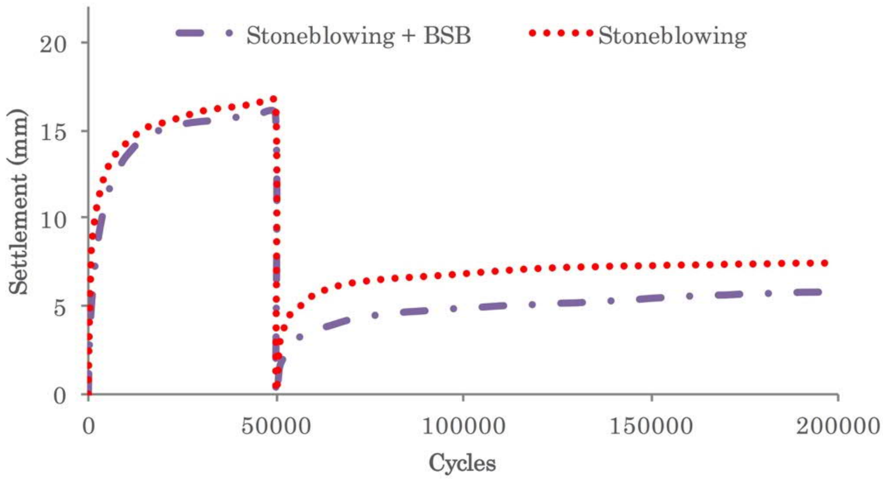

Figure 6.19 – Influence of BE stabilisation on settlement when applied during stoneblowing for clean ballast using the lager box (II).

Figure 6.20 shows the deformational behaviour of newly constructed BE stabilised ballast compared with unbound ballast, used as reference, from full-scale ballast box (II) tests.

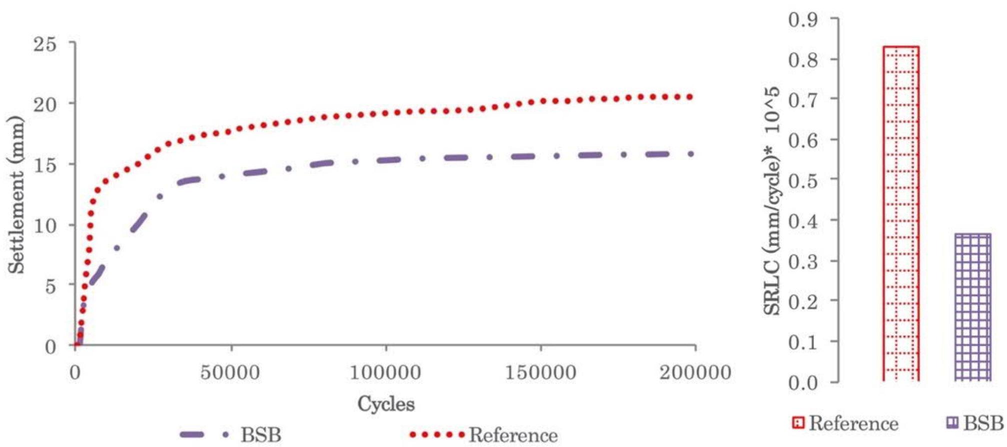

Figure 6.20 – Influence of BSB applied after new construction: Settlement and SRLC.

It can be noted that BSB provided a decrease in final settlement of approximately 25% in comparison with the conventional ballast without BE. This decrease is given in part by a lower initial settlement (first compaction) but also by the long-term deformation (SRLC of last 40,000 cycles) which is less than half that of the unbound reference ballast. This suggests that this technology applied to new tracks would provide longer intervals before maintenance to correct geometry is needed.

It is important to highlight that, when the same type of BE application (right after compaction, simulating the application to new tracks) was carried out at model-scale, higher reductions in final settlement values (approximately 60%) were observed. This is attributed to the higher number of contact points between particles (where bitumen emulsion acts as a gluing agent) present at model-scale, as found also for polyurethane stabilisation (Rostler et al. 1966). At the same time, the reduced volume stabilised (only below the sleeper/ballast contact area), despite being the zone characterised by the highest pressure, is deemed to have an influence on this result. Another possible factor can be the type of test used. Indeed, different from the box test, in the PUMA test material cannot move upwards while is slightly allowed to expand laterally. Thus, the higher variation in plastic deformation between bound and unbound material (more prone to rearrange) could be also attributed to this key difference between the two tests.

In Figure 6.21 the mechanical performance in terms of stiffness and energy dissipation for the fouled ballast series are reported. In these graphs, rates of stiffness and energy dissipation (as for the long term SRLC) are calculated for the last 40,000 cycles, when the behaviour was stable, as in Equation (6.2) and Equation (6.3):

$$Slope\ of\ Resilient\ modulus = \frac{R_N - R_0}{N} \tag{6.2}$$

$$Slope\ of\ Dissipated\ energy = \frac{DE_N - DE_0}{N} \tag{6.3}$$

where N is the number of cycles considered whereas the R_N, DE_N and R_0, DE_0 represent the resilient modulus and the dissipated energy per cycle values at the end and the beginning of the range considered, respectively.

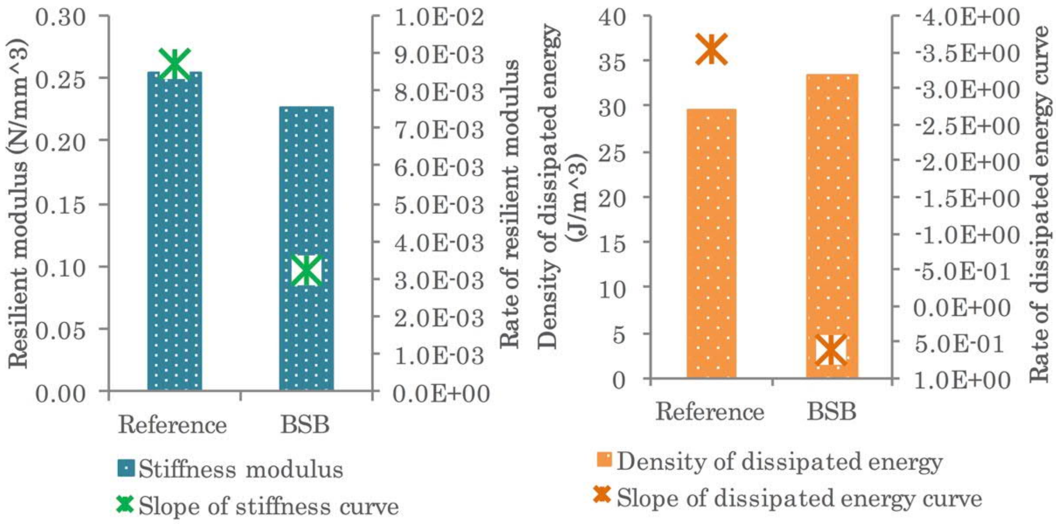

Figure 6.21 – Influence of BSB applied after new construction on ballast mechanical properties.

It can be observed that in this case again the influence of BE stabilisation on ballast mechanical properties is relatively low. These results, in comparison with those of model-scale, are attributed again to the different BSB conditions discussed for the settlement results. This aspect will be further discussed in Chapter 7.

Nonetheless, it is worth noting that the use of BE allowed for a more stable behaviour (lower slope of stiffness and dissipated energy curves), which could imply less variation in track performance during service life (Dahlberg 2004).

The use of BSB can have a significant impact also on track-bed durability. In this regard, Figure 6.22 and Figure 6.23 report the influence of BSB of ballast particle deterioration and stress transmitted to sublayers, respectively.

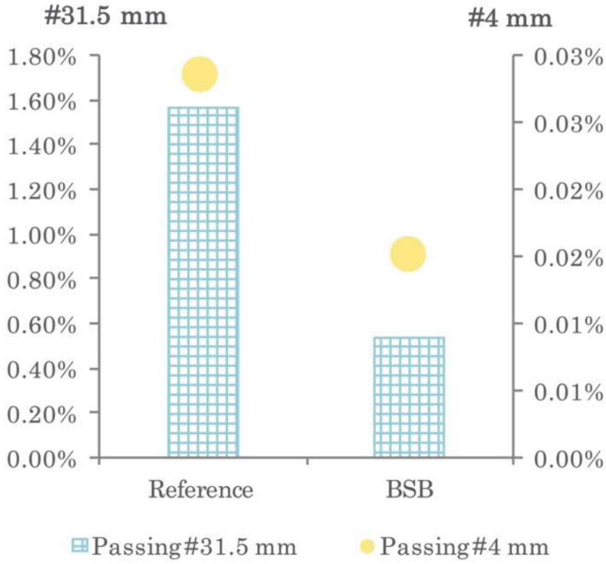

Figure 6.22 – Influence of BSB on ballast durability: variation of % by weight of particles with size lower than 31.5 mm and 4 mm.

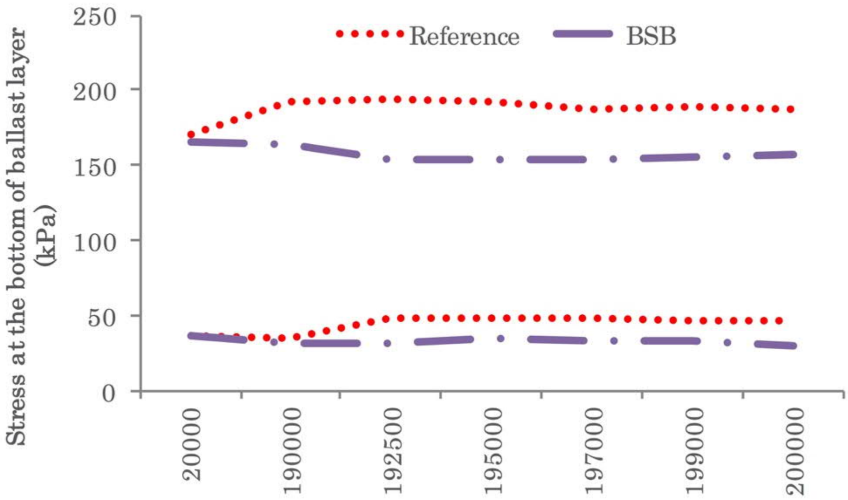

Figure 6.23 – Influence of BSB on stress beneath the ballast layer.

In particular, Figure 6.22 reports the increased amount (in % by weight) of particles with size lower than 31.5 mm and 4 mm, obtained from gradations before and after box tests (as in Section 6.4.2). It can be observed that bitumen by providing a cohesion component was able to significantly reduce (50% - 65%) the deterioration due to abrasion and breakage of particles.

At the same time, from Figure 6.23 it can be observed that, from a similar value of stress level of approximately 170 kPa (maximum stress at cycle 20,000), for the reference ballast stress increased by 10% (which can be attributed to progressive compaction) whereas for BSB a slight decrease (-5%) was measured. This difference was associated again with the addition of a cohesive component (bitumen) which allowed for a better stress distribution through the layer, as shown for other stabilising techniques (Boler 2012). This finding can represent an important benefit especially for field situations characterised by subgrades with poor mechanical properties (Indraratna et al. 2011).

6.5 Conclusions

This part of the research focused on the influence that bitumen stabilisation of a ballast layer can have on track-bed performance when coupled with conventional maintenance operations as well as for newly constructed tracks. Preliminary, full-scale flowability tests were used to select the type of BE to be used for full-scale ballast box tests. At the same time, additional tests investigating the influence of water for fouled ballast and BSB maintainability have been carried out.

The main conclusions are as follows:

- Properties of BE such as viscosity (related to binder content) as well as gradation of the granular layer can significantly influence the flowability of BE through that layer. For a fresh coarse-sized ballast layer, high viscosity BE (approximately 70% binder content) is suggested to minimise the amount of material lost. Nonetheless, depending on ballast properties and environmental conditions specific studies would be required to select the most appropriate BE.

- In order to increase ballast durability, bitumen stabilisation appears to be much more effective when applied at an early stage of ballast life. Under these circumstances (clean ballast), bitumen stabilisation maximises track performance in terms of settlement when coupled with tamping, providing a significant decrease to permanent deformation and to deformation rate (long-term behaviour). This allows for an important reduction in the frequency of such maintenance. The effects of stabilisation carried out after stoneblowing on settlement were lower. Nonetheless a long-term settlement improvement was observed as well as a contrasting effect on the stiffening of the track.
- In this regard, results indicate also that BE can have an important influence on track stiffness variation when a high volume of air voids is generated just after tamping during early stages of track life (with clean ballast), providing a more stable behaviour.
- As bitumen stabilisation allows for a reduction in maintenance interventions due to a decrease in ballast settlement (particularly in the case of tamping), this technique could lead to an important decrease in ballast degradation. In addition, as observed for the stoneblowing series, the increasing shear strength due to the cohesion component could reduce abrasion between particles and therefore ballast contamination.
- The effectiveness of BSB is drastically reduced for fouled ballast as a consequence of the reduced air voids which prevented homogenous stabilisation.
- Additional tests carried out for this type of fouled ballast showed that water addition had a higher influence at the first application. Nonetheless, for wet specimens, the progressive drying process could have led to an apparent cementation (negative pore pressure – increased adhesion) of fouled ballast which improved the resistance to permanent deformation with respect to the same specimen kept wet during the test (F3 and F4). These results jointly with those of previous chapters suggest that parameters such as the type of material, amount of fouling and presence

of water, could also play an important role in the effectiveness of stabilisation of ballast by bitumen emulsion. In this regard, more tests varying the type of ballast and the nature of contamination agents are needed to better understand the influence of bitumen stabilisation on the behaviour of already degraded ballast.

- Existing BSB track-beds would be ideally maintained by stoneblowing, which does not disturb the already compacted and stabilised layer. Nonetheless, a further application of bitumen stabilisation coupled with tamping seems to maintain the same effectiveness over time. In this regard, additional tests could be carried out in future works.
- The application of BSB for newly constructed tracks simulated in the full-scale box, as for the previous tests at model-scale, showed that, by decreasing initial settlement and settlement rate (long term behaviour), there are longer intervals before maintenance to correct geometry is needed. BSB also provided a more stable behaviour (lower slope of stiffness and dissipated energy curves), which indicates lower variations in track performance during service life. In addition, with respect to conventional ballast, this technology, by reducing (or limiting its increase associated with ballast settlement) stress transmitted to the sublayers and the degradation of ballast particles, has shown the potential of increasing track-bed durability.

In comparison with results obtained at model-scale, it was possible to note a lower improvement in terms of final settlement and lower influence on mechanical properties provided by BE stabilisation. This was attributed to the lower number of contact points between particles at full-scale, to the reduced volume of ballast stabilised in the box and to the type of test itself. All these aspects were, therefore, investigated in the following study using a full-scale PUMA presented in Chapter 7.

Chapter 7 - Large PUMA test

Results discussed in the previous chapter obtained using a full-scale ballast box test confirmed that BSB could represent an effective solution to increase intervals between maintenance interventions. This chapter presents results obtained using full-scale PUMA box tests on BSB.

7.1 Introduction

The philosophy of all testing (model-scale and full-scale) on the proposed technology was to investigate the main parameters affecting the stabilisation process and BSB performance.

The initial experimental phase was carried out at model-scale using the PUMA test. Firstly, the feasibility of BSB technology with bitumen emulsion A was assessed and results showed that this technology had the potential to increase the resistance to permanent deformation of the ballast layer. Nevertheless, the first BE used had a poor efficiency during the stabilisation process, allowing a high quantity of material to be lost.

For this reason, using the same scaled tests, the second step focused on the optimisation of BE properties to select the type and dosage of BE to be used for the following full-scale investigation.

From these phases, it was found that stabilising aggregate with bitumen emulsion could reduce the settlement by approximately 60% and had a non-negligible influence on resilient behaviour.

The following step was to validate with full-scale ballast box tests the previous results while investigating applicability and maintainability of the proposed technology. The results of this laboratory investigation showed that bitumen stabilisation provided a settlement reduction of approximately 25% while not having a significant influence on the mechanical behaviour of ballast layer. In this regard, while confirming the potential of this technology to reduce maintenance costs, the main differences with respect to the previous phases were attributed to the different scale and the test conditions (volume stabilised, type of test).

In this context, in order to have a better understanding of the relation between the two scales used it was decided to carry out full-scale PUMA tests. This is a new equipment designed to simulate in-situ conditions of ballast subjected to traffic loading. At the same time, this phase focused on the influence of bitumen stabilisation on the long-term ballast behaviour (more than one million cycles). This laboratory investigation was carried out in cooperation with AECOM Ltd in Nottingham (during a secondment planned within the SUP&R ITN project).

7.2 Materials

The ballast used in this study was a granite sourced from Mountsorrel quarry in Leicestershire (UK), which was provided by AECOM. Table 7.1 shows the main physical and mechanical properties of the ballast, which indicate its compliance to UK Network Rail standards (BS EN 933-2 1996, RT/CE/C/006 2002, BS EN 1097-2 2010, BS EN 1097-1 2011, BS EN 933-1 2012, BS EN 933-3 2012, BS EN 1097-6 2013).

Table 7.1 - Mechanical and physical properties of Mountsorrel quarry granite ballast (Lafarge Tarmac Ltd 2015).

Property	Standard	Test result	Network specification
Los Angeles Abrasion (%)	EN 1097-2	13	≤20
Micro Deval (%)	EN 1097-1	4	≤7
Flakiness index (%)	EN 933-3	FI_{20}	≤35
Fine particle content (%)	EN 933-1	G_FRB A	G_FRB A
Length (%)	RT/CE/S/006	L_{RB}A	L_{RB}A
Fines content (%)	EN 933-2	f_{RB} A	f_{RB} A
Particle Density (Mg/m³)	EN 1097-6	2.64	-

In a progress meeting with the partner involved (AECOM), it was decided to test two ballast gradations in order to extend the use of results obtained for an internal project looking for technologies to reduce the thickness of existing ballast layers.

These ballast gradations are that typically used for normal ballast (NB) and stoneblowing stones ballast (SB), as shown in Figure 7.1.

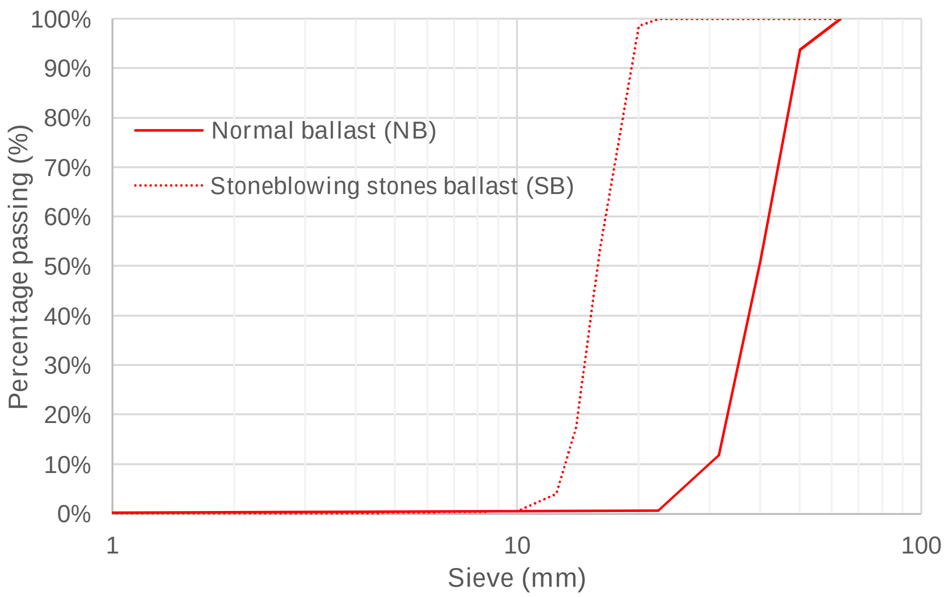

Figure 7.1 – Particle size distribution of the three gradations used.

Having selected from previous stages the most appropriate type, stabilisation was carried out using bitumen emulsion C. The optimum dosage of 3% by weight at model-scale was proportioned to these gradations in relation to the average ballast surface (the higher the surface the higher the BE dose needed), obtaining the dosages for each ballast as in Table 7.2.

Table 7.2 – Optimum BE C dosage in terms of percentage by weight for the ballast gradations used for full-scale PUMA test.

Normal ballast (NB)	Stoneblowing stones ballast (SB)
1.44%	3.69%

For normal ballast, it was shown in Chapter 6 that this dosage ensures the majority of BE C is retained within the ballast layer.

The test apparatus used, recently developed by Cooper Technology, consists essentially of a scaled-up version of the apparatus described in Section 4.3.1.2: eight steel curved wall segments and eight steel T-sections form a quasi-cylindrical chamber from which material is prevented from escaping when a load is applied (Figure 7.2).

Figure 7.2 – Full-scale PUMA test apparatus.

A rubber-lined steel band which confines the steel walls allows the possibility of wall movement under load, simulating the elasticity of surrounding material in-situ (Thom et al., 2013). As for the model-scale, the initial value of lateral stress can be set at the beginning of the test and monitored over the test. This stress typically accumulates progressively during the test with the number of repetition of vertical loading, simulating the in-situ condition. Lateral stress can be calculated from the strain gauge readings by Equation (4.1), where now h_b is 100 mm, r_s is 150 mm, h_s is 300 mm, while all the other parameters are as for Equation (4.1).

The desired vertical loading (measured by a load cell) is applied by a hydraulic system while vertical displacements are measured by means of a pair of Linear Variable Differential Transformers (LVDTs).

7.3 Methods

The main objectives of this laboratory investigation were (i) to better understand the relation between results obtained in the previous model scale and full scale tests, and (ii) to evaluate the long-term performance of bitumen stabilisation of ballast in terms of deformational behaviour and degradation of particles.

To answer the first objective, PUMA tests (in this up-scaled version of equipment used in Chapters 4 and 5) have been carried out using normal ballast (same gradation as clean ballast in Chapter 6). In this way, the differences in terms of final settlement and resilient behaviour between previous model scale and full scale tests could be associated either to the scale used or the test conditions (BSB volume, type of test, etc.).

The long-term behaviour was evaluated by increasing the number of loading repetitions (+1,000,000 loading cycles).

The testing plan used is summarised in Table 7.3.

Table 7.3 – Testing plan for full-scale PUMA tests.

Variables	Material tested	Test	Main parameters
-Ballast gradation	-Normal ballast (NB) -BSB – NB (C) -Stoneblowing stones ballast (SB) -BSB – SB (C)	-Large PUMA	-Plastic strain -Resilient modulus -Dissipated energy -Ballast deterioration

Each test was carried out using the following procedure.

Initially, the PUMA steel walls were confined by two thick steel bands in order to not damage the rubber-lined steel band with the strain gauges during sample preparation and conditioning.

For each ballast type, aggregate was placed inside the mould until it reached 300 mm depth in order to quantify the amount of material needed. Then, the specimen was removed to measure its gradation, necessary to measure particle deterioration at the end of the test.

After sieving operations, the ballast sample was poured again into the large PUMA mould and compacted. As for the full-scale ballast box (Chapter 6), also in this case the compaction was carried out by applying 100 cycles as conditioning for the sample.

After these operations, for reference unbound specimens the dynamic test was started. For BSB tests, specimens where stabilised by pouring at room temperature (approximately 20°C) the calculated amount of BE over the ballast. After a curing time of approximately 3 hours (quick setting BE), it was possible to start the PUMA test.

Figure 7.3 shows the appearance of the BSB after the emulsion had broken.

Figure 7.3 – Visual appearance of the stabilised specimen after emulsion setting before full-scale PUMA test.

Before starting the PUMA test, the rubber-lined steel band was placed and adjusted to apply an initial lateral pressure of 10 kPa, as representative of the in-situ confining pressure of self-standing ballast (Aursudkij et al. 2009) (as for PUMA tests in Chapter 4 and 5), while the thick steel bands used during compaction were removed in order to allow lateral movements.

To evaluate the influence of BSB on long-term behaviour a period of 1,200,000 load repetitions, corresponding to 30 MGT (25 t axle load), was considered. This number of cycles was reached by two steps: first 200,000 were applied (same number as in previous laboratory tests), then, after a day of rest, the other 1,000,000 cycles were applied.

Clearly, this number still represents a short period of ballast service life. However, as shown by other laboratory studies (Nurmikolu 2005), it was deemed to be long enough to highlight the phenomenon of ballast breakage.

In analogy with previous tests, the load amplitude was equivalent to 250 kPa under the sleeper applied at a frequency of 3 Hz – a frequency chosen in order to overcome initial problems with the hydraulic system.

Data were recorded during each cycle for the first 100 repetitions, each 100 cycles from cycle 100 to 10000 and then every 1000 cycles thereafter.

The main parameters analysed were the plastic strain, the resilient modulus, and the dissipated energy per cycle. Furthermore, to evaluate the influence of BE stabilisation on ballast degradation, gradations were measured before and after each test.

7.4 Results

Figure 7.4 shows the curves of settlement (minimum displacement values per cycle) recorded over the PUMA test for the scenarios analysed, while SLRC values are reported in Figure 7.5.

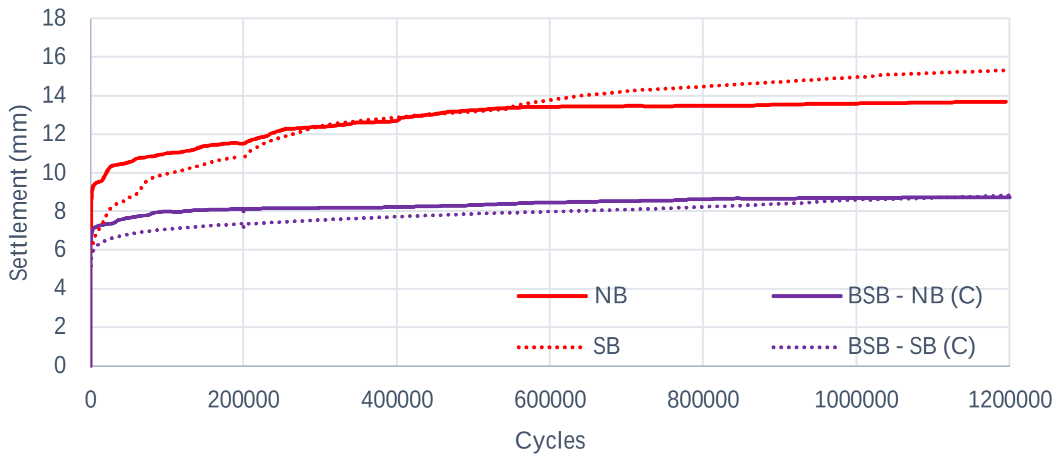

Figure 7.4 – Settlement over full-scale PUMA dynamic compression test for the scenarios analysed.

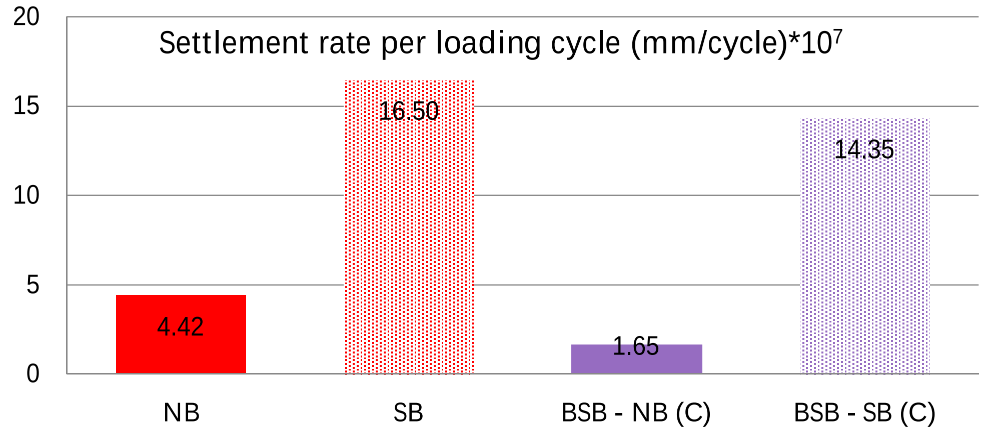

Figure 7.5 – SRLC (mm/cycle)*10^7 results for the scenarios analysed.

It can be observed that both BSB specimens exhibited lower final settlement and settlement rate than the reference ballasts, confirming again (see previous chapters) for these test conditions the positive effect provided by this technology, especially in the long-term. The reductions in settlement after 200,000 cycles (same number as for box tests) were slightly higher but very close to those obtained for clean ballast in chapter 6: approximately 27% and 29% for NB and SB, respectively. This indicates that it was not the type of test but the scale that was the main factor determining differences between results from model-scale PUMA tests and box tests in terms of BSB effectiveness (reductions in settlement with respect to unbound ballast). These reductions increase to approximately 34% and 42%, for NB and SB, respectively, after 1,200,000 cycles. This confirmed that BSB has a higher influence in the long term, as was found from box tests in chapter 6.

As regards the influence of ballast gradation, a similar behaviour can be observed for both bound and unbound materials. During the first part of the test (200,000 cycles) SB specimens exhibited lower settlement values than NB ones. This trend reversed in the long-term (from cycle 200,000 to cycle 1,200,000), as shown also by the considerably higher SLRC values for SB (Figure 7.5).

This was probably due to the lower initial air voids of SB gradation, which corresponded to a lower initial settlement. Once the initial compaction had taken place, smaller stones appeared to offer a lower shear strength (failure planes don't have to deviate much from their ideal lines in order to go around particles), favouring permanent deformation over the loading repetitions, for loading level used.

To evaluate the influence that the use of bitumen has on mechanical behaviour resilient modulus and energy dissipation were measured for all the material tested and results are shown in Figure 7.6.

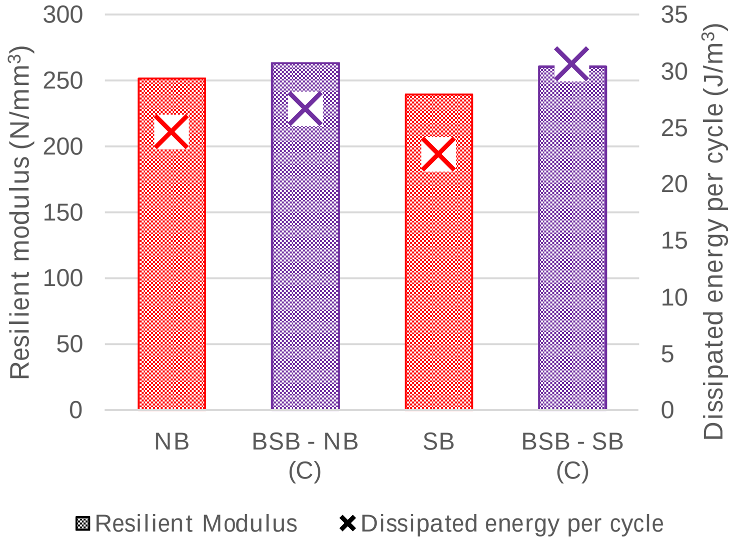

Figure 7.6 – Resilient modulus and dissipated energy per cycle for the scenarios analysed.

It can be observed that bitumen stabilisation did not provide significant variation in resilient properties when applied to normal ballast. As shown also in chapter 6, in this case, where there is a low number of contact points between particles, the influence of bitumen properties on the total material is relatively low. However, a little increase in the resilient modulus and energy dissipation was observed, which can be due to the stabilisation of the whole ballast volume in comparison with the box tests (chapter 6) where only the volume underlying the sleeper was stabilised.

For stoneblowing stones, instead, the number of contact points is considerably higher. In this case, the application of bitumen increased both stiffness and the ability to dissipate energy (viscoelastic material), which ties in with previous results obtained at model scale (chapters 4 and 5).

These results indicate that, differently from other stabilisation techniques, such as XiTrack® (Woodward et al. 2014), where a higher number of air voids are filled, bitumen stabilisation (carried out with the method and dosage presented) would not significantly affect in-field ballast mechanical properties. However, the use of different gradations combined with higher dosages (and types) of bitumen emulsions, could potentially modify these properties (as shown by model scale results). In this regard, future study could focus on the optimisation of this process for specific railway locations (switches, level crossings, bridge transitions, innovative track forms, etc.).

In order to evaluate the influence of bitumen stabilisation on particle deterioration, particle size distribution was measured before and after each PUMA tests and results are reported in Figure 7.7 and Figure 7.8.

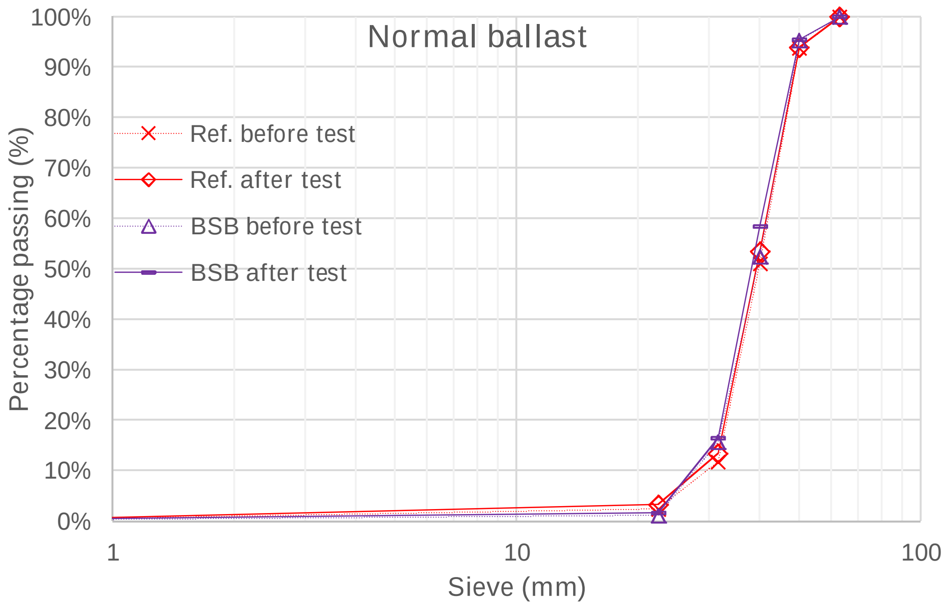

Figure 7.7 – Particle size distribution before and after PUMA test for NB.

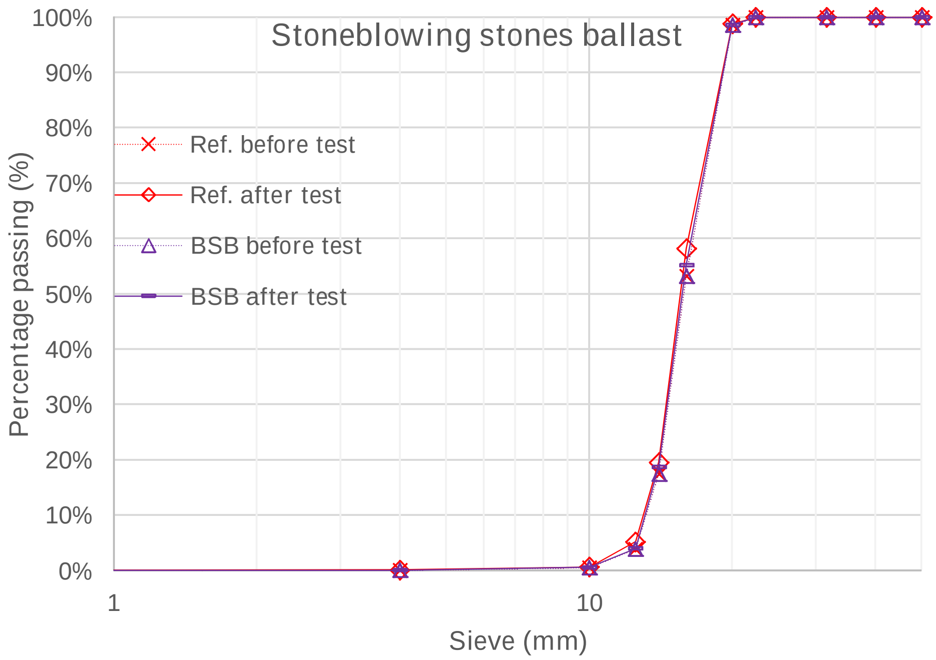

Figure 7.8 – Particle size distribution before and after PUMA test for SB.

It can be observed that in general bitumen stabilisation provided a better resistance to particle deterioration (due to breakage and abrasion – Figure 7.9) than the reference material. This was probably due to the addition of a cohesive component (bitumen) to the shear resistance with respect to unbound material (only frictional contacts between particles).

Of particular interest is the production of particles with size lower than 22.4 mm, which is the most relevant parameter used by rail authorities to determine when to clean or renew the ballast (Nurmikolu 2005, Berggren 2009). In this regard, the increase in particles lower than 22.4 mm for BSB – NB (C) was almost half that for normal ballast: 0.48% against 0.90%. This indicates that the use of bitumen as a stabilising agent can potentially also postpone major renewal due to excessive ballast contamination.

Figure 7.9 – Examples of particle breakage for reference ballast after PUMA test.

7.5 Conclusions

Full-scale PUMA laboratory testing carried out in this part of research aimed to gather a better understanding of the relation between the results obtained using the small-scale PUMA and those obtained using the full-scale ballast box.

In addition, the influence of bitumen stabilisation on the long-term ballast behaviour was investigated by extending the number of cycles to 1.2 Million, corresponding to 30 MGT (25t axle load).

For these conditions, two different gradations have been used to assess the influence of bitumen stabilisation on ballast behaviour: normal (conventional) ballast (NB) and stoneblowing stones ballast (SB). Results obtained led to the following conclusions:

- Overall, bitumen stabilisation confirmed to be an effective technique to reduce settlement and settlement rate of ballast, potentially increasing intervals between maintenance to correct track geometry.
- In particular, the settlement reduction after 200,000 cycles for NB was similar (slightly higher) to that obtained in the box tests, for the same gradation. This indicates that the scale factor instead of the test type is the

main factor controlling the effectiveness of BSB in terms of permanent deformation reduction.

- A similar conclusion can be drawn in terms of stiffness and DE variations due to BE stabilisation. Full-scale PUMA results reflected those obtained in box tests. However, a small increase in both properties was observed for BSB-NB (C), which is attributed to the stabilisation of the whole ballast volume in comparison with the box tests (chapter 6) where only the volume underlying the sleeper was stabilised.
- When considering, instead, lower size aggregate (SB), both stiffness and DE increased when sample was stabilised with BE, confirming what obtained for small-scale PUMA testing. This confirms that, when increasing the number of contact points, it increases also the influence of viscoelastic properties given by the bitumen. This indicates that the use of different gradations combined with higher dosages (and types) of bitumen emulsions, could potentially modify track-bed mechanical properties in a beneficial manner.
- As regard the long-term behaviour, it was found that BSB could have an even higher influence on ballast settlement rate and particle degradation when considering a longer window of traffic (30 MGT). This indicates that the application of this technology can potentially postpone both minor and major maintenance operations.
- Also, for both unbound and stabilised ballast, the use of stoneblowing stones (SB) gradation for the total (300 mm) depth of ballast layer, which appeared to reduce settlement in the short term (200,000 cycles), resulted in worse performance in terms of deformational behaviour in the long term. This was attributed to the fact that, after the initial compaction, smaller stones appeared to offer a lower shear strength since failure planes don't have to deviate much from their ideal lines in order to go around particles.

- Nevertheless, the improvement given by the presence of bitumen, was evident also for this gradation, being the final settlement very similar for both BSB-N (C) and BSB-SB (C).

Key findings obtained from this sections, but also from previous ones, consistently show evidence of the fact that bitumen stabilisation can reduce number of maintenance interventions due to geometry corrections and excessive particle degradation. In this regard, it was deemed interesting to attempt estimating the impact of BSB on maintenance strategies and consequently assess its feasibility in terms of economic and environmental impacts, which are investigated in the next chapters.

Chapter 8 - Integrated maintenance model for BSB

8.1 Introduction

Simulative laboratory tests carried out at model-scale and full-scale have shown that BSB technology has the potential to improve track geometry resiliency and reduce ballast degradation. This potential was especially highlighted by the full-scale PUMA tests with more than one million cycle repetitions, where the improvement given by bitumen stabilisation in terms of long-term settlement was considerably higher than that obtained in the first 200,000 cycles.

However, the adoption of such a technology in existing tracks would increase economic and environmental costs related to the upgrade of maintenance machines, the use of bitumen emulsion, the modified productivity of maintenance operations, among others. These burdens should be compensated by the reduction in maintenance frequency in order to deliver economic, social and environmental benefits over a track-bed lifecycle. Indeed, the scope of this research was to investigate new solutions to increase sustainability of traditional ballasted tracks.

Thus, the final part of this research aims to assess the sustainability of the technology here investigated in comparison with current practices. For this purpose, a novel integrated method will be used to estimate minor and major interventions for both traditional ballast (unbound) and stabilised ballast BSB (bound).

This model combines the evolution of the standard deviation (SD) of track irregularities with traffic and the level of contamination of ballast allowing calculation of the timing of maintenance activities (Shimatake 1997, Pires 2016). To understand how variations of a set of parameters and assumptions affect the robustness of the model a sensitivity analysis to the traffic volume and the quality level set for the infrastructure has been carried out.

8.2 BSB guidelines

At this stage, BSB technology has been developed through laboratory experiments simulative of field conditions in order to evaluate its effectiveness and the main factors affecting the stabilisation process and mechanical behaviour. However, more information is needed to provide guidance on BSB application and maintainability in the field while allowing the estimation of its costs and impacts. For this purpose, this section aims to offer some guidelines on the use of BSB for future field applications based on the development procedure and the assumptions made in this research.

- Application method:

The initial concept behind this technology was to reduce maintenance of existing ballasted tracks with a relatively economic solution to extend ballast service life, which is also relatively easy to apply. In this regard, in order to minimise the traffic disruption, bitumen stabilisation would be ideally applied during a routine maintenance operation to correct track geometry such as tamping or stoneblowing. The calculated amount of BE would be sprayed over the ballast surface by a system analogous to that used by the stoneblower where the sleeper is raised up during the maintenance process, as illustrated in Figure 8.1.

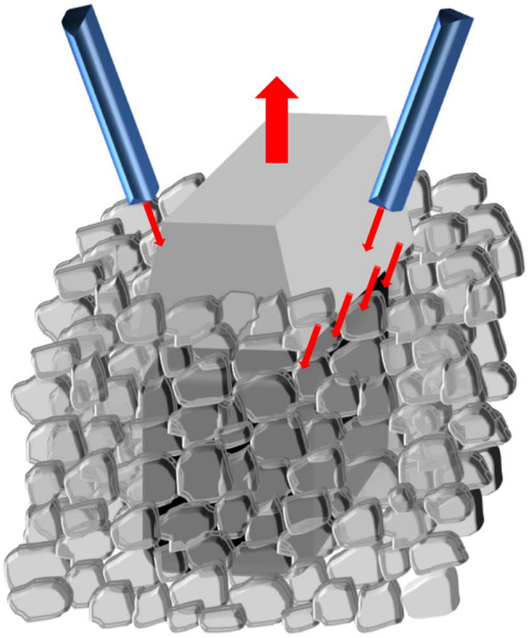

Figure 8.1 – Schematic illustration of ballast stabilisation process with bitumen emulsion.

To carry out this operation, the ordinary tamping and stoneblowing machines would need to include an additional railcar storing the bitumen emulsion and a system to blow the calculated amount of BE for each specific section. It would be useful to install more tanks to store bitumen emulsions with different viscosity, necessary to stabilise ballast with different degrees of voids contamination.

- Ballast volume stabilised:

In order to stabilise only the ballast subjected to the highest contact pressure (Shenton 1975, Pires 2016) it is considered that one third of the sleeper length per sleeper end should be treated by this operation. This procedure, which was simulated in the full-scale box tests (Chapter 6), represents a convenient way to use the same machine to perform both geometry correction and ballast stabilisation with bitumen at the same time. For instance, an optimum dosage for clean ballast was found to be 1.44% by weight of the ballast underlying the sleeper/ballast contact area (Chapter 6), typically equating to about 1.5 litres per sleeper end. As an example, considering a ballast bulk density of 1600 kg/m^3 (Aursudkij et al. 2009, Indraratna et al. 2011, Merheb et al. 2014), a monoblock concrete sleeper 280 mm long and 240 mm wide with a sleeper spacing of 600 mm and a ballast layer depth of 300 mm, 355 tons of ballast per km would be involved in this type of stabilisation. Thus, 5.1 tons of bitumen emulsion would be necessary for 1 km of track.

By stabilising this volume of ballast, an improved resistance to permanent deformation in terms of both initial settlement and long-term settlement rate was observed (see Chapter 6). Nevertheless, the full-section stabilisation of the ballast layer could increase this performance. In this case, however, a more complex system injecting BE should be installed in the maintenance cars.

- BSB track-bed maintainability:

Despite having shown the potential for a significant reduction in the need for both minor and major maintenance operations, bitumen stabilised ballast track-bed will require a certain amount of maintenance to restore track geometry and will need renewal at the end of its life. Indeed, based on the initial concept, the stabilised layer would ideally be maintained by stoneblowing in order not to alter the cohesive bridges between particles given by bitumen application. This operation, simulated in the full-scale ballast box (Chapter 6), would not modify the BSB structure and so represents an optimum way to restore track geometry while preserving the improvements brought about by BE application (Figure 6.17). However, stoneblowers are available in only a few countries, tamping being the most common maintenance process used for geometry correction worldwide. In contrast to stoneblowing, tamping may damage the BSB structure due to the vibrating action of tines. In this regard, as with other stabilisation techniques (Lakušic et al. 2010, Kennedy et al. 2013, Laurans et al. 2016), BSB can be considered to have built-in safety to the extent that the loss of cohesion would result in the ballast reverting back to an unbound state. Nevertheless, until further studies on BSB maintainability are conducted, it would be conservative to assume an additional BE application where tamping is used to correct track geometry.

- BSB end of life:

By the same principle, at this stage of the technology development, especially when using lifecycle approaches to assess the economic feasibility and environmental impacts of this innovative technology, it would be conservative to consider the total replacement of old BSB during renewals. In this regard, future studies should focus on the maintainability of BSB through methods which can optimise the reuse of bitumen coated aggregate, allowing recycling of BSB during renewal operations and increasing savings from a lifecycle point of view.

8.3 Track geometry degradation

In order to define the maintenance strategies for each scenario considered, the initial track quality, the component deterioration laws and the limits for the quality indexes need to be known so that specific maintenance interventions can be forecasted.

After estimating the maintenance work, it will be possible to calculate their durations (based on machine working rates) and related costs (possession hours). This step is necessary not only to quantify the type, the number and duration of each maintenance operations but also to allocate costs at different times. This will allow discounting of every cost to the present value and comparison of different scenarios (net present value – Chapter 10).

For this purpose, it is necessary to establish the quality level of the infrastructure based on which the future maintenance can be estimated.

As discussed in Chapter 2, track geometry degradation is affected by several factors, among which traffic loads and speed, construction materials and methods, and maintenance history are the most relevant (Audley and Andrews 2013). Track geometry is described by several parameters, the most important being (BS EN 13848-5:2008+A1:2010 2010): vertical alignment (or longitudinal level), horizontal alignment, gauge, cant and twist (Figure 8.2).

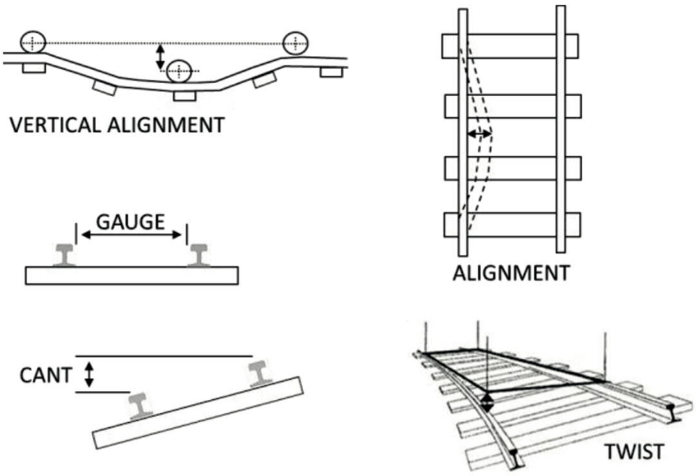

Figure 8.2 – Track quality parameters (Pires 2016).

Standards prescribe minimum and maximum allowable values for these parameters based on the type of railway line. BS EN 13848 (BS EN 13848-5:2008+A1:2010 2010) states the existence of three indicators of track quality: extreme values for isolated defects, standard deviation (SD) in a typical length (200 m), and mean value.

Depending on the type of line and the speed, there are three main limits for these indicators above which different actions need to be undertaken (BS EN 13848-5:2008+A1:2010 2010):

- Immediate Action Limit (IAL): refers to the value which, if exceeded, requires taking measures to reduce the risk of derailment to an acceptable level. This can be done either by closing the line, reducing speed or by correction of track geometry;
- Intervention Limit (IL): refers to the value which, if exceeded, requires corrective maintenance in order that the immediate action limit shall not be reached before the next inspection;

- Alert Limit (AL): refers to the value which, if exceeded, requires that the track geometry condition is analysed and considered in the regularly planned maintenance operations.

As an example, Table 8.1 reports the intervals corresponding to these three levels for track gauge isolated defects as a function of the track speed (BS EN 13848-5:2008+A1:2010 2010):

Table 8.1 – Limits for AL, IL and IAL for track gauge isolated defects according to BS EN 13848 (adapted from BS EN 13848-5:2008+A1:2010 2010).

Speed (in km/h)	Nominal track gauge to peak value (in mm) AL		Nominal track gauge to peak value (in mm) IL		Nominal track gauge to peak value (in mm) IAL	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
V ≤ 80	-7	+25	-9	+30	-11	+35
80 < V ≤ 120	-7	+25	-9	+30	-11	+35
120 < V ≤ 160	-6	+25	-8	+30	-10	+35
160 < V ≤ 230	-4	+20	-5	+23	-7	+28
230 < V ≤ 300	-3	+20	-4	+23	-5	+28

In order to plan and/or predict maintenance interventions, rail authorities and practitioners often use the standard deviation as a convenient measure of quantifying the geometry quality of a track section (Chrismer & Selig, 1991), since it can be used to describe track geometry to a considerable degree of accuracy (Selig and Waters 1994).

In this regard, Table 8.2 shows the alert limits for the longitudinal level SD according to European Standards (BS EN 13848-5:2008+A1:2010 2010).

Table 8.2 – Longitudinal level AL standard deviation according to BS EN 13848 (adapted from BS EN 13848-5:2008+A1:2010 2010).

Speed (in km/h)	Standard deviation (SD) (in mm) AL	
	Minimum	Maximum
V ≤ 80	2.3	3
80 < V ≤ 120	1.8	2.7
120 < V ≤ 160	1.4	2.4
160 < V ≤ 230	1.2	1.9
230 < V ≤ 300	1	1.5

A similar classification is given by Network Rail standards. Table 8.3 shows the limits for SD for the vertical alignment depending on the speed range (NR/L2/TRK/001/mod12 2015).

Table 8.3 – Track geometry quality band Standard Deviation (SD) values (in mm) for 35m wavelength filter of longitudinal level (top) (NR/L2/TRK/001/mod12 2015).

Speed band (in mph)	Standard Deviation (SD) track geometry quality band for 35 m wavelength filter (in mm)				
	Good	Satisfactory	Poor	Very poor	Maximum
10 < V ≤ 20	5.2	7.4	8.3	9.9	> 9.9
25 < V ≤ 30	4.3	6.1	7.0	7.7	> 7.7
35 < V ≤ 40	4.1	5.8	6.7	7.2	> 7.2
45 < V ≤ 50	3.8	5.4	6.3	6.7	> 6.7
55 < V ≤ 60	3.5	5.0	5.9	6.3	> 6.3
65 < V ≤ 70	3.0	4.3	5.4	6.0	> 6.0
75 < V ≤ 80	2.7	3.8	4.8	5.7	> 5.7
85 < V ≤ 95	2.2	3.2	4.0	5.3	> 5.3
100 < V ≤ 110	1.9	2.7	3.4	5.0	> 5.0
115 < V ≤ 125	1.7	2.4	3.0	4.7	> 4.7

8.4 Track degradation models

When quality indices exceed the above-mentioned limits, maintenance is needed to restore quality. However, as mentioned in Chapter 2, maintenance can contribute to ballast deterioration, thus decreasing its effectiveness over time.

This typically causes an increasing frequency of interventions over time, which eventually does not allow any sensible post-maintenance improvement of track quality (Pires 2016). In this case, major maintenance operations such as renewals are the most convenient solutions.

Once the limits for the track quality geometry are defined, it is possible to estimate maintenance activities for the period of analysis. For this purpose, the use of track degradation models is necessary to predict the time when maintenance is needed to restore track quality. This task is an essential element in maintenance planning. In this regard, the loss of track quality is due to a combination of many factors, the major one being the repetitive passage of trains (Pires 2016). Experience shows that track quality degradation is a function of load amplitude and number of repetitions (Million Gross Tons, MGT) (Hausgaard 2013).

Over the past 30 years, several attempts have been employed to develop analytical models to predict degradation of railway tracks. An extensive literature review (Audley and Andrews 2013, Caetano and Teixeira 2016, Pires 2016) revealed that field data of track geometry degradation (SD of track irregularities) are best fitted by linear empirical laws as in Equation (8.1):

$$SD(MGT) = A + C \cdot MGT \tag{8.1}$$

where SD(MGT) is the standard deviation corresponding to the traffic in MGT; A is the initial value of standard deviation; and C is the deterioration rate – the coefficient which relates the standard deviation to the cumulative traffic after the initial degradation phase (A).

By periodic inspection of the track this relationship can be determined for each specific section. However, according to Veit (Veit 2006), wide variations are observed in the deterioration rate. Generally, it is observed that deterioration rate is smaller for high initial track quality levels (Veit 2006), which emphasizes the importance of designing, constructing and managing railway track at the highest possible quality level. This variability is also present within the same track section: the same loading level, indeed, due to the heterogeneity and anisotropy of all granular layers, can cause different local settlements, leading to the phenomenon of suspended sleepers. This can then amplify total track settlements because the sleepers located on both sides of a suspended sleeper must support higher loads (Dahlberg 2004), leading to increasing maintenance frequency.

According to Esveld (Esveld 2001), excluding quick deterioration occurring immediately after tamping, track deterioration rate increases linearly with the number of maintenance operations. Esveld (Esveld 2001) reports some mean deterioration rates varying from 0.007 to 0.02 mm/MGT. Similar results (0.005 to 0.025 mm/MGT) were reported by Khouy (Khouy 2011) for a Swedish line with mixed passenger and freight traffic. Slightly lower values, varying between 0.00217 and 0.0119 mm/MGT, were presented by Hawari and Murray (Hawari and Murray 2008) for three heavy haul lines in Australia.

While it is the differential settlement which largely causes geometric track irregularities, this is a complex phenomenon to be modelled because of its dependence on heterogeneity of track-bed granular layers. Thus, most of the models consider track settlement (or track vertical strain) as the main controlling factor in track degradation (Shenton 1985, Chrismer and Selig 1991, Shimatake 1997). This is a convenient parameter which can be simulated through field trials and laboratory tests and can be used for comparing different design and maintenance technologies/strategies especially at the early stage of the development process.

However, in order to relate settlement to maintenance requirements, there is a need to establish a link between track irregularities, which vary along the track, and track average settlement. In this regard, vertical alignment (and its standard deviation) constitute the most representative measurement of track quality (Audley and Andrews 2013). Selig and Waters (Selig and Waters 1994) and Berggren (Berggren 2009) reported studies showing that, excluding the initial settlement just after maintenance, the SD of track irregularities grows almost proportionally to track settlement over at least a moderate range of ballast life (Figure 8.3).

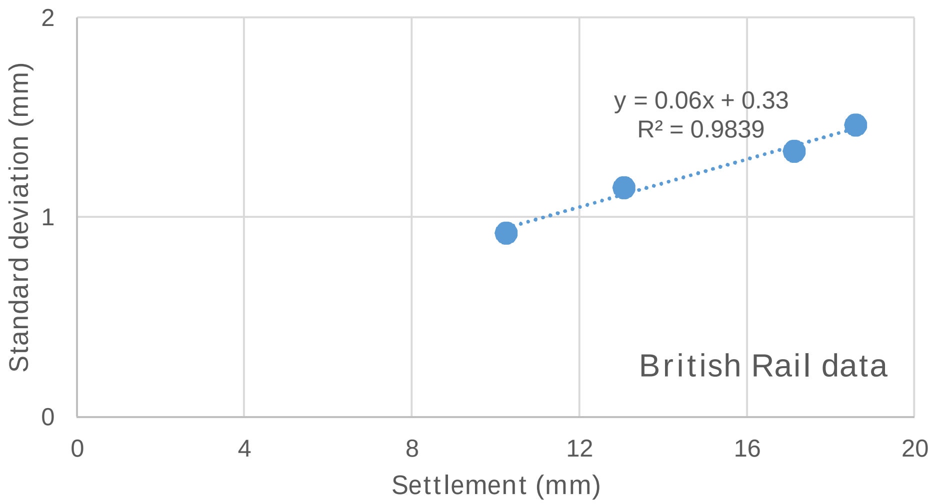

Figure 8.3 – Relationship between the standard deviation of track irregularity and average track settlement (adapted from Selig and Waters 1994).

At the same time, as discussed in Chapter 2, ballast settlement provides the highest contribution to total track-bed settlement, while the other layers (when not stressed over their bearing capacity) usually make only a minor contribution to further settlement (Figure 8.4) (Selig and Waters 1994).

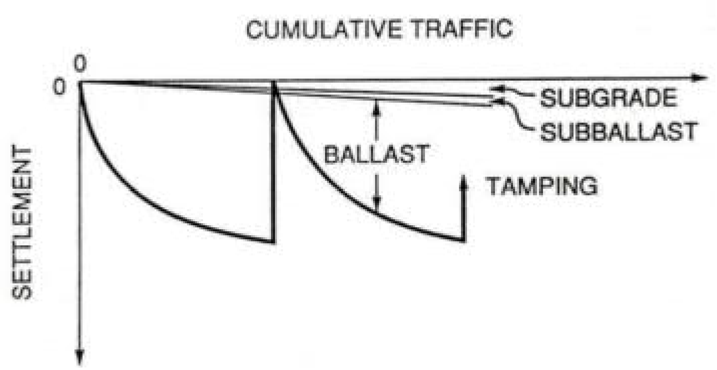

Figure 8.4 – Contribution to the total settlement of track-bed granular layers (Selig and Waters 1994).

8.5 Development of an integrated track deterioration model

To schedule maintenance activities over a period of analysis, track degradation models, evaluating the evolution of track quality indicators, need to be used. Two indicators were considered for the evaluation of maintenance strategies of both BSB and the reference (unbound) ballast: the standard deviation of track irregularities (vertical alignment) and the ballast contamination level. The minor and major maintenance operations here considered (tamping and renewal) are scheduled after critical levels of track geometry (SD) and ballast layer contamination are reached.

The evolution of the standard deviation of track irregularities with traffic for both reference ballast and BSB was calculated using Equation 8.1.

For this equation, the coefficient A, which is the initial value of standard deviation, was assumed to be equal to 0.33 mm (Shimatake 1997, Pires 2016). This was assumed to be the same for both materials because it represents the initial condition of the track after construction or major renewal.

To evaluate the coefficient C, which controls the rate of degradation with the traffic, the value of settlement rate per loading cycle (SRLC, calculated as curve slope over the last 40,000 cycles) from full-scale laboratory tests on BSB and reference ballast carried out using a ballast box was used (Figure 6.20 - Chapter 6).

SRLC values were converted to SD using the correlation proposed by Selig and Waters (Selig and Waters 1994) for British Rail, as in Equations (8.2) and (8.3):

$$C_{Ref} = SRLC_{Ref} \cdot 40000 \cdot 0.06 = 0.02\,mm/MGT \tag{8.2}$$

$$C_{BSB} = SRLC_{BSB} \cdot 40000 \cdot 0.06 = 0.008\,mm/MGT \tag{8.3}$$

In these equations, the SRLC values were firstly converted from mm of settlement/cycle to mm/MGT (40000 factor – 25 t axle) and then to mm of SD/MGT (0.06 - Figure 8.3).

The C_{Ref} value, calculated in this way, ties in with those reported by other authors using field measurements (0.005-0.025 mm/MGT) (Esveld 2001, Khouy 2011).

Although the degradation rates may vary between tamping cycles, in this model for forecasting purposes, they were assumed to be constant. At the same time, in order to take into account the progressive loss of effectiveness of maintenance (Audley and Andrews 2013), an efficiency of 95% in restoring the geometry after tamping, compared to the previous intervention, was assumed (Shimatake 1997, Caetano and Teixeira 2016, Pires 2016).

Another important parameter used to determine the appropriate timing of renewals is ballast contamination level (Pires 2016). In this regard, current practice is usually that railway infrastructure managers refer to predetermined values of MGT thresholds or other indicators, using as a criterion the level of ballast contamination. This indicator of degradation of the ballast layer must not exceed specific limits. Nevertheless, these values vary between countries (Bruzek et al. 2016), with no common requirements and a lack of consensus on grain-size diameter and fouling parameters used to define contamination levels. In European countries, for instance, one suggested limit is 30% for particles passing the 22.4 mm sieve (Nurmikolu 2005).

Several studies have evaluated ballast degradation in test arrangements simulating traffic loading. An extensive review of these studies is provided by Nurmikolu (2005). The intention of the present analysis is to use laboratory results of ballast particle deterioration obtained within this research in order to predict the level of contamination in the ballast. For this purpose, in agreement with European standards (Nurmikolu 2005, BS EN 13450:2013 2013), ballast degradation, D(MGT), has been defined as the percentage of particles passing the 22.4 mm sieve. Two contributions are considered in the evaluation of ballast degradation: the mineral contamination due to the progressive abrasion and breakage under the cyclic loading and the contamination due to maintenance operations (Audley and Andrews 2013), as in Equations 8.4 and 8.5:

$$D_{ref}(MGT) = D_{traffic,ref} \cdot MGT + D_{tamping} \cdot N_{tamping}(MGT) \quad (8.4)$$

$$D_{BSB}(MGT) = D_{traffic,BSB} \cdot MGT + (D_{tamping} + D_{BSB}) \cdot N_{tamping+BSB}(MGT) \quad (8.5)$$

where $D_{traffic,ref}$ and $D_{traffic,BSB}$ are the percentages of particles passing the 22.4 mm sieve per MGT for reference ballast and BSB, respectively, obtained from full-scale PUMA tests (Figure 7.7 – Chapter 7); $D_{tamping}$ = 0.5% is the percentage of particle passing the 22.4 mm sieve generated per tamping operation (Nurmikolu 2005); D_{BSB} = 1.52% is the additional percentage of material passing the 22.4 mm sieve due to the addition of BE (calculated from the dosage used for clean ballast); $N_{tamping}$ and $N_{tamping+BSB}$ are the number of maintenance operations for reference ballast and BSB, respectively.

Having defined both models, it is possible to predict minor and major maintenance operations as a function of MGT, as shown in Figure 8.5 and Figure 8.6, where the sudden improvements represent the tamping and renewal actions, respectively.

In this scenario, maintenance strategies are defined as a function of traffic for both tamping (indicated as Reference) and tamping + BSB (indicated as BSB) considering a SD limit of 2 mm (assuming a medium speed line) (BS EN 13848-5:2008+A1:2010 2010) and a 30% limit for particles passing the 22.4 mm sieve (Nurmikolu 2005).

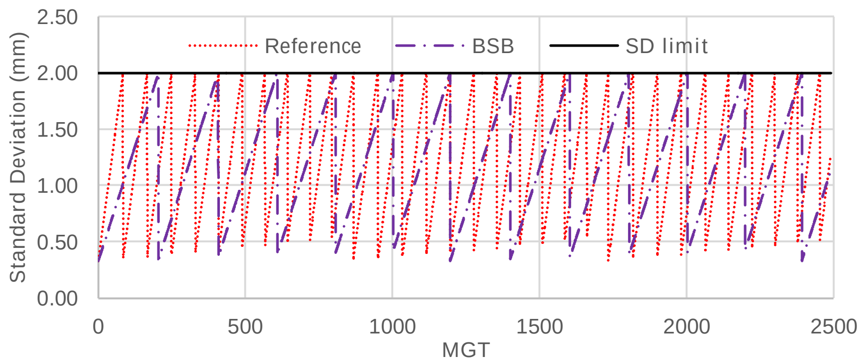

Figure 8.5 – Evolution of standard deviation of track irregularities with MGT for reference ballast and BSB for an SD limit of 2 mm.

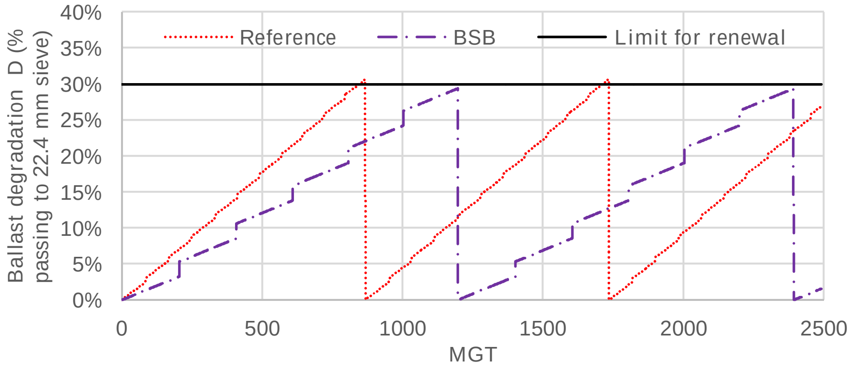

Figure 8.6 – Evolution of ballast contamination due to MGT and tamping operations for reference ballast and BSB for a 30% limit of particles passing the 22.4 mm sieve.

It is possible to observe increased intervals between maintenance activities due to the use of BSB which, if proven in reality, could result in important economic and environmental benefits.

In the following section a sensitivity analysis will be presented in order to understand how variations in the set of parameters and assumptions affect the output from the model. Thus, the relative effects of different factors may be evaluated and compared. Two parameters have been considered with different levels: SD limit and annual MGT.

8.6 Influence of traffic and quality level on maintenance strategies

In order to understand how variations of certain parameters and modelling assumptions affect the outcomes, and consequently the possible advantages of using BSB instead of traditional ballast, a sensitivity analysis was carried out. Thus, the relative effects of different factors may be evaluated and compared.

In this research, two parameters were considered with different values: SD limit and annual MGT. The standards prescribe maximum allowable values for SD that can be different for different countries. Varying SD means that the acceptable track quality level changes and thereby the timing for minor maintenance activities.

Therefore, the sensitivity analysis was firstly carried out by varying the SD limit from 1.5 mm to 4 mm (with intervals of 0.5 mm) while keeping constant and equal to 20 MGT the initial traffic volume (medium traffic). Afterwards, the sensitivity of results to the cumulated traffic expressed in MGT was ascertained by considering to additional values, namely 10 (light traffic) and 40 MGT (heavy traffic) (Hensley and Rose 2000), while keeping constant the initial SD limits. The traffic growth rate was assumed to be 0.5% per year while a 30% limit is taken for particles passing the 22.4 mm sieve (Nurmikolu 2005, Berggren 2009). In this research, which focuses only on maintenance operations related to the ballast layer, the period of analysis was taken to be 60 years (MAINLINE Deliverable 5.4 2013, Pires 2016). Based on these assumptions, the results of this sensitivity analysis are summarised in Figure 8.7 and Figure 8.8.

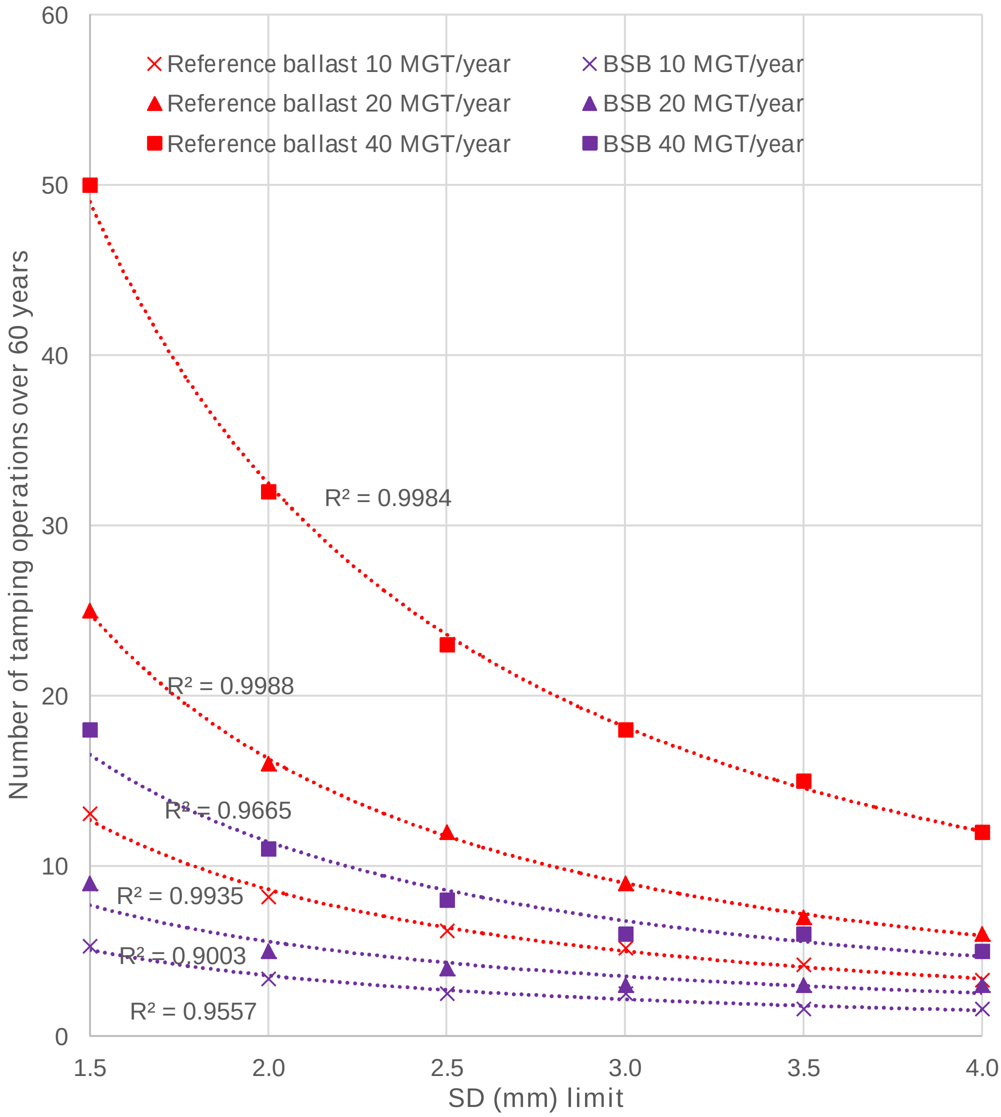

Figure 8.7 – Evolution of the number of tamping cycles over the period of analysis (60 years) with SD limit for traffic levels considered (10, 20 and 40 MGT/year) for reference ballast and BSB.

Table 8.4 – Power laws ($y = B\,x^{-F}$) coefficients from Figure 8.7.

Power laws coefficients	10 MGT		20 MGT		40 MGT	
	Reference ballast	BSB	Reference ballast	BSB	Reference ballast	BSB
B	21.871	8.343	44.991	12.191	87.556	27.875
F	-1.344	-1.228	-1.465	-1.133	-1.432	-1.287

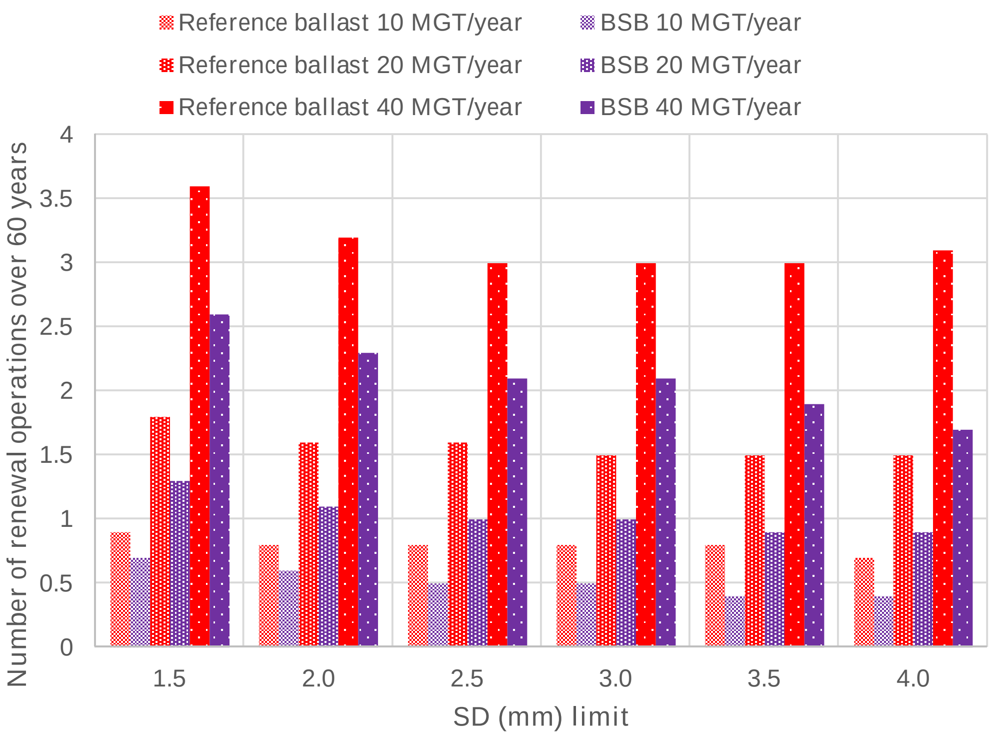

Figure 8.8 – Evolution of the number of renewal operations over the period of analysis (60 years) with SD limit for traffic levels considered (10, 20 and 40 MGT/year) for reference ballast and BSB.

As expected, since BSB gives a lower settlement rate, the number of tamping operations is reduced with respect to the reference ballast for all the level of traffic and SD limit. The amplitude of this reduction, approximately 60% ±10%, appears to be slightly affected by both parameters.

The effect of this reduction can then be appreciated also looking at the ballast contamination predictions: while for a single maintenance operation BSB makes a higher contribution to material passing 22.4 mm (due to addition of BE, considered as a contaminant), the reduced number of interventions together with a lower degradation rate increases the intervals between renewals in comparison to the reference ballast. This improvement generally increases with higher SD limits (lower quality level of track geometry), as can be noted from Figure 8.8. In this regard, it is interesting to observe that, while for reference ballast the number of renewals is not significantly affected by the quality level, for BSB it decreases almost proportionally with the SD limit.

Indeed, as for the case of reference ballast, also for BSB little variations between scenarios would be expected, because the number of tamping operations gives a lower contribution to contamination compared to traffic. However, when the intervals between minor operations become relatively long (BSB scenarios with increasing SD limits), the lower particle degradation rate given by bitumen stabilisation plays the most important role in increasing ballast service life.

It is worth remarking that, for each scenario, the intervals between tamping operations progressively decrease due to the loss of efficiency of the operation itself (95% efficiency which implies a decrease in A coefficient in Eq. 8.1) and the assumed increase in traffic (0.5% per year).

Furthermore, it may be observed that for each scenario the evolution of the number of tamping operations with the SD limit is well fitted (R^2 values reported in Figure 8.7) by a power law (coefficients tabulated in Table 8.4), indicating how maintenance costs and impacts are not proportional to the quality level of the infrastructure.

8.7 Conclusions

This chapter aimed at evaluating the potential advantages of the application of bitumen stabilised ballast defining a novel maintenance strategy for traditional ballasted track-beds. A protocol for the application of BSB technology and its associated maintenance strategy was defined. An integrated model, based on laboratory tests simulative of field conditions, was used to estimate minor and major interventions for both traditional ballast (unbound) and stabilised ballast BSB (bound). The integrated model developed, by combining the evolution of SD with traffic and the level of contamination of ballast, allowed evaluation of the timing of corrective maintenance activities. A sensitivity analysis related to traffic volume and SD limit has been carried out in order to understand how variations affect the robustness of the model.

From the results obtained it can be concluded that: (i) overall the use of BSB can increase intervals between both minor and major maintenance activities; (ii) the reduction in maintenance operations to correct geometry due to the use of BSB is almost independent of the quality level set for the infrastructure and the traffic level while the reduction in number of renewals provided by ballast stabilisation is generally greater with higher SD limits; (iii) according to the proposed model, the evolution of the number of tamping operations with the SD limit follows a power law, thus indicating that costs and impacts due to minor maintenance are not proportional to the quality level set for the infrastructure.

The lower number of maintenance operations expected when BSB is adopted, represents a substantial step forward in reducing the use of non-renewable resources. Indeed, even allowing for the cost of bitumen emulsion, the improvement in ballast performance, which increases the durability of its function, is likely to result in net benefits in terms of environmental and economic impact. Therefore, in order to evaluate the feasibility and sustainability of BSB, the following phases will focus on life cycle cost analysis (LCCA) and life cycle assessment (LCA) of such a technology, based on the maintenance strategies developed in this Chapter.

Moreover, for future studies the integrated model proposed, which is deterministic in nature, could usefully be graded by introducing a probabilistic approach, taking into account the variability of the different parameters.

Chapter 9 - LCA of BSB

9.1 Introduction

Incorporating the principles of sustainability when constructing or maintaining transport infrastructure is becoming more and more an essential requirement for reducing undesirable impacts on the environment and human health.

In order to ascertain if the BSB track-bed is indeed better than the traditional ballasted track-bed from the environmental perspective, it is crucial to adopt a life cycle approach to identify and quantify the potential environmental burdens arising from the use of this solution. This need can be accomplished with the support of Life-Cycle Assessment (LCA) methodology (BS EN ISO 14040 2006). LCA, which is a data-driven, systematic methodology, has proven to effectively estimate the environmental burdens caused by a product, process, or service throughout its life cycle (Matthews et al. 2014).

LCA quantifies the environmental impacts of the complete life cycle of products which include processes, or services and encompass the extraction and processing of raw materials, manufacturing, transportation, maintenance, use, and end-of-life (Consoli and SETAC (Society) 1993).

LCA is historically relatively recent as it started being used in the 1970s. The application of LCA to railway infrastructure is even more recent (Horvath 2006, Chang and Kendall 2011, Vandanjon et al. 2012, Westin and Kågeson 2012) and analysis is often focused on the comparison of different modes of transport (Spielmann and Scholz 2005, Federici et al. 2008).

Analysing the materials, processes and transport emissions related to construction, maintenance and end-of-life phases, Milford and Allwood (Milford and Allwood 2010) concluded that by maximising the durability of the track-bed components it is possible to reduce significantly the emissions of CO_2 during the life cycle of the infrastructure.

In view of this, the main objective of this chapter is therefore to present a comparative LCA of traditional ballasted track-bed and BSB track-bed implemented in a rail track. This analysis allows the potential environmental impacts deriving from the use of this innovative technology to be identified and quantified.

9.2 Methods

A comparative attributional (Tillman 2000) and process-based LCA study is performed according to the ISO 14040 series (BS EN ISO 14040 2006). This calculates and compares the potential environmental impacts associated with the construction and maintenance of traditional ballasted and BSB track-bed.

The stages adopted in this study include goal and scope definition, inventory analysis, impact assessment, and interpretation.

9.2.1 Goal

The main goal of this analysis is to quantify the life cycle environmental impacts arising from the use of BSB technology as innovative maintenance practice. The results are compared with the life cycle impacts caused by the use of traditional ballast, as a reference. The findings of this analysis are intended to be used by engineering experts and practitioners to make more assertive judgments on the advantages and disadvantages associated with the use of emerging sustainable strategies and practices for railway track-bed construction, maintenance and rehabilitation.

9.2.2 System boundaries

The LCA has been performed from cradle to grave, thus, from resource extraction to the construction site, and including the transportation of materials, ordinary maintenance activities (tamping) and major interventions (renewal) with the ultimate goal of highlighting the principal potential differences, in terms of environmental burdens, between BSB and traditional ballast. A scheme of the system boundaries adopted is represented in Figure 9.1.

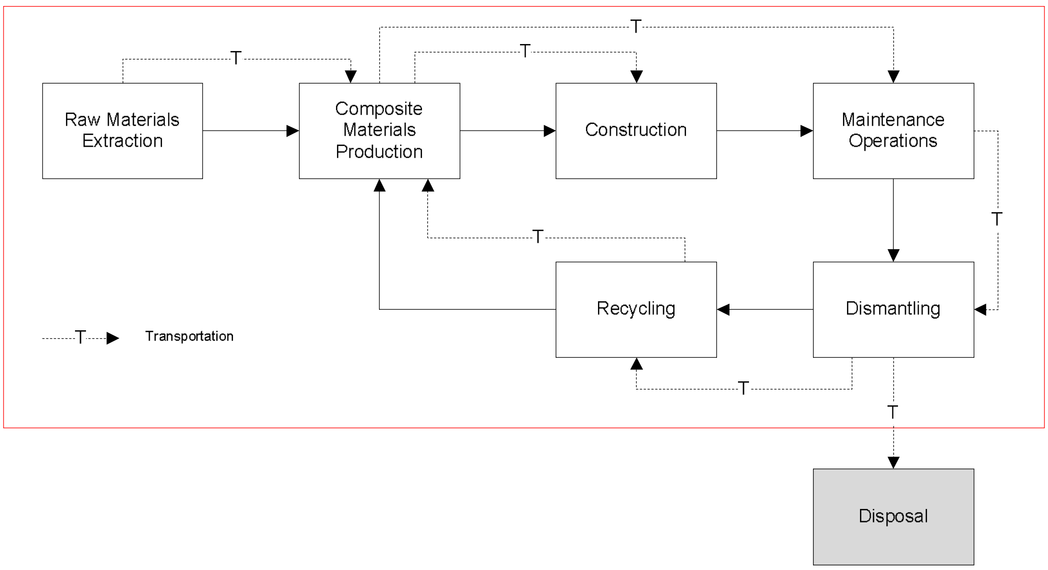

Figure 9.1 – Schematic representation of the life cycle stages considered in this research.

Specifically, the system boundaries of the proposed LCA model comprise individual but interconnected processes related to raw material extraction, composite material production and all the activities at the construction site. The resource extraction and composite material production consists of the acquisition and processing of raw material: bitumen production at refinery; extraction, crushing and sieving of aggregates. The construction phase includes ballast spreading and the use of specific construction equipment and machinery. The maintenance phase accounts for the operations involved in the performance of minor and major maintenance activities. The transportation of materials to and from the construction site and between intermediate facilities are also considered.

For this comparative analysis, only the ballast layer has been considered, since all the other track components are assumed to give the same impacts and therefore are taken out from this analysis. Nevertheless, the smoother degradation of track geometry potentially given by the use of BSB could also increase the life cycle of the other components of the track superstructure, reducing, thus, their maintenance burdens. In this regard, after evaluating these other impacts, future studies should take into account also these factors for a more detailed analysis.

9.2.3 Functional Unit

The functional unit for both solutions (traditional ballasted track-bed and BSB) is the maintenance of the quality level of a typical section of 1-km length of a ballast layer 30 cm deep, with an average (at the middle depth) width of 4 m, over 60 years for an initial traffic load of 20 Million Gross Tons (MGT) with a growth rate of 0.5% per year. This corresponds to a medium traffic volume (Hensley and Rose 2000).

9.2.4 Life cycle inventory (LCI)

The life cycle inventory (LCI) phase consists of the primary and secondary data collection and modelling of the system. Primary data are specifically related to the processes for obtaining the product or service studied in the LCA. In turn, secondary data represent generic or average data for the product or service subject to analysis. The provenance of that data includes literature, research groups, national and international databases and expert opinion (European Commission Joint Research Center - Institute for Environment and Sustainability (EC JRC - IES) 2010). In the present work, both primary and secondary data have been considered as detailed in the following sub-paragraphs. LCI data were collected from literature and interviews with designer, companies and experts involved in infrastructures construction works. Furthermore, the Construction materials database extension, the professional database of Gabi software, has been used as the main references for collecting from-cradle-to-grave LCIs of the materials involved in the system. Reference values for the productivity and working hours of the machinery involved were collected from literature (Kiani et al. 2008).

9.2.4.1 Ballast and BSB production

The virgin aggregates required for the ballast were modelled as crushed gravel and the inventory data associated with their production were obtained from the Construction materials database extension of Gabi software. For modelling the production of BSB material it is necessary to model the production of bitumen emulsion. The same database has been used for the LCI data corresponding to bitumen emulsion production. It comprises all the flows of materials and energy associated with the extraction, transport and refinement of crude oil. Table 9.1 summarises the principal characteristics of both materials.

Table 9.1 – Main characteristics of traditional ballast and BSB.

Type of solution	Components	Particle Density (kg/m^3)	Bulk density (kg/m^3)	Total quantity of ballast (kg/FU)	Quantity of ballast stabilised with bitumen emulsion (kg/FU)	Total quantity of bitumen emulsion (kg/FU)
Traditional ballast	Crushed gravel	2700	1600	1920000	-	-
BSB	Crushed gravel	2700	1623	1920000	354816	5109
	Bitumen emulsion	1060				

9.2.4.2 Machineries for construction, minor maintenance and major maintenance operations

Table 9.2 reports the working rates (productivity) of machines employed during the installation of ballast (construction phase) and maintenance operations (Shimatake 1997, Calla 2003, McMichael and McNaughton 2003, Kiani et al. 2008, MAINLINE Deliverable 5.4 2013, Pires 2016).

Table 9.2 – Productivity and fuel consumption of the machinery used in this analysis.

Operation	Productivity (h/km)	Diesel fuel consumption (l/km)
New construction/renewal	13.33	99.6
In-situ tamping of ballast	1.16	60.0
In-situ tamping of ballast + BSB	1.79	70.0

In the case of BSB, it is necessary to inject the bitumen emulsion (BE) at ambient temperature onto the ballast; thus, the tamper is followed by a rail cargo-tank containing bitumen emulsion. Therefore, the fuel consumption in this case includes not only the ballast-spreading machine but also the rail 'emulsion tanker' ("operation, maintenance, railway track [Railway]" available in the Construction materials database extension of Gabi software).

Ballast track-bed is renewed during its life cycle following the same specifications as for initial construction. Therefore, the same processes as for initial construction have been used.

9.2.4.3 Transportation of materials

The crushed gravel aggregate must be transported onto site. It was assumed that the materials (both aggregate and bitumen emulsion) move from the quarry and plants by truck, transported to the closest maintenance station for a distance of 100 km. Afterwards, they move from the station to the construction site on freight trains for a distance of 100 km. Therefore, the environmental impacts resulting from the transportation of materials are due to the emissions released by the combustion process of the transportation vehicles or the electricity consumed. All materials were assumed to be hauled by heavy duty vehicles, and the process "GLO: Truck, Euro 3, 20 - 26t gross weight / 17.3 t payload capacity ts <u-so>" described in the Construction materials database extension of Gabi software was used to determine the environmental burden associated with the transportation of materials on the road. Additionally, transportation movements performed by rail were modelled by means of the "GLO: Rail transport cargo - Electric, average train, gross tonne weight 1000t / 726t payload capacity ts <u-so>" in the Construction materials database extension of Gabi software.

9.2.4.4 Dismantling, recycling of materials and disposal

When the renewal is performed, the different materials are dismantled and then either recycled or landfilled. The End-of-Life (EoL) phase includes: i) dismantling of the track-bed; ii) transport to waste processing; iii) waste processing for reuse or recycling; iv) material landfill (Kupfer et al. 2017).

Due to the high level of contamination at the end of its service life, spent ballast has been considered as gravel for embankment material, e.g. fill for road construction without any structural role. BSB contains residual bitumen from bitumen emulsion and it could be recycled in upper layers of the road structure, similarly to RAP. Nevertheless, without sufficient information about the recycling process and performance of this material a conservative approach has been adopted and the dismantled BSB has been considered inert material for embankments (the same percentage and allocation as for traditional ballast).

9.2.5 Life cycle impact assessment (LCIA)

The life cycle impact assessment (LCIA) stage of the standardised LCA methodology comprises several steps, namely, classification, characterization, normalization, grouping and weighting (BS EN ISO 14040 2006). Among these steps, classification and characterisation were undertaken in this study.

The LCA was modelled in Gabi Professional Academy LCA software® (GaBi ts Software 7.3.3). The calculation of the impact category indicator results was performed at midpoint level by applying the LCIA ReCiPe method (Goedkoop et al. 2013). Only the analysis at midpoint level has been conducted without aggregating results at endpoint level in order to keep the uncertainty as low as possible. Indeed, each aggregation step contributes to increasing the uncertainty in the results (Hauschild and Huijbregts 2015). The aggregation of the different impacts categories with their relative weights and damage pathways is left to engineering experts and practitioners to make more assertive judgments based on more reliable results.

Specifically, the following impact categories were considered: climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, marine eutrophication, metal depletion, ozone layer depletion, particulate matter formation, terrestrial acidification, terrestrial ecotoxicity and water depletion. The ‘land use’ impact category was not taken into account in this analysis due to its high uncertainty (Latunussa et al. 2016).

9.2.6 Minor and major maintenance operations: triggers and scenarios analysed

The scenarios analysed in this chapter are all the outputs (maintenance strategies) obtained from the integrated model presented in Chapter 8, including the sensitivity analysis to the traffic level and the SD limit.

As mentioned in the previous chapter, maintenance operations are triggered by the limits assumed for both track geometry (SD) and contamination level, which are based on the cumulative traffic (growing at a constant rate every year). As a consequence, it would be possible to compare two different scenarios with the same total number of maintenance operations (e.g. renewal, which has the highest impact) but carried out in different years. Thus, in order to take into account the residual value (Lee 2002) of each maintenance operation (expected life span), and allow for a more precise comparative LCA between scenarios, at the year 60 (the last year of the period of analysis) each maintenance operation has been converted for its effective 'use', obtaining, therefore, a non-integer total number of each type of maintenance activity (see Figure 8.7 and Figure 8.8). Table 9.3 summarises these values.

Table 9.3 – Number of minor (N_T) and major (N_R) maintenance operations (including residual values) for both reference ballast and BSB as a function of SD limit and traffic level.

SD limit (mm)	10 MGT				20 MGT				40 MGT			
	Reference ballast		BSB		Reference ballast		BSB		Reference ballast		BSB	
	N_T	N_R	N_T	N_R	N_T	N_R	N_T	N_R	N_T	N_R	N_T	N_R
1.5	13.6	0.9	5.3	0.7	25.7	1.8	9.3	1.3	50.8	3.6	18.6	2.6
2.0	8.8	0.8	3.6	0.6	16.6	1.6	6.0	1.1	32.4	3.2	12.0	2.3
2.5	6.7	0.8	2.7	0.5	12.3	1.6	4.4	1.0	24.7	3.0	8.7	2.1
3.0	5.4	0.8	2.2	0.5	9.6	1.5	4.4	1.0	18.4	3.0	6.6	2.1
3.5	4.5	0.8	2.0	0.4	7.9	1.5	3.6	0.9	15.9	3.0	6.3	1.9
4.0	3.8	0.7	1.6	0.4	6.7	1.5	3.2	0.9	12.4	3.1	5.3	1.7

9.3 LCA results and discussion

Figure 9.2 reports the comparative analysis of tamping + BSB (minor maintenance for the BSB scenario) in relation to only tamping (traditional ballasted track, used as reference) across the impact categories of interest, for a single operation. These results are to be understood as follows: positive relative numbers mean that the BSB improves the LCIA results in relation to those associated with the traditional ballast (a positive variation means a benefit for the environment – for instance, lower production of CO_2e.) while negative numbers represent a worsening of the environmental and energy profile.

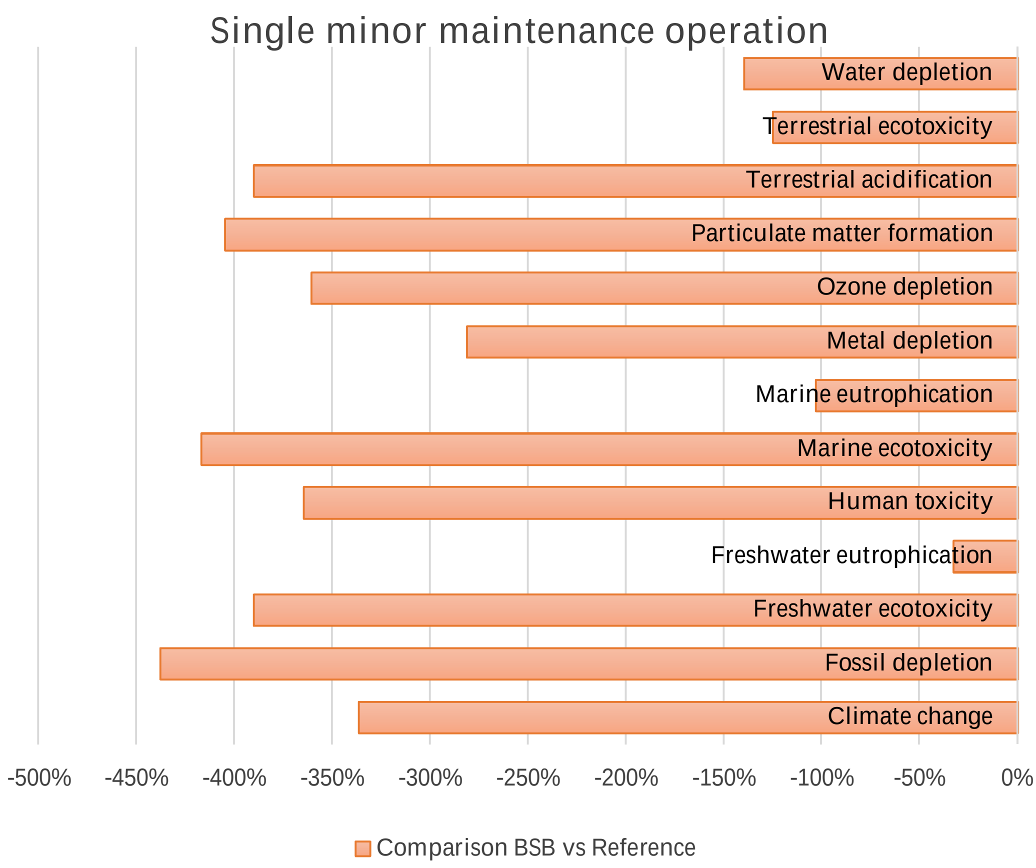

Figure 9.2 – Comparative life cycle impacts of BSB vs reference ballast (ReCiPe results midpoint method) for single minor maintenance operation.

As expected, for a single minor maintenance operation the use of BSB overall has a higher impact due to the addition of BE. This increase is significant for almost all indicators but least for water depletion, terrestrial ecotoxicity, marine and freshwater eutrophication.

The higher impact given by BSB could be compensated by the reduced frequency of minor maintenance operations due to a more stable geometry degradation. For this purpose, in reference to the scenarios analysed in section 8.6 (see also Table 9.3), LCA results due only to the minor maintenance operations are reported in Figure 9.3, Figure 9.4 and Figure 9.5 for 10 MGT, 20 MGT and 40 MGT, respectively.

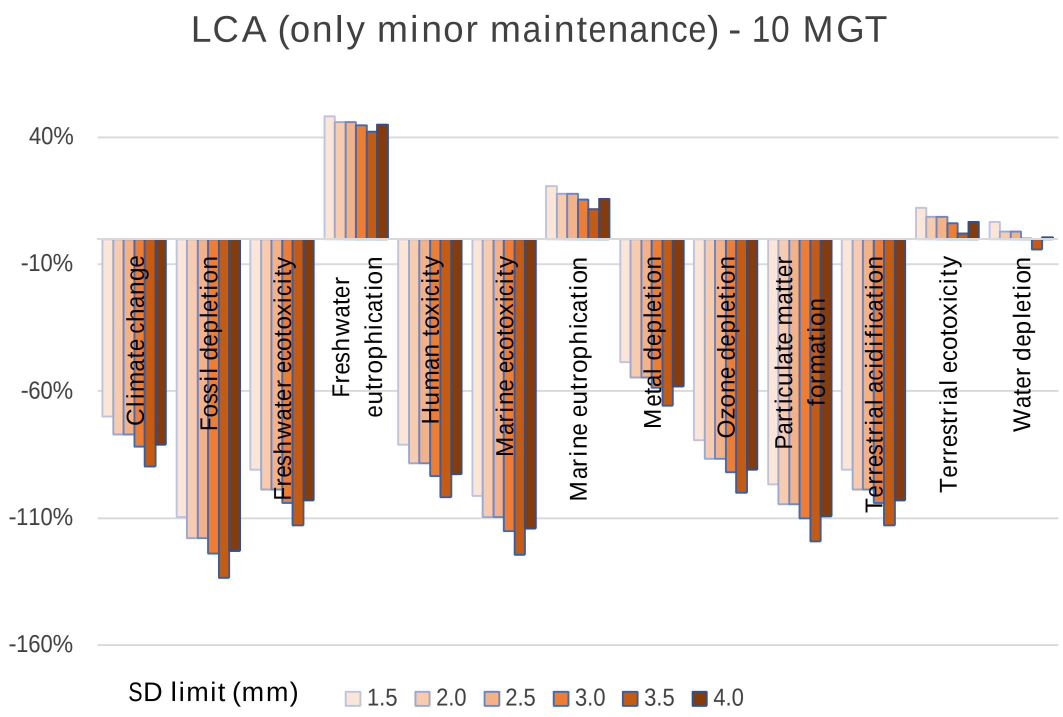

Figure 9.3 – Comparative life cycle impacts of BSB vs reference ballast (ReCiPe results midpoint method) due only to minor maintenance operations over the period of analysis for 10 MGT.

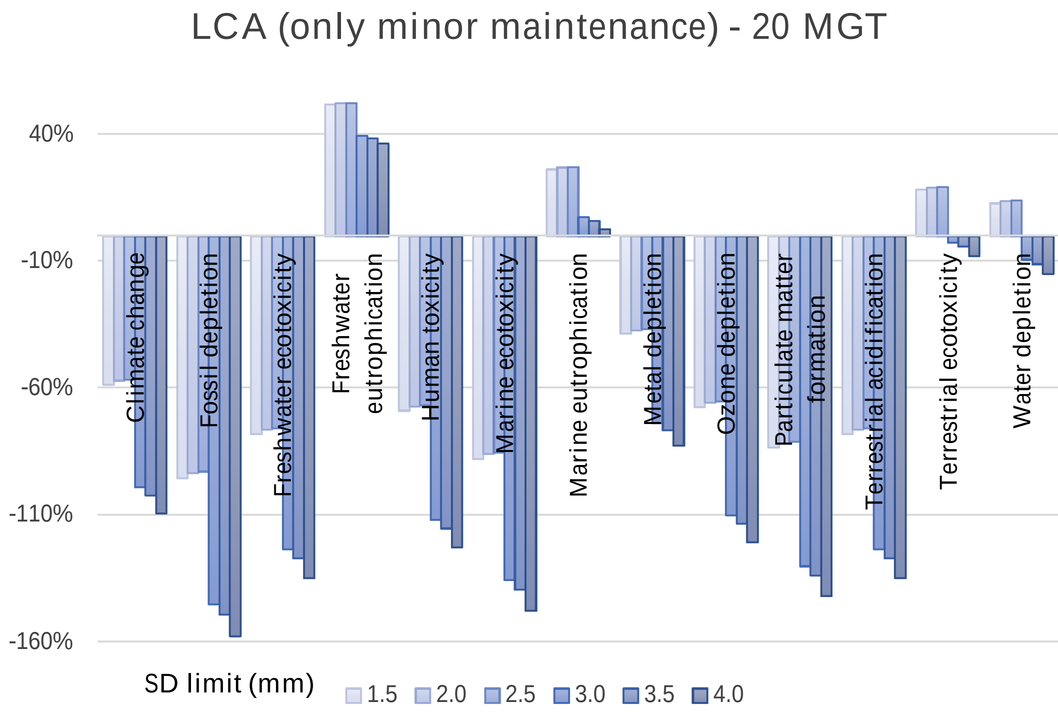

Figure 9.4 – Comparative life cycle impacts of BSB vs reference ballast (ReCiPe results midpoint method) due only to minor maintenance operations over the period of analysis for 20 MGT.

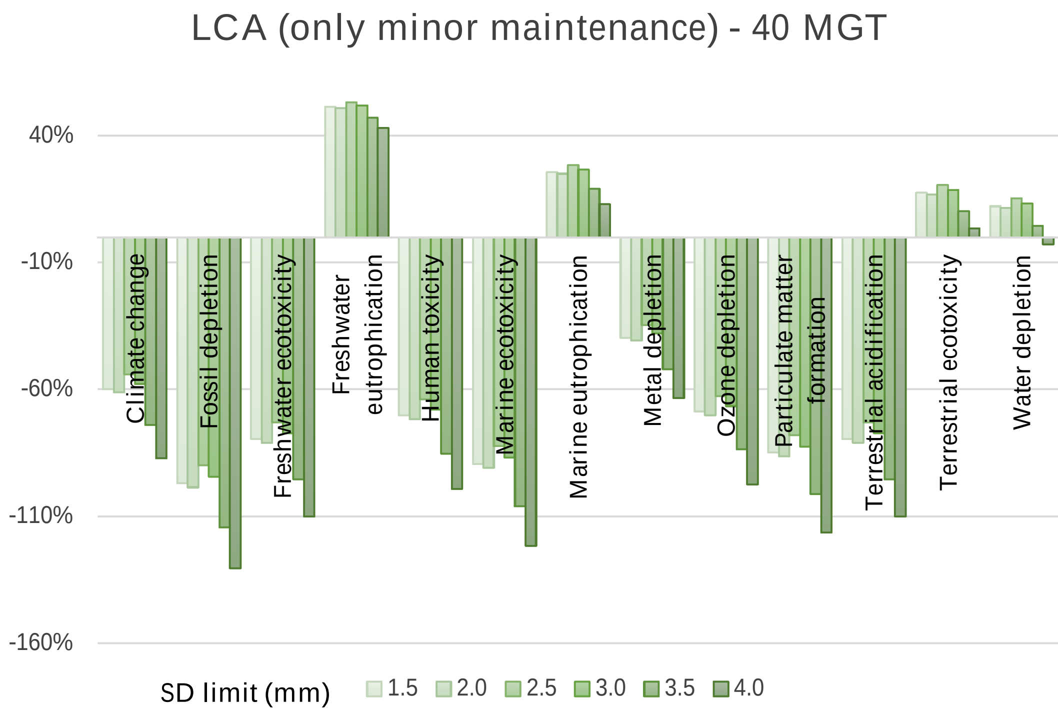

Figure 9.5 – Comparative life cycle impacts of BSB vs reference ballast (ReCiPe results midpoint method) due only to minor maintenance operations over the period of analysis for 40 MGT.

It can be noted that, despite the reduced minor maintenance frequency due to bitumen stabilisation, the life cycle impact of BSB considering only minor maintenance is overall higher than that of reference ballast (with the exception of the four indicators previously mentioned). This impact decreases when annual traffic increases and generally increases with decreasing quality levels of track geometry (higher SD limits). These results indicate that, based on the assumptions made (bitumen stabilisation repeated in the same dosage every time geometry needs to be corrected), from an environmental point of view, only considering the reduction in the number of tamping operations, BSB is less sustainable than traditional ballast.

Nevertheless, the integrated model used in chapter 8 showed that the use of BSB would also increase the interval between major maintenance operations due to the lower particle degradation. For instance, climate change LCA results (again in terms of BSB savings) due only to the major maintenance operations (renewals) are reported in Figure 9.6 as a function of traffic level and SD limit.

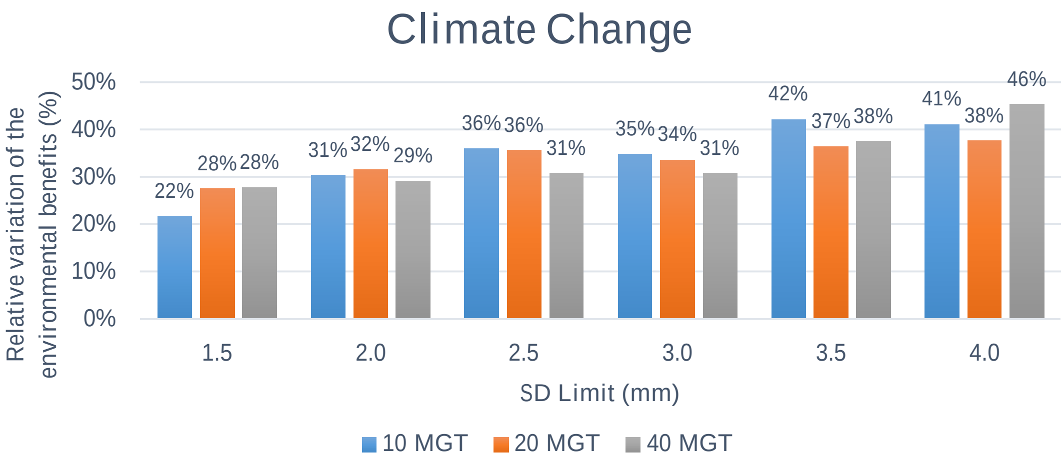

Figure 9.6 – Comparative life cycle impacts on climate change of BSB vs reference ballast (ReCiPe results midpoint method) due only to major maintenance operations as a function of traffic level and SD limit.

It can be noted that the advantages in using BSB instead of traditional ballast are visible in the renewal subsystem phase. Indeed, the increased interval between renewals (dismantling plus new construction) due to the use of BSB provides a positive overall effect, which increases with lower quality level of geometry.

It is worth noting that the trend shown for climate change is the same (in relative variation terms) for all the other indicators. In this case, indeed, the impact of a single renewal is assumed to be the same for every scenario, and therefore the life cycle impact is determined exclusively by the frequency of the operation (according to results obtained in section 8.6).

The improvement brought by BSB to major maintenance is particularly important to the extent that this operation provides the highest overall contribution to the total LCA. This can be observed from Figure 9.7 and Figure 9.8, where for 20 MGT and SD limit of 2 mm, the contribution in percentage of construction, minor maintenance and renewals phases to the total LCA indicators are reported for reference ballast and BSB, respectively.

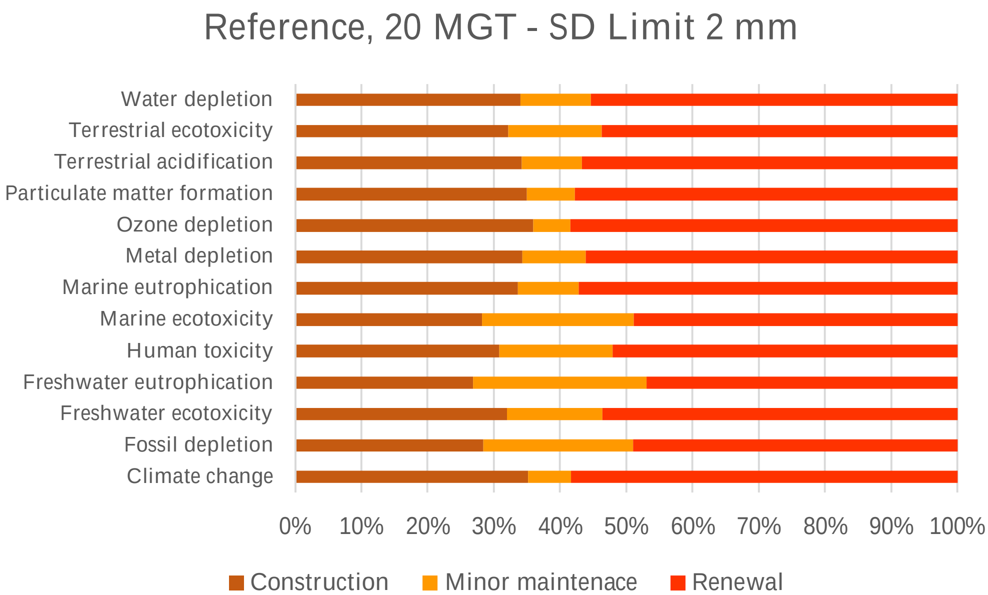

Figure 9.7 – Contribution of construction, minor maintenance and renewals phases to the total LCA indicators for reference ballast - 20 MGT and SD limit of 2 mm.

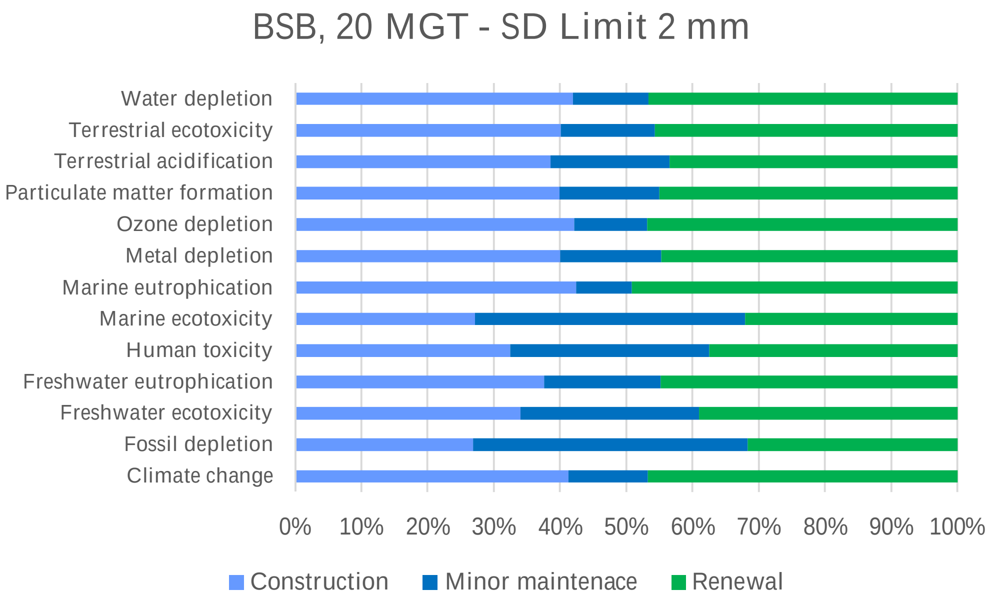

Figure 9.8 – Contribution of construction, minor maintenance and renewals phases to the total LCA indicators for BSB - 20 MGT and SD limit of 2 mm.

It should be noted that the contribution of minor maintenance to the total impacts is low if compared with construction and renewal. For instance, in Figure 9.9 and Figure 9.10 the same trend can also be appreciated in absolute values for the climate change, which is one of the most relevant indicators for LCA.

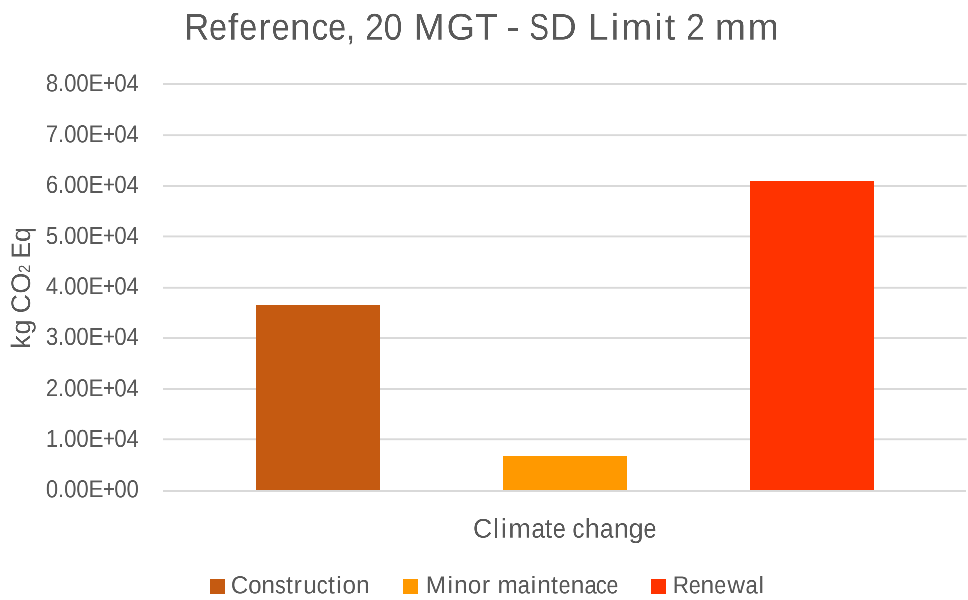

Figure 9.9 – Contribution of construction, minor maintenance and renewals phases to the total LCA climate change indicator for reference ballast - 20 MGT and SD limit of 2 mm.

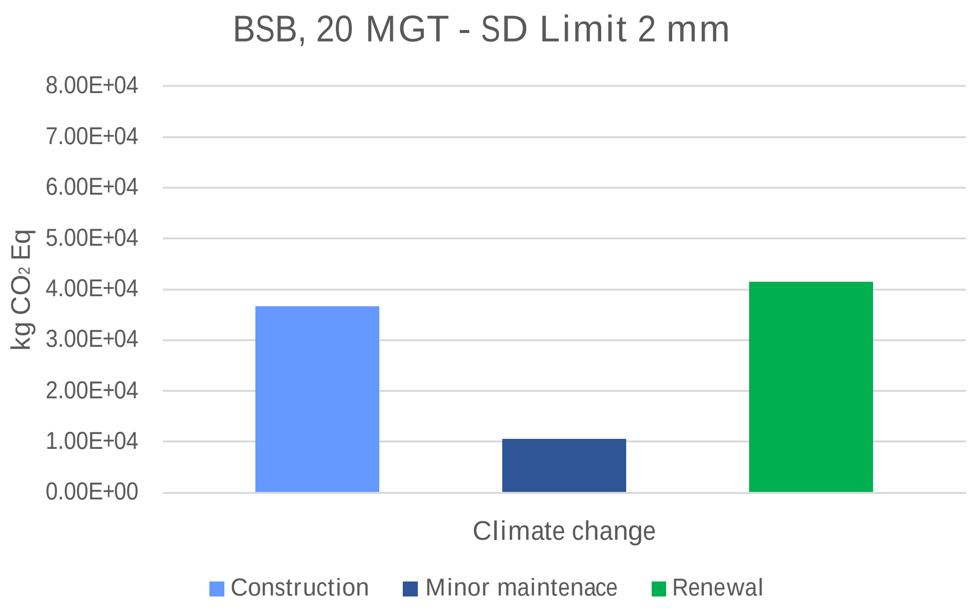

Figure 9.10 – Contribution of construction, minor maintenance and renewals phases to the total LCA climate change indicator for BSB - 20 MGT and SD limit of 2 mm.

By comparing Figure 9.9 and Figure 9.10, indeed, it may be observed that, for this scenario (20 MGT – SD limit 2 mm), the total life cycle impact of BSB in terms of kg of CO_2e is lower than that of reference ballast. Using BSB, therefore, provides the great advantage of reducing major maintenance interventions responsible for higher environmental impact and energy consumption.

The results of the total comparative LCA for all the indicators and scenarios, as a function of SD limit, are reported in Figure 9.11, Figure 9.12 and Figure 9.13 for 10 MGT, 20 MGT and 40 MGT, respectively.

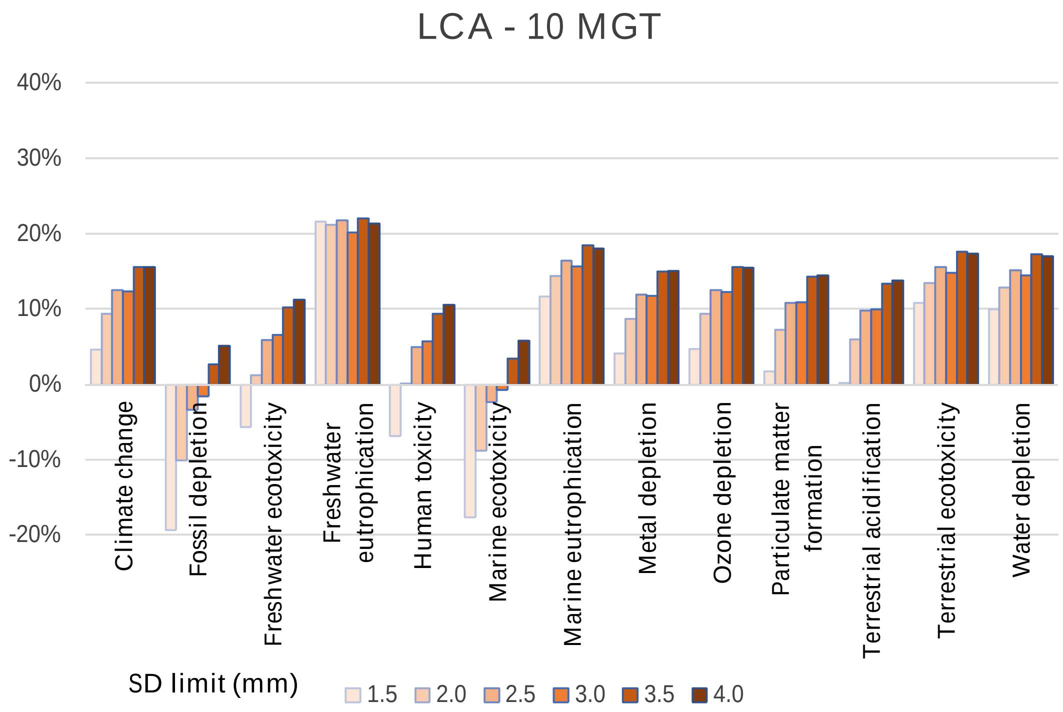

Figure 9.11 – Comparative life cycle impacts of BSB vs reference ballast (ReCiPe results midpoint method) over the period of analysis for 10 MGT.

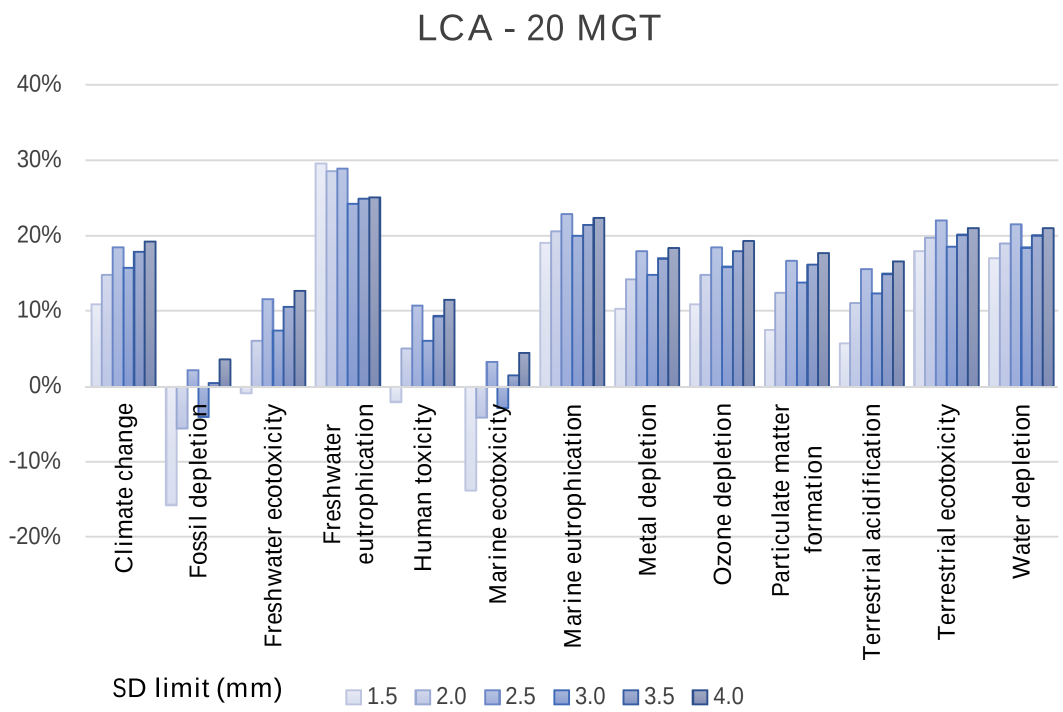

Figure 9.12 – Comparative life cycle impacts of BSB vs reference ballast (ReCiPe results midpoint method) over the period of analysis for 20 MGT.

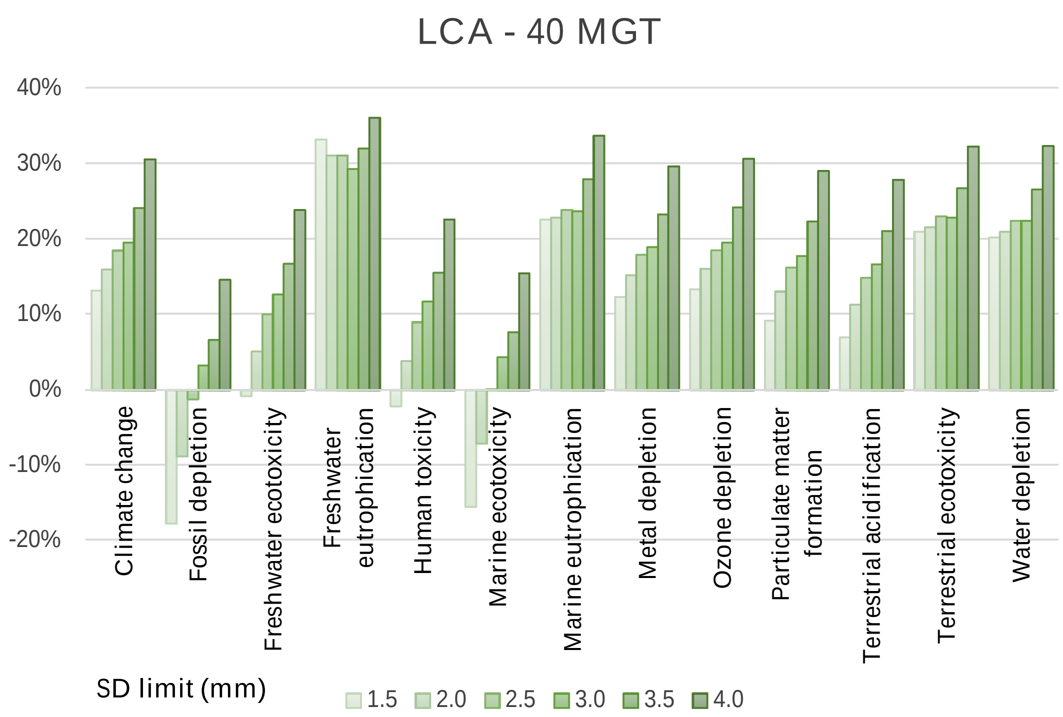

Figure 9.13 – Comparative life cycle impacts of BSB vs reference ballast (ReCiPe results midpoint method) over the period of analysis for 40 MGT.

From this analysis, it can be noted that, for the majority of the scenarios analysed, a track-bed structure with a BSB layer could bring substantial improvements in the environmental impact profile of the infrastructure. This is mainly due to the reduced number of renewals (which present the highest impacts) for BSB scenarios, which can increase the sustainability compared to traditional ballasted track-bed. This improvement increases with higher traffic levels and with lower quality levels of geometry.

9.4 Conclusions

This chapter has compared the life cycle environmental impacts of two track-bed systems: traditional ballasted track-bed and BSB. When considering only the minor maintenance, the LCA results show that for the majority of the indicators, the higher impact due to the use of bitumen emulsion is not compensated by the reduction in maintenance frequency. The higher advantage in using BSB, instead, can be exploited when also considering renewals because BSB technology ensures a higher durability of the material and the track quality, allowing the use of a scarce non-renewable raw material to be minimised.

Indeed, the whole LCA shows that for the majority of the indicators environmental impacts can be significantly reduced by the use of BSB.

A sensitivity analysis was undertaken to evaluate the different outcomes in response to variations in some of the most relevant input values affecting the maintenance activities of the track-bed: the track geometry quality level and the annual traffic. The analysis has shown that, based on the assumptions made, BSB would act positively in environmental impact reduction independent of the traffic and the track quality level. The advantages of BSB in reducing the environmental impact are generally highest when the tolerance on the track quality level increases and with heavy traffic lines.

The present analysis offers an overview of the environmental sustainability assessment of BSB as a maintenance strategy that allows increased durability of the ballast layer and reduced use of non-renewable resources. The calculations performed were based on several hypotheses and thus can be considered neither exhaustive nor generalised. Precisely because the assumptions were not exhaustive, the research work presented opens the way to extend the study to other materials, evaluating for instance the possible BSB recycling rate, different volumes of traffic or SD limits that would affect the maintenance timing, etc.

Moreover, the availability of data to be used in the LCA of these types of materials is still very limited. Therefore, further research effort should be employed to produce a more complete and robust LCI that will certainly improve the overall quality of the LCA.

In addition, future studies should consider the possibility of recycling old BSB for new track-bed (using rejuvenators with warm or cold processes), which could further increase the sustainability of this solution.

Chapter 10 - LCCA of BSB

In the previous chapter the environmental impacts of BSB were evaluated through a life cycle assessment. In order to have a wider view of burdens and benefits derived from the adoption of such a technology, this chapter focuses on the evaluation of life cycle costs over the same period of analysis (60 years).

10.1 Introduction

Ballasted tracks require relevant resources to ensure efficiency and functionality with time. For instance, for some specific lines, this type of track, presenting higher maintenance costs, can be less suitable than slab track considering all life-cycle costs (Esveld 2001, Sugrue 2013, CEMOSA 2014, Profillidis 2016).

In this regard, Life-Cycle Cost Analysis (LCCA) is an effective technique that enables quantification of the costs of alternative options for a given infrastructure. This method is a systematic process that takes into account different impacts, offering a long-term evaluation of different alternatives. The process requires the sum of the monetary equivalency of all advantages, disadvantages and costs at their respective time of occurrence throughout the period of analysis. Subsequently, they are converted into a common time domain so that different solutions may be compared on the same time scale (Ozbay et al. 2003). A robust LCC framework would be able to link life-cycle analysis studies to the monetary cost systems used by decision-makers. To do so, discount rate is a fundamental parameter allowing every cost to be converted to the reference time. This last parameter can be estimated as defined by BS ISO 15686-5 (BS ISO 15686-5:2017 2017), as will be further discussed in section 10.2.2.

Generally, LCCA considers only the investments from one actor, i.e. agency, and thus focuses only on financial aspects (construction and future maintenance) (Ness et al. 2007). This type of approach is also called conventional LCC (Swarr et al. 2011). A comprehensive LCCA extends the analysis to the operational costs and the environmental costs in addition to agency costs (Swarr et al. 2011, De Langhe 2017).

In this research, in order to evaluate the possible saving arising from the use of BSB track-bed, a comprehensive LCCA including agency costs, operational costs and environmental costs (climate change) has been carried out. As for the LCA discussed in the previous chapter, all these costs are related to the ballast layer only.

Certain assumptions are necessary to complete this type of analysis. Because of the uncertainties arising from these assumptions, a sensitivity analysis of the most relevant parameters was carried out.

10.2 Methods

Based on results obtained from another European project (MAINLINE Deliverable 5.4 2013), in which an exhaustive review of existing life cycle tools was carried out, the following method has been adopted.

10.2.1 Calculation of costs

As for the LCA, the LCCA will include only the evaluation of those costs which vary between all the scenarios (from chapter 8). Indeed, it is often sufficient to itemise the differences between possible options to allow a comparison between the options considered (MAINLINE Deliverable 5.4 2013).

In the analysis, costs are divided into classifications as follows:

- Agency costs;
- Operational costs;
- Environmental costs (monetisation of environmental burdens).

All these costs will be treated as simultaneous outcomes of any intervention or operation.

10.2.1.1 Agency costs

These costs are those directly covered by the agency when an operation such as new construction, minor maintenance or major renewals (which includes the dismantling and disposal of materials) has to be carried out.

The cost for a single operation includes the cost of labour, materials, taxes and transportation. Table 10.1 reports the cost for a single operation afforded by the agency used for this analysis. These values have been collected and evaluated from literature and interviews with companies and experts (Shimatake 1997, McMichael and McNaughton 2003, SMARTRAIL 2014, Moreno-Martinez 2016).

Table 10.1 – Agency costs for single operation per 1 km (functional unit).

Operation	Agency costs per km
New construction/renewal	€ 94,647.00
In-situ tamping of ballast	€ 7,219.00
In-situ tamping of ballast + BSB	€ 9,454.00

10.2.1.2 Operational costs

Operational costs are related to the impacts (service delays, disruptions, unavailability) that each operation or intervention has on the ordinary railway service.

For this comparative analysis, these costs have been evaluated based on the productivity of each operation (Table 9.2) (Shimatake 1997, Calla 2003, McMichael and McNaughton 2003, Pires 2016) and the train delay costs (Lovett, Dick, and Barkan 2015). These costs, which include crew, locomotives, fuel, railcars, and lading range from € 170 to more than € 900 per train-hour depending on the train composition (Schafer and Barkan 2008, Lai and Barkan 2009, Dingler et al. 2011, Schlake et al. 2012, Lovett, Dick, and Barkan 2015). Based on Lovett et al. (Lovett, Dick, Ruppert, et al. 2015) an average cost of € 900 per train-hour was assumed.

It is reasonable to assume that tamping and tamping + BE are performed during non-operative time (maintenance night shifts). Therefore, for the LCCA only new construction/renewal operational costs have been considered, as a function of traffic level, by multiplying the average number of trains/hour by the cost of delay and the productivity of the operation, as reported in Table 10.2.

Table 10.2 – Operational costs for each new construction/renewal per 1 km (functional unit) as a function of traffic level.

Operation	10 MGT	20 MGT	40 MGT
New construction/renewal	€ 8,559.50	€ 17,119	€ 34,238

10.2.1.3 Environmental costs

These costs are those indirect costs to which all society is subjected as consequence of the environmental impacts derived from each operation/intervention. Typically, these costs are evaluated by converting one or more LCA indicators into monetary values.

One of the most relevant indicators (MAINLINE Deliverable 5.3 2013) is the amount of CO_2e (climate change due to greenhouse gas emission), which will be the only environmental indicator considered within this analysis.

After completing a life cycle assessment (chapter 9), it is necessary, therefore, to evaluate the cost of carbon (CO_2e). In this regard, there are two common approaches: (i) social damage cost of carbon and (ii) marginal abatement cost (avoidance cost) (MAINLINE Deliverable 5.3 2013). The social damage cost of carbon refers to the value of damage due to the additional greenhouse gas emission of carbon into the atmosphere while the marginal abatement cost represents the cost to reduce the carbon emission by the same amount. There is no general agreement amongst European Countries on a standard method for evaluating the ‘carbon cost’, this procedure being normally determined by the policies and guidelines set by individual countries. For instance, the UK carbon evaluation guidance (UK Department of Energy and Climate Change 2011) is based on the marginal abatement cost method. Table 10.3 reports an extract from the UK carbon values and sensitivities in terms of real £ (of 2011 value).

Table 10.3 – UK Non-traded carbon cost factors in GBP/tonne $CO_{2}e$ (Real £2011) (adapted from UK Department of Energy and Climate Change 2011).

Year	Low	Central	High
2010	27	55	82
2011	28	56	83
2012	28	56	85
2013	29	57	86
2014	29	58	87
2015	30	59	89
2016	30	60	90
2017	30	61	91
2018	31	62	93
2019	31	63	94
2020	32	64	95
…	…	…	…
2076	121	326	532
2077	119	326	534
2078	117	326	535
2079	115	325	535
2080	113	324	535

Due to uncertainties related to estimating cost factor values, typically a sensitivity analysis is carried out using the lower and upper values to arrive at lower and upper-bound estimates of the carbon impact. Thus, in order to include this analysis in the present LCCA, low, medium and high values have been averaged for the period 2017-2077 and converted (Morley 2017, X-Rates 2017) to Euros (of 2017 value – conversion factor = 1.18), as reported in Table 10.4.

Table 10.4 – Monetisation factors for CO_2e in €/tonne (Real €2017) used in the present analysis (UK Department of Energy and Climate Change 2011, Morley 2017, X-Rates 2017).

Low	Central	High
111	249	387

10.2.2 Net Present Value (NPV): conversion of cash flows

In order to compare, in terms of costs, different options using a life cycle approach, it is convenient to discount all costs to a reference time (e.g. year 2017).

This technique allows conversion of cash flows occurring at different times to a common time to reflect the time value of money. Once discounted, all the cost components for each scenario can be summed up in order to obtain the Net Present Value (NPV) and allow for comparison between scenarios which involve interventions of various costs occurring at various times.

Each cost component is discounted to the reference year using Equation (10.1):

$$C_0 = \frac{C_y}{(1+r)^y} \tag{10.1}$$

where C_0 is the cost of the operation/intervention converted to the reference time, C_y is the estimated cost of the operation/intervention to be carried out at year y (relative to the reference year) and r is the discount rate.

This last parameter can be estimated as defined by ISO 15686-5 (ISO 15686 2008). A distinction has to be made between real and nominal rate. The difference between these two rates is that the nominal rate takes into account general inflation and deflation. These last two factors are not included in the real discount rate, which, assuming inflation/deflation is equally applied to all costs, reflects the real earning power of money. For the present study, the real discount rate will be used in order to exclude the impact of future inflation in the LCC analysis. By referring to the interest rate used to determine the present value of future costs, the discount rate is generally determined as interest on national bonds when the analysis is for public sector projects. As an example, the UK Treasury published a recommended real discount rate of 3.5% (MAINLINE Deliverable 5.4 2013), which is assumed as the baseline for the present LCCA.

The discount rate is assumed constant over the period of analysis. Thus, the NPV for each scenario can be evaluated by using Equation (10.2):

$$NPV = \sum_{y=0}^{n} \frac{AC_y + OC_y + EC_y}{(1+r)^y} \tag{10.2}$$

where AC_y, OC_y, and EC_y are the agency costs, operational costs, and environmental costs, respectively, estimated for year y, and n = 60 is the number of years.

10.2.3 Residual value

The residual value of a component or a system is the net worth at the end of the LCCA period of analysis. It can be positive or negative. A negative residual value indicates that there is value associated with the asset.

This concept aims to embody the notion that the asset is not completely worn out or retains some value for future use, at the end of the period of analysis. For instance, a track-bed recently replaced could ensure service for more than 30 years so that if this operation is carried out right before the end of the period of analysis there will be the need to take into account the residual ‘benefit’ because, under steady-state assumptions, subsequent uses would not need to start from scratch. For this reason, LCCA generally includes residual value as this is a tangible asset (Lee 2002).

The residual values of construction and maintenance operations, such as those considered in this study, with remaining service life can be calculated as a crude approximation, by linearly prorating their total initial costs (Lee 2002), as in Equation 10.3:

$$RV = \frac{residual\ service\ life}{total\ servise\ life} \times initial\ total\ cost \qquad (10.3)$$

For the scenarios analysed the ratio between the residual and total service life of each operation at the end of the period of analysis is the remainder from the next whole number from the data reported in Table 9.3. The initial total costs include agency costs, operational costs and environmental costs.

As for all the other costs, this negative cost is also discounted (at the last year of the period of analysis: 60th year).

10.3 Results and discussion

The following sections report LCCA results over the period of analysis for 1 km of track related to the baseline scenarios (SD limit 2.0 mm, 20 MGT, central CO_2e factor from Table 10.4, and discount rate of 3.5%) and the sensitivity analysis of the outcomes to the main parameters.

10.3.1 Baseline scenarios

Figure 10.1 and Figure 10.2 show the costs of each category forecast over the period of analysis for reference ballast and BSB, respectively.

In these column plots costs are reported each time a maintenance operation takes place (i.e. non-linear time scale in the horizontal axis), according to the maintenance strategies evaluated in Chapter 8. The costs associated to the same maintenance operation varies (in particular decreases) from year to year as a consequence of the discounting technique. The negative cost reported in year 60 is the residual value of the last renewal operation at the end of the period of analysis (Section 10.2.3).

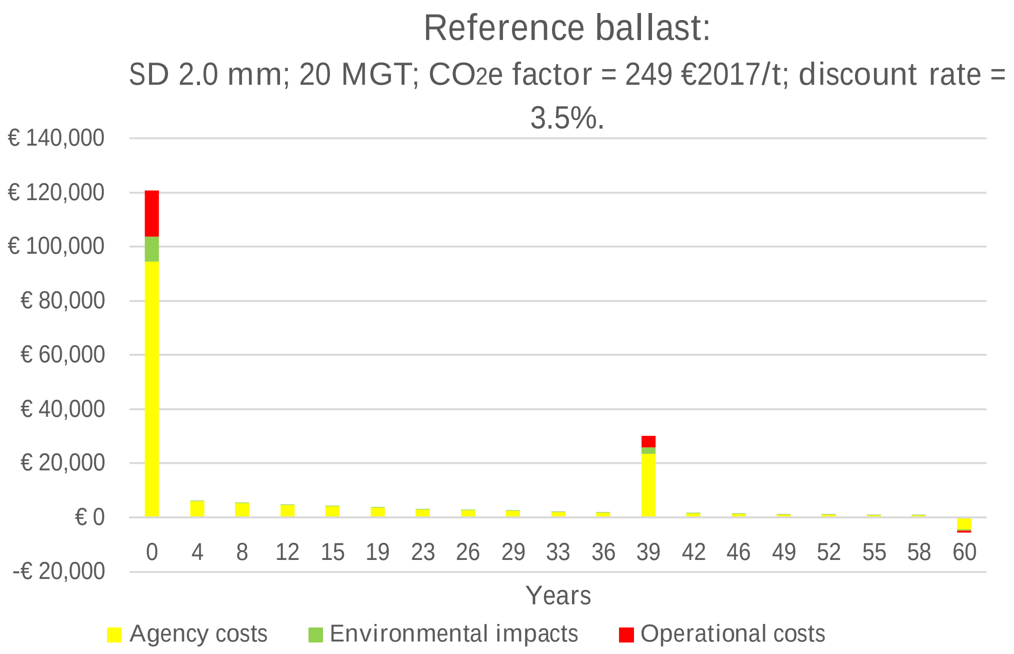

Figure 10.1 – Detailed life cycle costs for reference ballast in the baseline scenario (SD limit 2.0 mm and 20 MGT) maintenance strategy.

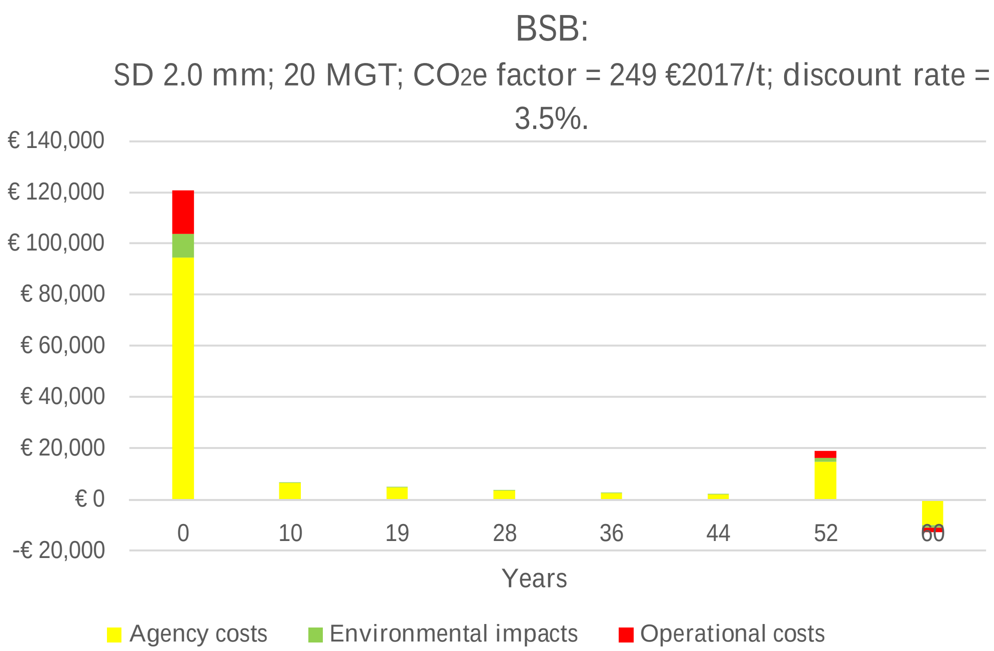

Figure 10.2 – Detailed life cycle costs for BSB in the baseline scenario (SD limit 2.0 mm and 20 MGT) maintenance strategy.

From these figures, the high influence on future costs of the discount rate can immediately be noted. In this regard, this parameter will also be the object of a sensitivity analysis in the following section.

It is worth noting that the residual value is higher for BSB. In this case, indeed, the renewal, having a lower frequency is expected closer to the end of the period of analysis and will give a longer durability than in the case of reference ballast.

The total cumulated costs over the period of analysis are reported for both alternatives in Figure 10.3 and Figure 10.4.

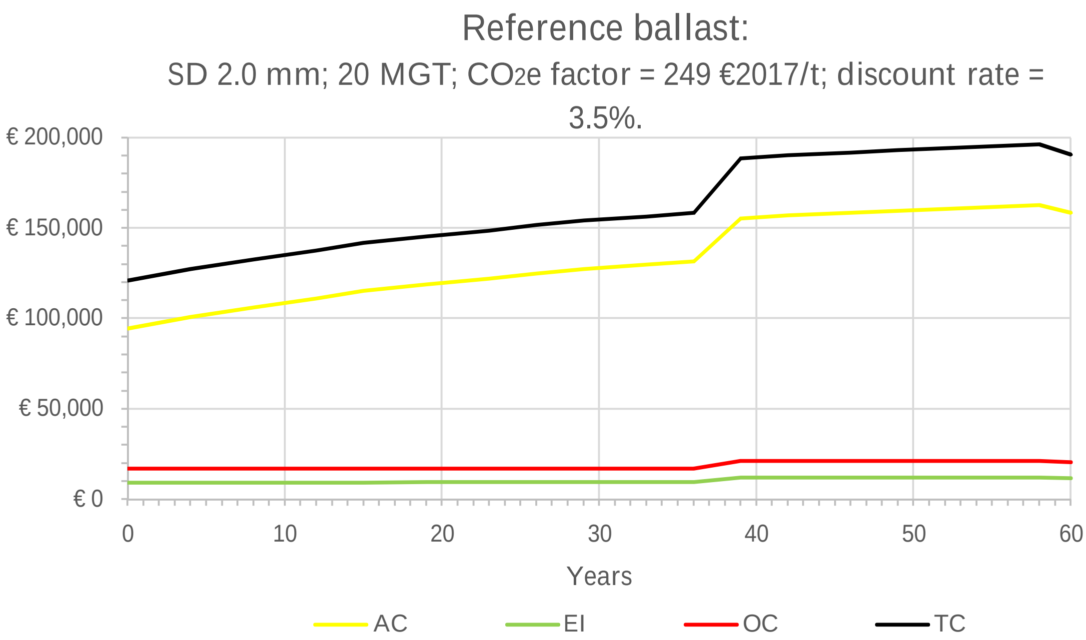

Figure 10.3 – Trend over period of analysis of agency costs (AC), environmental impacts (EI), operational costs (OC) and total costs (TC) for reference ballast in the baseline scenario (SD limit 2.0 mm and 20 MGT) maintenance strategy.

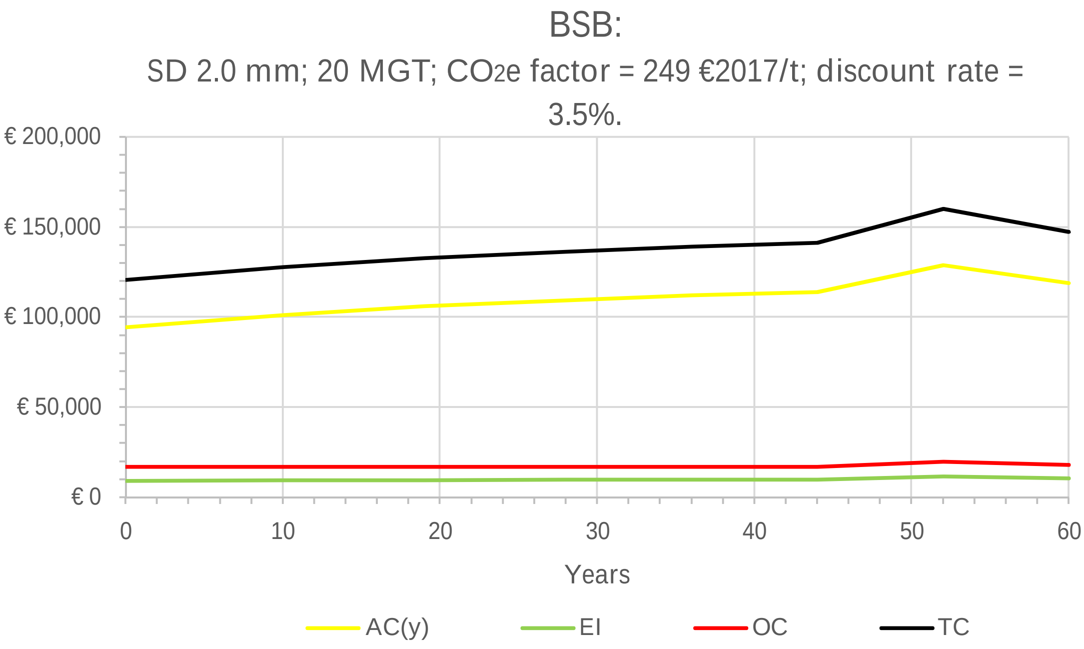

Figure 10.4 – Trend over period of analysis of agency costs (AC), environmental impacts (EI), operational costs (OC) and total costs (TC) for BSB in the baseline scenario (SD limit 2.0 mm and 20 MGT) maintenance strategy.

These figures show that, in this baseline scenario, BSB would reduce total life cycle costs (NPV) of traditional track-bed by approximately 25%. This reduction is mainly due to the agency costs while a marginal influence is observed in the operational and environmental costs. In this regard, it can be asserted that the use of bitumen emulsion as a stabilising agent, while having a higher impact for a single operation, would not produce any increase in life cycle environmental costs. This is due to the higher durability expected for BSB.

10.3.2 Sensitivity analysis

In order to understand how variations of certain parameters and assumptions could affect the LCCA outcomes and, consequently, the benefits provided by BSB in reference to traditional ballast, a sensitivity analysis was carried out.

10.3.2.1 Sensitivity to traffic level and track-bed geometry quality

Traffic level and SD limit have firstly been analysed by using the same ranges as those used in the LCA (chapter 9) while keeping constant the carbon factor (central CO_2e from Table 10.4) and the discount rate (3.5%). Results, in terms of Net Present Value (NPV) are shown in Figure 10.5, Figure 10.6 and Figure 10.7.

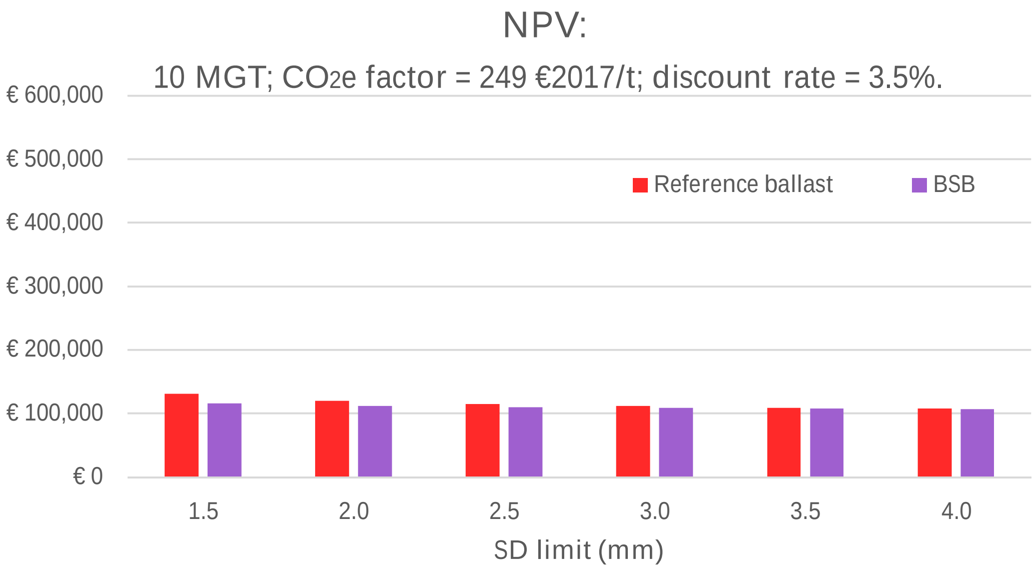

Figure 10.5 – NPV variations with SD limit for both BSB and reference ballast for medium traffic level (10 MGT), central CO_2e factor (Table 10.4) and discount rate = 3.5%.

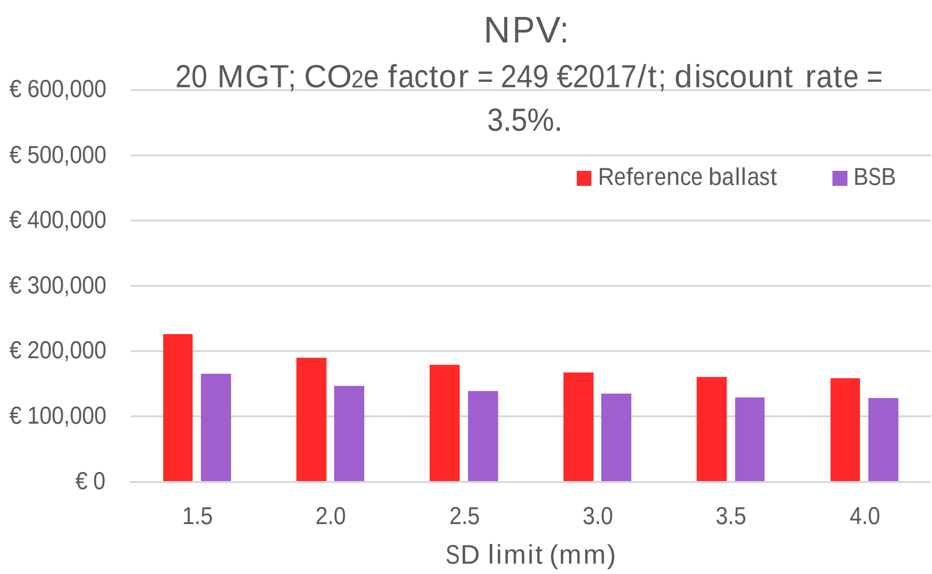

Figure 10.6 – NPV variations with SD limit for both BSB and reference ballast for medium traffic level (20 MGT), central CO_2e factor (Table 10.4) and discount rate = 3.5%.

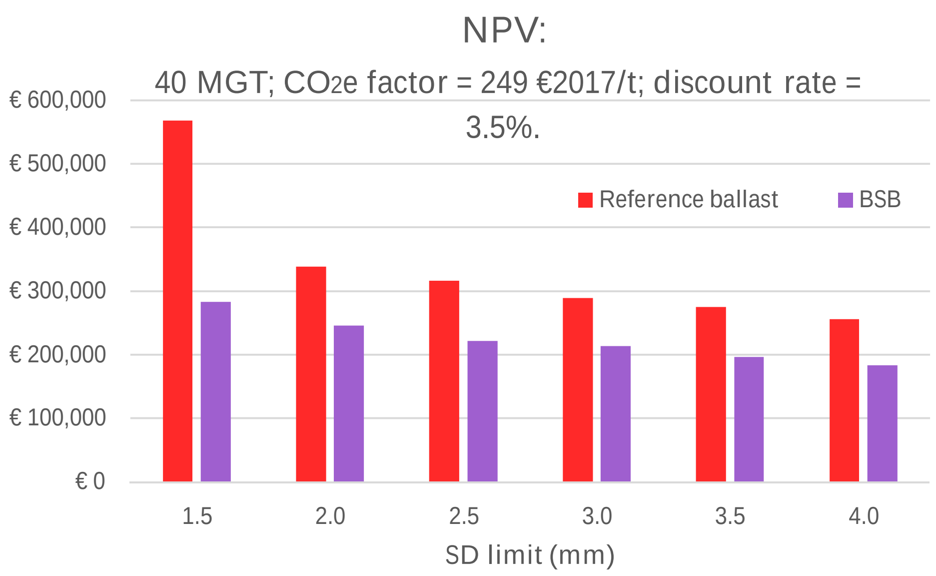

Figure 10.7 – NPV variations with SD limit for both BSB and reference ballast for high traffic level (40 MGT), central CO_{2e} factor (Table 10.4) and discount rate = 3.5%.

It can be noted that for low traffic level the influence of BSB on NPV is not significant, savings ranging from approximately 0.5 to 7%. In addition, for this traffic the influence of SD on total costs is also less relevant.

By increasing the traffic, savings estimated by the use of BSB progressively increase, reaching approximately 50% for 40 MGT and 1.5 SD limit.

It is worth remarking that, for any traffic level, BSB savings decrease with decreasing quality set for track geometry. This trend is apparently in contrast with those observed for maintenance strategies (Chapter 8) and LCA (Chapter 9), in terms of reduction in number of major maintenance interventions and environmental impact reduction, respectively. However, this is attributed to the role played by the discount rate in LCCA, which gives higher relevance to the costs afforded in the first part of the period of analysis. In this regard, the sensitivity of results to discount rate is discussed in section 10.3.2.3.

Overall, therefore, these findings indicate that bitumen stabilisation would be more profitable for important and congested lines rather than peripheral ones.

10.3.2.2 Sensitivity to carbon cost factor

Figure 10.8 reports the sensitivity analysis of NPV for both BSB and reference ballast related to the carbon monetisation factor (Section 10.2.1.3), keeping constant all the other parameters as in the baseline scenario.

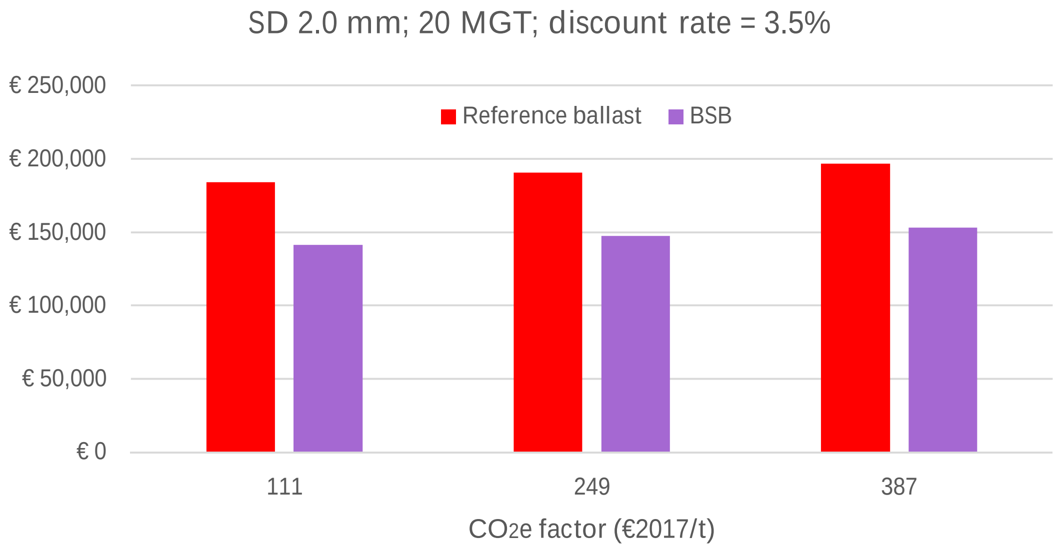

Figure 10.8 – NPV sensitivity to CO_2e factor for both BSB and reference ballast for high traffic level (20 MGT), SD limit of 2 mm and discount rate = 3.5%.

By comparing the same alternatives, different values of carbon factor produce variations of approximately 3-4% to the NPVs, indicating the relatively low influence that environmental impacts have on the life cycle costs. As a consequence, the savings provided by the use of BSB are not significantly influenced by the carbon factor, varying from approximately 30% (low CO_2e) to approximately 28.5% (high CO_2e).

10.3.2.3 Sensitivity to discount rate

In order to understand the variation of NPV for both BSB and reference ballast with the discount rate, a sensitivity analysis to this factor within the range reported in Figure 10.9 has been carried out.

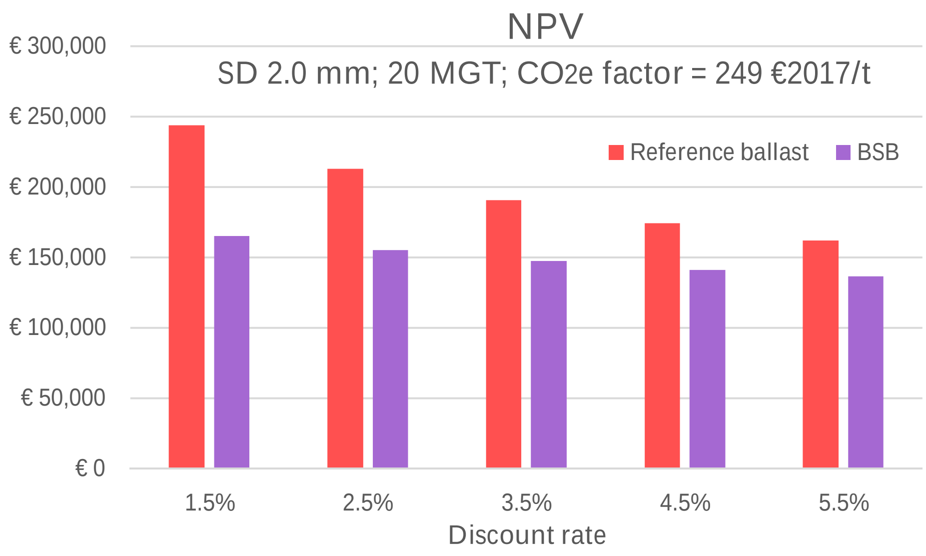

Figure 10.9 – NPV sensitivity to discount rate for both BSB and reference ballast for high traffic level (20 MGT), SD limit of 2 mm and central CO2e factor (Table 10.4).

It can be clearly observed that this parameter has a significant influence not only on the NPV of each alternative (which decreases with higher discount rate) but also on the ratio between alternatives (savings expected by the use of BSB). In this regard, BSB seems to be more profitable for low values of discount rate (approximately 30% savings for a discount rate of 1.5%) than for high values (approximately 15% savings for a discount rate of 5.5%). This is due to the fact that for reference ballast (maintenance strategies – Chapter 8) a higher number of maintenance operations is forecast than for BSB over the period of analysis, and this has a high influence on the total NPV. Indeed, higher discount rates reduce the burden of more frequent maintenance from a lifecycle perspective, thus decreasing the benefits offered by a more durable solution.

The same concept explains why the savings provided by BSB are higher when maintenance operations are more frequent (low SD limit) in the first years of the period of analysis.

10.4 Conclusions

This chapter has compared the life cycle costs of two track-bed alternatives: traditional ballasted track-bed and BSB. This comprehensive LCCA has included agency costs, operational costs and environmental costs. Based on the assumptions made, the results obtained from baseline scenarios and sensitivity analyses have led to the following conclusions:

- Comparison between baseline scenarios (medium traffic level, 2 mm SD, central carbon conversion factor and baseline discount rate) showed that BSB can provide non-negligible savings (approximately 25%) in a 60-years period of analysis with respect to traditional ballasted track-bed.
- For both alternatives, the agency costs are by far the most relevant (covering more than 80% of the total life cycle costs) while environmental costs give the lowest contribution (only around 5%).
- These results are significantly influenced by the traffic level and the SD limit (quality of geometry). Specifically, higher levels of traffic and quality of geometry set for the infrastructure correspond to higher savings provided by BSB (going from a minimum of 0.5% to a maximum of 50%). This indicates that bitumen stabilisation would be more profitable for important and congested lines rather than peripheral ones. This trend, apparently in contrast with previous chapters, is attributed to the discounting approach, which gives greater weight to the costs accrued in the first part of the period of analysis.
- The influence of carbon conversion factor on results is relatively low, as could be expected by the overall low contribution of these costs to the total LCC.
- On the other hand, the discount rate has a significant influence on results: lower values of discount rate correspond to higher savings provided by the BSB alternative. This is due to the fact that higher discount rates reduce the contribution to the total costs of future maintenance, thus decreasing the benefits offered by an alternative with longer durability.

- Overall, it can be concluded that independent of the intensity of traffic, quality of geometry, carbon factor and discount rate, BSB could offer a more economical solution from a life cycle perspective than traditional ballasted track-bed.

In previous chapters it was discussed about the potential for BSB in reducing vibration (by increasing the energy dissipation within the layer). In this regard, future LCCA studies on BSB should attempt to consider also the social cost savings potentially achieve by the reduction of vibrations.

Chapter 11 - Conclusions and future works

11.1 Conclusions

The aim of the work described in this thesis was to contribute to increasing the sustainability of railway transportation systems. The main objective was, thus, to develop and propose a novel solution, namely bitumen stabilised ballast (BSB), to decrease costs and burdens related to the minor and major maintenance of traditional ballasted track-bed.

For this purpose, the work firstly focused on the review of current design and maintenance solutions to reduce ballasted track maintenance, and the main factors affecting their performance.

The feasibility of the proposed alternative (BSB) and the main factors affecting performance were then assessed through model-scale testing (small-scale PUMA).

Results obtained were therefore validated using full-scale ballast box tests, investigating also the practicability and maintainability of BSB technology.

The full-scale PUMA testing had the objective of correlating previous model-scale PUMA and full-scale ballast box findings and evaluating long-term performance.

Based on laboratory results, a performance-based integrated model has been developed to predict maintenance operations for the proposed technology in comparison to traditional ballast. This allowed estimating both life-cycle environmental and economic costs of these alternatives in order to assess the potential benefits brought by the application of BSB to existing track-beds.

Given the results obtained, the main conclusions drawn are reported as follows:

- The use of bitumen emulsion (BE) as a stabilisation agent can provide a significant decrease in ballast permanent deformation and deformation rate, greater when the dosage is increased, as shown by model-scale PUMA tests. This indicates a good potential for BSB to improve both the short-term and the long-term in-field ballast deformational behaviour.
- In this regard, the use of harder bitumen for BSB can offer a better resistance to permanent deformation.
- At the same scale, bitumen stabilisation is also associated with an increase in resilient modulus and energy dissipation, attributed to the additional viscoelastic component offered by the bitumen. In this regard, the use of polymer modified bitumen can provide a more stable behaviour over time in terms of stiffness. This suggests that BSB could also be employed to modify track-bed mechanical behaviour and reduce noise and vibrations. However, this aspect needs to be verified at full-scale.
- Increasing the viscosity of bitumen emulsion decreases the percentage of material lost during the stabilisation process, thereby providing improved stabilisation efficiency. This indicates that, depending on the field condition (ballast gradation) and ballast depth to be stabilised, a specific BE could be designed to obtain the desired results in terms of BSB behaviour and stabilisation efficiency.
- Full-scale ballast box tests show that bitumen stabilisation applied during a maintenance operation can improve track-bed post-maintenance performance, in terms of settlement and settlement rate. Indeed, BSB is particularly effective at increasing intervals between tamping operations.
- In this regard, bitumen stabilisation appears to be much more effective when applied at an early stage of ballast life (clean ballast), while its effectiveness drastically reduces for fouled ballast. This is mainly attributed to the reduced air voids which prevented homogenous stabilisation.

- As regards BSB maintainability, BSB track-beds would ideally be maintained by stoneblowing, which does not disturb the already compacted and stabilised layer. Nonetheless, a further application of bitumen stabilisation coupled with tamping seems to maintain the same effectiveness over time.
- The application of BSB for newly constructed track-beds seems to provide similar improvements to those obtained when applied after tamping.
- It is worth mentioning that, with the dosage used at full-scale, only 1.52% of the total volume (3.7% of total air voids for clean ballast) is taken up by the bitumen, which still allows drainage through the ballast layer, as reported for similar stabilisation techniques.
- Nevertheless, by comparing ballast box results with those obtained at model-scale, it is possible to note a lower improvement in terms of final settlement and a lower influence on mechanical properties (stiffness and energy dissipation) provided by bitumen stabilisation. This was attributed to the lower number of contact points between particles at full-scale, to the reduced volume percentage of ballast stabilised in the box and to the type of test itself.
- Tests carried out using full-scale PUMA show that the settlement reduction due to the bitumen stabilisation after the same number of cycles is similar (slightly higher) to that obtained in the full-scale box tests, for the same gradation. This confirms that the scale factor, instead of the test type, is the main factor controlling the effectiveness of BSB in terms of permanent deformation reduction.
- A similar conclusion can be drawn in terms of stiffness and dissipated energy variations in the presence of BE: full-scale PUMA results reflected those obtained in box tests. However, a small increase in both parameters is observed, which is attributed to the stabilisation of the whole ballast volume in comparison with the box tests where only the volume underlying the sleeper was stabilised.

- Tests carried out for lower size aggregate (stoneblower aggregate) show that both stiffness and dissipated energy can increase when the sample is stabilised with bitumen emulsion. This confirms (by small-scale PUMA testing) that, when increasing the number of contact points, the influence of viscoelastic properties given by the bitumen also increases. This indicates that the use of different gradations combined with higher dosages (and types) of bitumen emulsion, can potentially modify full-scale track-bed mechanical properties.
- For both the gradations considered, long-term behaviour (30 MGT), in terms of settlement rate and particle degradation, can be significantly improved by BSB. This indicates that the application of this technology can potentially postpone both minor and major maintenance operations.
- As a direct consequence of experimental findings, the integrated model developed in order to evaluate maintenance strategies of traditional ballast and BSB, reflects the fact that the use of BSB can increase intervals between both minor and major maintenance activities.
- The sensitivity analysis carried out show that the reduction of maintenance operations for track geometry correction (tamping) provided by BSB is almost independent of the quality level set for the infrastructure, i.e. the limit of standard deviation (SD) of track irregularities, and of the traffic level.
- The reduction in number of renewals provided by BSB generally increases with increasing SD limits (higher tolerance on track irregularities).
- Based on the proposed model, the evolution of the number of minor maintenance operations with the SD limit follows a power law. This indicates that costs and burdens due minor maintenance would not be proportional to the quality level set for the infrastructure.
- LCA carried out to compare these two alternatives show that, when considering only minor maintenance, BSB is less sustainable than traditional ballasted track for the majority of the impact indicators. This is

attributed to the higher impact of use of bitumen emulsion, which is not compensated by the reduction in tamping frequency.

- However, when considering the whole LCA, which includes also major maintenance operations, BSB appears to be more sustainable than traditional ballast.
- Sensitivity analysis shows that BSB would act positively in environmental impact reduction independent of traffic and track quality level. The advantages of BSB in reducing the environmental impacts are generally higher when the tolerance on the track quality level increases and with heavy traffic lines.
- Based on results of a comprehensive LCCA, BSB can provide important savings (approximately 25%) with respect to traditional ballasted track-bed.
- For both alternatives, the agency costs are by far the most relevant while operational costs and environmental costs give lower contributions.
- Sensitivity analysis shows that results are significantly influenced by the traffic level and the quality of geometry set for the infrastructure. Specifically, BSB would be more profitable for important and congested lines rather than peripheral ones (going from a minimum of 0.5% to a maximum of 50% savings in relation to traditional ballast). In this regard, the trend of savings with SD limit variation is different from those observed for maintenance strategies and LCA, in terms of reduction in the number of major maintenance interventions and environmental impact reduction, respectively. This was attributed to the discounting approach, which gives higher relevance to the costs accruing in the first part of the period of analysis.
- The influence of carbon conversion factor on results is relatively low, as expected by the overall low contribution of environmental costs to the total net present value.
- Decreasing the discount rate corresponds to higher savings provided by the BSB. This is due to the fact that increasing the discount rate

corresponds to a reduced contribution to the total costs of future maintenance, thus decreasing the benefits offered by an alternative with longer durability.

Overall, it can be concluded that Bitumen Stabilised Ballast (BSB) represents a solution which potentially offer a more durable track geometry and a reduced degradation for traditional ballasted track-beds. As a direct consequence, the reduction in maintenance frequency associated with the use of BSB appear to bring important economic and environmental savings in a life cycle perspective, independent of traffic intensity, quality of geometry, carbon factor and discount rate, in relation to traditional ballasted track.

11.2 Future works

In the light of the results obtained in this thesis, bitumen stabilisation can be considered a promising solution to increase sustainability of traditional railway systems. However, increasing the understanding of BSB behaviour for different gradations, applicability and maintainability among other aspects, would lead to a more precise assessment giving more assurance of its in-track behaviour and the benefits expected from its use.

For this purpose, the following points are recommended for future research work:

- Results obtained from model-scale and full-scale tests indicated that the type of ballast, the amount of fouling and the presence of water, could play an important role in the effectiveness of stabilisation of ballast by bitumen emulsion. In this regard, more tests varying the type of ballast and the nature of contamination agents are needed to better understand the influence of bitumen stabilisation on the behaviour of already degraded ballast.
- Bitumen emulsion viscosity and gradation of the granular layer can significantly influence the flowability of BE through ballast layer. For a

fresh coarse-sized ballast layer, high viscosity BE was used to minimise the amount of material lost. However, depending on ballast properties and environmental conditions specific studies would be required to select the most appropriate BE and its dosage.

- It was also observed that the use of different gradations combined with higher dosages (and types) of bitumen emulsions (exploring also anionic emulsions), could potentially increase ballast resistance to permanent deformation and modify mechanical properties of the ballast layer. In addition, it was seen that the percentage of ballast stabilised could also influence these parameters. In this regard, future studies should focus on further understanding these factors towards the optimisation of costs/benefits associated with this technology. The variation of mechanical properties could be particularly advantageous for specific railway locations such as switches, level crossings, bridge transitions, innovative track forms, etc.
- The effect of bitumen type on BSB behaviour also needs further understanding. In this respect, more types of bitumen should be used to evaluate the influence of their properties on BSB resistance to permanent deformation and mechanical behaviour.
- Also the applicability would need further investigation. On the one hand, indeed, a technological system to blow the bitumen emulsion at the sleeper/ballast interface (similar to the stoneblowing process) would need to be developed. On the other hand, if the full layer of ballast is considered, a different system would need to be proposed and developed, which is likely to have a lower productivity.
- The influence of environmental factors, such as the presence of water, the thermal cycles and the effect of temperature in general, on bitumen bonds and therefore BSB behaviour, are other important aspects to be addressed in future works.
- These will closely affect the need for future maintenance and the type of operations to be carried out when correcting geometry of BSB track-beds.

In this regard, the optimum amount for future bitumen emulsion application and/or the possibility of heating the BSB volume during tamping should be investigated.

- The above-mentioned points should ultimately be assessed through full-scale in-field experiments.
- With respect to the evaluation of potential benefits, the integrated model proposed, which is deterministic in nature, could usefully be upgraded by introducing a probabilistic approach, taking into account the variability of the different parameters. In this regard, a higher number of long-term tests would increase the reliability of deterioration rates adopted.
- For both LCA and LCCA, the comparative analysis focused only on the ballast layer, while all the other track components were assumed to give the same impacts and therefore were taken out from the analysis. However, the smoother degradation of track geometry potentially offered by BSB could also increase the durability of the other components of track superstructure, thus reducing their maintenance burdens. In this regard, the evaluation of these other impacts could be also addressed in future studies.

Overall, both LCA and LCCA were based on several hypotheses and thus cannot be considered either exhaustive or generalised. Precisely, because the assumptions were not exhaustive, the research work presented opens the way to extend the study to other materials, evaluating for instance the possible BSB recycling rate, different volume of traffic or SD limit that would affect the maintenance timing, etc.

Moreover, the availability of data for the application of this technology to railways is very limited. Therefore, based also on the above-mentioned points, further research effort should be employed to produce a more complete and robust analysis evaluating costs/benefits associated with the use of bitumen stabilised ballast.

References

Aggregate Industries UK Ltd, 2013. Aggregates for railway ballast, Bardon Hill Quarry.

Airey, G.D., 2004. Fundamental Binder and Practical Mixture Evaluation of Polymer Modified Bituminous Materials. International Journal of Pavement Engineering, 5 (3), 137–151.

Ajayi, O., Le Pen, L., Zervos, A., and Powrie, W., 2014. Effects of random fibre reinforcement on the density of granular materials. In: Geomechanics from Micro to Macro. United Kingdom, 1363–1367.

Amsler, P., 1986. Railway track maintenance using geotextile. In: Procedings of 3rd International Conference on Geotextiles. Vienna, 1037–1041.

Anbazhagan, P., Bharatha, T.P., and Amarajeevi, G., 2012. Study of Ballast Fouling in Railway Track Formations. Indian Geotechnical Journal, 42 (2), 87–99.

Anderson, W.F. and Fair, P., 2008. Behavior of Railroad Ballast under Monotonic and Cyclic Loading. Journal of Geotechnical and Geoenvironmental Engineering, 134 (3), 316–327.

Anderson, W.F. and Key, A.J., 2000. Model Testing of Two-Layer Railway Track Ballast. Journal of Geotechnical and Geoenvironmental Engineering, 126 (4), 317–323.

Andersson, A., Berglund, H., Blomberg, J., and Yman, O., 2013. The influence of stiffness variations in railway tracks, 1–101.

AREMA, 2006. Economics of railway engineering and operations – construction and maintenance operations. American Railway Engineering and Maintenance-of-Way Association, Vol. 4, Chapter, Part 10.

Atalar, C., Das, B.M., Shin, E.C., and Kim, D.H., 2001. Settlement of geogrid-reinforced railroad bed due to cyclic load. In: Procedings of 15th Int. Conf. on Soil Mech. Geotech. Engg. Istanbul, 2045–2048.

Audley, M. and Andrews, J., 2013. The effects of tamping on railway track geometry degradation. In: Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 376–391.

Aursudkij, B., 2007. A laboratory study of railway ballast behaviour under traffic loading and tamping maintenance. The University of Nottingham.

Aursudkij, B., McDowell, G.R., and Collop, A., 2009. Cyclic loading of railway ballast under triaxial conditions and in a railway test facility. Granular Matter, 11 (6), 391–401.

Bach, D. and Veit, P., 2013. Evaluation of attrition tests for railway ballast.

Banimahd, M., Woodward, P.K., Kennedy, J., and Medero, G., 2013. Three-dimensional modelling of high speed ballasted railway tracks. Proceedings of the Institution of Civil Engineers, 166 (2), 113–123.

Baumgartner, J.P., 2001. Prices and costs in the railway sector. École Polytechnique fédérale de Lausanne. Laboratoire d'Intermodalité de Transports et de Planification.

Berggren, E., 2009. Railway Track Stiffness Dynamic Measurements and Evaluation for Efficient Maintenance.

Bertacchi, P. and Bellotti, R., 1977. Experimental research on materials for rockfill dams. In: Trans. 10th Int. Cong. Large Dams, Vol. 1. Montreal, Canada, 511–529.

Bizjak, K.F., Knez, F., Lenart, S., and Slanc, K., 2017. Life-cycle assessment and repair of the railway transition zones of an existing bridge using geocomposite materials. Structure and Infrastructure Engineering, 13 (3), 331–344.

Bocci, M., Grilli, A., Cardone, F., and Ferrotti, G., 2014. Full-depth reclamation for the rehabilitation of local roads: a case study. International Journal of Pavement Engineering, 15 (3), 191–201.

Bogacz, R., Czyczuła, W., and Konowrocki, R., 2014. Influence of sleepers shape and configuration on track-train dynamics. Shock and Vibration, 2014.

Boler, H., 2012. On the shear strenght of the polyurethane coated railroad ballast. University of Illinois at Urbana-Champaign.

Brown, S.F., 1996. Soil mechanics in pavement engineering. Géotechnique, 46 (3), 383–426.

Brown, S.F., Kwan, J., and Thom, N., 2007. Identifying the key parameters that influence geogrid reinforcement of railway ballast. Geotextiles and Geomembranes, 25 (6), 326–335.

Bruzek, R., Stark, T.D., Wilk, S., Thompson II, H.B., and Sussman, T.R., 2016. Fouled Ballast Definitions and Parameters. In: Proceedings of the 2016 Joint Rail Conference JRC2016. 1–7.

BS EN 1097-1, 2011. Tests for mechanical and physical properties of aggregates, Part 1: Determination of the resistance to wear (micro-Deval). British Standard Institution.

BS EN 1097-2, 2010. Tests for mechanical and physical properties of aggregates, Part 2: Methods for the determination of resistance to fragmentation. British Standard Institution.

BS EN 1097-6, 2013. Tests for mechanical and physical properties of aggregates. Determination of particle density and water absorption.

BS EN 12849:2009, 2009. Bitumen and bituminous binders - Determination of settling tendency of bituminous emulsions.

BS EN 13450:2013, 2013. Aggregates for railway ballast. British Standard Institution.

BS EN 13848-5:2008+A1:2010, 2010. Railway applications - Track - Track geometry quality - Part 5: Geometric quality levels - Plain line.

BS EN 933-1, 2012. Tests for geometrical properties of aggregates, Part 1: Determination of particle size distribution - Sieving method. British Standard Institution.

BS EN 933-2, 1996. Tests for geometrical properties of aggregates. Determination of particle size distribution. Test sieves, nominal size of apertures.

BS EN 933-3, 2012. Tests for geometrical properties of aggregates, Part 3: Determination of particle shape - Flakiness index. British Standard Institution.

BS EN ISO 14040, 2006. Environmental management - Life cycle assessment - Principles and framework.

BS ISO 15686-5:2017, 2017. Buildings and constructed assets — Service life planning - Part 5: Life-cycle costing.

Buonanno, A. and Mele, R., 2000. The use of bituminous mix subballast in the Italian State Railways. In: 2nd Eurasphalt and Eurobitume Congress. Barcelona.

Caetano, L.F. and Teixeira, P.F., 2016. Predictive Maintenance Model for Ballast Tamping. Journal of Transportation Engineering, 142 (4), 4016006.

Calla, C., 2003. Two Layered Ballast System for Improved Performance of Railway Track. Coventry University.

Carrascal, I., Casado, J.A., Dego, S., and Polanco, J.A., 2010. Comportamiento mecanico frente a esfuerzoz dinamicos de manta elastomerica para la atenuacion de vibraciones en ferrocarriles [online]. Available from: http://life2010-recytrack.com/docs/comportamientomecanico.pdf [Accessed 12 Jun 2014].

Carrascal, I., Casado, J.A., Dego, S., and Polanco, J.A., 2011. Atenuación frente a impacto en sistemas de sujeción ferroviaria de alta velocidad. Anales Mecánica de la Fractura, 28, 713–718.

CEMOSA, 2014. Design requirements and improved guidelines for design (track loading, resilience & RAMS). Capacity for Rail.

Chang, B. and Kendall, A., 2011. Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system. Transportation Research Part D 1, 16, 429–434.

Chen, C., McDowell, G.R., and Thom, N., 2012. Discrete element modelling of cyclic loads of geogrid-reinforced ballast under confined and unconfined conditions. Geotextiles and Geomembranes, 35, 76–86.

Chomicz-kowalska, A. and Maciejewski, K., 2015. Multivariate optimization of recycled road base cold mixtures with foamed bitumen. Procedia Engineering, 108, 436–444.

Chrismer, S.M., 1990. Track surfacing with conventional tamping and stone injection. In: ARR Technical Center: 32. Chicago, Illinois.

Chrismer, S.M. and Selig, E.T., 1991. Mechanics-based model to predict ballast-related maintenance timing and costs. International heavy haul railway conference, TRB, 208–211.

Collings, D., Hughes, M., Grobler, J., Jenkins, K., Jooste, F., Long, F., and Thompson, H., 2009. Technical Guideline: Bitumen Stabilised Materials.

Consoli, F. and SETAC (Society), 1993. Guidelines for Life-Cycle Assessment: A 'Code of Practice' from the workshop held at Sesimbra, Portugal, 31 March – 3 April 1993 Society of Environmental Toxicology and Chemistry (SETAC).

Cope, G.H., 1993. British Railway Track, Design, Construction and Maintenance. The Permanent Way Institution.

D'Angelo, G., Thom, N., and Lo Presti, D., 2015. Laboratory Simulation of Field Loading Conditions and Maintenance Operations. In: International Conference Railway Engineering 2015. Edinburgh.

Dahlberg, T., 2004. Railway track settlements - a literature review. Report for the EU project SUPERTRACK, Linkoping University, Sweden.

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

Dash, S.K. and Shivadas, A.S., 2012. Performance Improvement of Railway Ballast Using Geocells. Indian Geotechnical Journal, 42 (3), 186–193.

Derringer, G.C. and Suich, D., 1980. Simultaneous optimization of several response variables. Journal of Quality Technology, 12 (4), 214–219.

Dersch, M.S., Tutumluer, E., Mareno, A., Peeler, C.T., and Bower, D.K., 2011. Characterization of polyurethane coated railroad ballast behavior. In: 90th Annual Meeting of the Transportation Research Board. Washington, D.C.

Dersch, M.S., Tutumluer, E., Peeler, C.T., and Bower, D.K., 2010. Polyurethane Coating of Railroad Ballast Aggregate for Improved Performance. In: 2010 Joint Rail Conference, Volume 1. ASME, 337–342.

Dingler, M., Lai, Y.-C., and Barkan, C.P.L., 2011. Economics of Expanding Capacity on a Single Track Heavy Haul Railway Line. In: Proceedings of the 2011 International Heavy Haul Association.

Dold, M. and Potocan, S., 2013. Long-term behaviour of Sylomer ballast mats. Rail technology review, vol. 13. ISSN 1869-7801.

Dunn, C.S. and Bora, P.K., 1972. Shear strength of untreated road base aggregates measured by variable lateral pressure triaxial cell. Journal of Materials, 7 (2), 131–142.

Ebrahimi, A. and Keene, A.K., 2011. Maintenance Planning of Railway Ballast. AREMA Annual Conference.

Ebrahimi, A., Tinjum, J.M., and Edil, T.B., 2010. Large-Scale, Cyclic Triaxial Testing of Rail Ballast. AREMA 2010 Annual Conference & Exposition, 1–24.

Ebrahimi, A., Tinjum, J.M., and Edil, T.B., 2012. Protocol for Testing Fouled Railway Ballast in Large-Scale Cyclic Triaxial Equipment. Geotechnical Testing Journal, 35 (5), 1–9.

Ebrahimi, A., Tinjum, J.M., and Edil, T.B., 2015. Deformational Behavior of Fouled Railway Ballast. Can. Geotech. J., 52 (3), 344–355.

EC, 2016. EU Reference Scenario 2016: Energy, transport and GHG emissions - Trends to 2050. Luxembourg.

EC, 2017a. Paris Agreement [online]. Available from: https://ec.europa.eu/clima/policies/international/negotiations/paris_en#tab-0-0 [Accessed 8 Aug 2017].

EC, 2017b. Transport [online]. Available from: https://ec.europa.eu/clima/policies/international/paris_protocol/transport_en [Accessed 8 Aug 2017].

Edwards, J.P., Thom, N., and Fleming, P.R., 2005. Accelerated Laboratory Based Mechanistic Testing of Unbound Materials within the Newly Developed NAT Springbox. In: 84th Transportation Research Board Meeting. Washington, D.C.

Esveld, C., 2001. Modern railway track. Second Edi. Traffic.

European Commission Joint Research Center - Institute for Environment and Sustainability (EC JRC - IES), 2010. International reference life cycle data system (ILCD) handbook - general guide for life cycle assessment - detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg: Publications Office of the European Union.

Fair, P., 2003. The geotechnical behaviour of ballast materials for railway track maintenance. University of Sheffield.

Fair, P. and Anderson, W.F., 2003. Railway track maintenance using the Stoneblower. Proceedings of the ICE - Transport, 156 (August), 155–167.

Federici, M., Ulgiati, S., and Basosi, R., 2008. A thermodynamic, environmental and material flow analysis of the Italian highway and railway transport systems. Energy, 33 (5), 760–775.

Ferreira, T.M., 2007. Influence of incorporating a bituminous sub-ballast layer on the performations of railway trackbed. Universidade Técnica de Lisboa, Portugal.

Ferreira, T.M. and Teixeira, P.F., 2011. Impact of different drainage solutions in the behavior of railway trackbed layers due to atmospheric actions. 9th World Congress on Railway Reserach - May 22-26, 1–14.

Fischer, S., Eller, B., Kada, Z., and Németh, A., 2015. Railway construction. Győr, Hungary: Universitas-Gyor Nonprofit Kft.

Fischer, S. and Horvát, F., 2011. Superstructure stabilization of ballast bedded railway tracks with geogrids. Hungarian Journal of Industrial Chemistry Veszprém, 39, 101–106.

Fischer, S. and Szatmári, T., 2016. Investigation of the geogrid-granular soil combination layer with laboratory multi-level shear box test. In: 6th European Geosynthetics Congress. Ljubljana, Slovenia.

Fortin, J.P., 1982. La deformée dynamique de la voie. Revue generale des Chemins de Fer.

Frederick, C.O. and Round, D.J., 1985. Vertical track loading – Track technology for the next decade. Vehicle System Dynamic Journal - Special Supplement, (24), 222–233.

Furukawa, A., 2016. Recent Tendencies in Ballasted Track Maintenance. Railway Technical Research Institute, 57 (2).

Goedkoop, M.J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., and Van Zelm, R., 2013. Recipe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level;

First edition Report I: Characterisation.

Goncu, F., 2012. Mechanics of Granular Materials : Constitutive Behavior and Pattern Transformation. Technische Universiteit Delft.

Goswami, T., 2014. A laboratory study on use of bitumen emulsion in gravel road. Odisha, India.

Greening, P.A.K., Gourley, C.S., and Tournee, J.M., 1999. Increasing skills of labour-based contractors through transfer of appropriate road surfacing technology. In: 7th Conference on asphalt pavement for Southern Africa. 1–16.

Gremmler, 2016. Web page [online]. Available from: http://gremmler.de/en/systems/ballast-bonding/ [Accessed 20 Jun 2012].

Harrison, H.D., Selig, E.T., Dean, F.E., and Stewart, H.E., 1986. Correlation of concrete tie track performance in revenue service and at the facility for accelerated service testing.

Hauschild, M.Z. and Huijbregts, M.A.J., 2015. Chapter 1. In Life cycle impact assessment. In: Hauschild and Huijbregt (eds), ed. Introducing Life Cycle Impact Assessment. Springer.

Hausgaard, E., 2013. Framework for Railway Phase-based Planning. In: Annual transport conference. 1–14.

Hawari, H.M. and Murray, M.H., 2008. Deterioration of railway track on heavy haul lines. In: Conference on Railway Engineering. RTSA, Australia.

Hensley, M.. and Rose, J.G., 2000. Design, construction and performance of Hot Mix Asphalt for railway trackbeds. 1st World Conference of Asphalt Pavements, 11.

Ho, C., Faghihi-Kashani, H., Hyslip, J., and Moorhead, W., 2015. Full scale cyclic testing of an under sleeper application of resiliently bound ballast. In: Proceedings of Railway Engineering Conference. Edinburgh, Scotland.

Holtz, W.G. and Gibbs, H.J., 1956. Triaxial Shear Tests on Pervious Gravelly Soils. Journal of the Soil Mechanics and Foundations Division, 82 (1), 1–22.

Horníček, L., Tyc, P., Lidmila, M., Krejčiříková, H., Jasanský, P., and Břešťovský, P., 2010. An investigation of the effect of under-ballast reinforcing geogrids in laboratory and operating conditions. In: Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 269–277.

Horton, M., 2014. Stiffness in Tensar Geogrids and Applications in Railway Maintenance.

Horvath, A., 2006. Environmental Assessment of Freight Transportation in the

U.S. (11 pp). The International Journal of Life Cycle Assessment, 11 (4), 229–239.

Huang, H., Tutumluer, E., and Dombrow, W., 2009. Laboratory Characterization of Fouled Railroad Ballast Behavior. Transportation Research Record: Journal of the Transportation Research Board, (2117), 93–101.

Hunt, G.A. and Wood, J., 2005. Review of the effect of track stiffness on track performance. Rail Safety & Standards Board. Research Project T372.

Indraratna, B., Hussaini, S.K.K., and Vinod, J.S., 2013. The lateral displacement response of geogrid-reinforced ballast under cyclic loading. Geotextiles and Geomembranes, 39, 20–29.

Indraratna, B., Ionescu, D., and Christie, D., 1998. Shear Behavior of Railway Ballast Based on Large-Scale Triaxial Tests. Journal of Geotechnical and Geoenvironmental Engineering, 124 (May), 439–449.

Indraratna, B., Khabbaz, H., and Salim, W., 2004. A laboratory study on improvement of railway ballast using geosynthetics. In: Geo-Trans 2004: Geotechnical engineering for transportation projects. Los Angeles, USA, 617–626.

Indraratna, B., Khabbaz, H., Salim, W., and Christie, D., 2006. Geotechnical properties of ballast and the role of geosynthetics in rail track stabilisation. Journal of Ground Improvement, 10 (3), 91–102.

Indraratna, B., Khabbaz, H., Salim, W., Lackenby, J., and Christie, D., 2004. Ballast characteristics and the effects of geosynthetics on rail track deformation. In: Int. Conference on Geosynthetics and Geoenvironmental Engineering. Mumbai, India, 3–12.

Indraratna, B., Nimbalkar, S., and Christe, D., 2009. The performance of rail track incorporating the effects of ballast breakage , confining pressure and geosynthetic reinforcement. In: 8th International Conference on the Bearing Capacity of Roads, Railways, and Airfields. London, UK: Taylor & Francis, 5–24.

Indraratna, B., Nimbalkar, S., Christie, D., Rujikiatkamjorn, C., and Vinod, J., 2010. Field Assessment of the Performance of a Ballasted Rail Track with and without Geosynthetics. Journal of Geotechnical and Geoenvironmental Engineering, 136 (July), 907–917.

Indraratna, B., Nimbalkar, S., and Rujikiatkamjorn, C., 2012. Stabilising railway embankments with geosynthetic grids and drains and a class A prediction of track behaviour. In: International Symposium on Sustainable Geosynthetics and Green Technology for Climate Change (SGCC). Bangkok, Thailand, 21–40.

Indraratna, B., Nimbalkar, S., and Rujikiatkamjorn, C., 2014. Enhancement of rail track performance through utilisation of geosynthetic inclusions. Geotechnical Engineering, 45 (1), 17–27.

Indraratna, B. and Salim, W., 2003. Deformation and Degradation Mechanics of Recycled Ballast Stabilised With Geosynthetics. Soils and Foundations, 43 (4), 35–46.

Indraratna, B., Salim, W., and Rujikiatkamjorn, C., 2011. Advanced Rail Geotechnology - Ballasted Track.

Indraratna, B., Shahin, M., and Salim, W., 2005. Use of Geosynthetics for Stabilizing Recycled Ballast in Railway Track Substructures. Proceedings of NAGS2005/GRI 19 Cooperative Conference, 1–15.

Indraratna, B., Sun, Y., and Nimbalkar, S., 2016. Laboratory Assessment of the Role of Particle Size Distribution on the Deformation and Degradation of Ballast under Cyclic Loading. Journal of Geotechnical and Geoenvironmental Engineering, (March), 04016016.

Ionescu, D., 2004. Evaluation of the engineering behaviour of railway ballast. PhD Dissertation. University of Wollongong, Wollongong, Australia.

Ionescu, D., Fedele, D.T., Trounce, M.R., and Petrolito, J., 2016. Deformation and Degradation Characteristics of Sand-Contaminated Railway Ballast. In: J. Pombo, ed. Proceedings of the Third International Conference on Railway Technology: Research, Development and Maintenance. Cagliari, Italy: Civil-Comp Press, 1–13.

ISO 15686, 2008. Part 5 Buildings and Constructed Assets Service Life Planning – Life Cycle Costing.

Jeffs, T. and Tew, G.P., 1991. A review of Track Design Procedures - Sleepers and Ballast. TRL Report TRL611. Railways of Australia.

Jimenez–Redondo, N., Bosso, N., Zeni, L., Minardo, A., Schubert, F., Heinicke, F., and Simroth, A., 2012. Automated and Cost Effective Maintenance for Railway (ACEM–Rail). Procedia - Social and Behavioral Sciences, 48, 1058–1067.

Jing, G.Q., Zhou, Y.D., Lin, J., and Zhang, J., 2012. Ballast flying mechanism and sensitivity factors analysis. International Journal on Smart Sensing and Intelligent Systems, 5 (4), 928–939.

Jung, W., Lee, S., Lee, J., Kwon, M., and Ju, B., 2014. Analytical Study of the Vibration Attenuation with respect to Trackbed Systems. International Journal of Railway, 7 (2), 40–45.

Kaewunruen, S. and Remennikov, A.M., 2008a. Dynamic properties of railway track and its components: a state-of-the-art review. In: B. Weiss, ed. New Research on Acoustics. New York, 197–220.

Kaewunruen, S. and Remennikov, A.M., 2008b. An experimental evaluation of the attenuation effect of rail pad on flexural behaviour of railway concrete sleeper under severa impact loads. In: Proceeding of the 2008 Australian structureal engineering conference. Melbourne, Australia.

Keene, A.K., Edil, T.B., Fratta, D., and Tinjum, J.M., 2013. Modeling the Effect of Polyurethane Stabilization on Rail Track Response. In: Geo-Congress. 1–10.

Keene, A.K., Edil, T.B., and Tinjum, J.M., 2012. Mitigating Ballast Fouling Impact and Enhancing Rail Freight Capacity.

Kelly, D., 2015. XiTRACK Polyurethane Ballast Reinforcement - Case studies. Balfour Beatty Rail Limited, (00235437), 1–11.

Kennedy, J., 2011. A full-scale laboratory investigation into railway track substructure performance and ballast reinforcement. Heriot-Watt University.

Kennedy, J., Woodward, P.K., Medero, G., and Banimahd, M., 2013. Reducing railway track settlement using three-dimensional polyurethane polymer reinforcement of the ballast. Construction and Building Materials, 44, 615–625.

Kennedy, J., Woodward, P.K., Medero, G., and McKinney, J., 2009. Full-scale cyclic geopavement & railway accelerated fatigue testing. In: 0th international railway engineering conference. London, University of Westminster.

Khouy, I.A., 2011. Optimization of track geometry maintenance - A study of track geometry degradation to specify optimal inspection intervals. Luleå University of Technology.

Kiani, M., Ceney, H., and Parry, T., 2008. Environmental life-cycle assessment of railway track beds. Proceedings of the ICE - Engineering Sustainability, 161 (June), 135–142.

Kjærnsli, B. and Sande, A., 1963. Compressibility of some coarse-grained materials. In: Proceedings of European Conf. Soil Mech. Found. Enggr., Vol. 1. Wiesbaden, Germany, 245–251.

Kolbuszewski, J. and Frederick, M.R., 1963. The significance of particle shape and size on the mechanical behaviour of granular materials. In: European Conference on the Soil Mechanics and Foundation Engineering. 253–263.

Kupfer, T., Baitz, M., Colodel, C.M., Kokborg, M., Schöll, S., Rudolf, M., Thellier, L., Gonzalez, M., Schuller, O., Hengstler, J., Stoffregen, A., Köhler, A., and Thylmann, D., 2017. GaBi Database & Modelling Principles. thinkstep GaBi.

Kwan, C.C.J., 2006. Geogrid Reinforcement of Railway Ballast. University of Nottingham.

Lacalle-Jiménez, H.I., 2017. Airfield pavement design with cold recycled materials. The University of Nottingham, UK.

Lacalle-Jiménez, H.I., Edwards, J.P., and Thom, N.H., 2017. Analysis of stiffness and fatigue resistance of cold recycled asphalt mixtures manufactured with foamed bitumen for their application to airfield pavement design. Materiales de Construcción, 67 (327).

Lackenby, J., Indraratna, B., McDowell, G., and Christie, D., 2007. Effect of confining pressure on ballast degradation and deformation under cyclic triaxial loading. Géotechnique, 55 (4), 325–328.

Lafarge Tarmac Ltd, 2015. Aggregate properties data.

Lai, Y.-C. and Barkan, C.P.L., 2009. Enhanced Parametric Railway Capacity Evaluation Tool. Transportation Research Record: Journal of the Transportation Research Board, 2117 (1), 33–40.

Lakušic, S., Ahac, M., and Haladin, I., 2010. Track stability using ballast bonding method. In: 10th Slovenski kongres o cestah in prometu. Portoroz.

De Langhe, K., 2017. The importance of external costs for assessing the potential of trams and trains for urban freight distribution. Research in Transportation Business and Management, 24 (June), 114–122.

Laryea, S., Baghsorkhi, M.S., Ferellec, J., Mcdowell, G.R., and Chen, C., 2014. Experimental and numerical discrete element analyses have been performed to investigate. Transportation Geotechnics, 1 (4), 225–240.

Latunussa, C.E.L., Ardente, F., Blengini, G.A., and Mancini, L., 2016. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Solar Energy Materials and Solar Cells, 156, 101–111.

Laurans, E., Pouligny, P., Michel, W., Ferrellec, J., Geoffrey, G., and Bertholet, A., 2016. Surface gluing of ballast to reduce ballast creep on HSL. In: 11th World Congress on Railway Research.

Lechner, B., 2011. Railway Concrete Pavements. In: 2nd International Conference on Best Practices for Concret Pavements. Florianapolis.

Lee, D.B., 2002. Fundamentals of Life-Cycle Cost Analysis. Transportation Research Record: Journal of the Transportation Research Board, (02), 203–210.

Leshchinsky, B.A., 2012. Enhancing Ballast Performance using Geocell Confinement. Columbia University.

Lesueur, D., 2015. Interview.

Li, D., Rose, J.G., and LoPresti, J., 2001. Test of hot-mix asphalt trackbed over soft subgrade under heavy axle loads. Technology Digest-01-009, Assoc. of American Railroads, April.

Li, D. and Selig, E.T., 1998. Method for railroad. Journal of Geotechnical and Geoenvironmental Engineering, 124 (April), 316–322.

Lim, W.L., 2004. Mechanics of railway ballast behaviour. University of Nottingham, UK.

López-Pita, A., 2006. Infraestructuras ferroviarias. Universidad Politécnica de Cataluña, Barcelona, Spain.

López-Pita, A., 2010. Alta Velocidad en el Ferrocarril. Universidad Politécnica de Cataluña, Barcelona, Spain.

Lopez Pita, A., Teixeira, P.F., and Robusté, F., 2004. High speed and track deterioration: the role of vertical stiffness of the track. Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit, 218 (1), 31–40.

Lovett, A.H., Dick, C.T., and Barkan, C.P.L., 2015. Determining Freight Train Delay Costs on Railroad Lines in North America. In: Proceedings of the International Association of Railway Operations Research (IAROR) 6th International Conference on Railway Operations Modelling and Analysis. Tokyo, Japan.

Lovett, A.H., Dick, C.T., Ruppert, C.J., and Barkan, C.P.L., 2015. Cost and delay of railroad timber and concrete crosstie maintenance and replacement. Transportation Research Record: Journal of the Transportation Research Board, 2476, 37–44.

Lu, M., 2008. Discrete element modelling of railway ballast under triaxial conditions. Civil Engineering.

MAINLINE Deliverable 5.3, 2013. Deliverable 5.3: Recommendations for Format of a Life Cycle Assessment Tool (LCAT).

MAINLINE Deliverable 5.4, 2013. Proposed methodology for a Life Cycle Assessment Tool (LCAT).

Manzo-Constanzo, N., López-Pita, A., Fontsere, V., Ausilio, A., De Ambri, E., and Basei, E., 2015. NEOBALLAST®: seeking for the ballast of the future. In: Proceedings of the Third International Conference on Railway Technology. Cagliari, Italy, 3–4.

Marachi, N.D., Chan, C.K., and Seed, H.B., 1972. Evaluation of Properties of Rockfill Materials. Journal of the Soil Mechanics and Foundations Division, 98 (1), 95–114.

Marachi, N.D., Chan, C.K., Seed, H.B., and Duncan, J.M., 1969. Strength and Deformation Characteristics of Rockfill Materials. State of California Department of Water Resources.

Marsal, R.J., 1967. Large-Scale Testing of Rockfill Materials. Journal of the Soil Mechanics and Foundations Division, 93 (2), 27–43.

Matthews, H.S., Hendrickson, C.T., and Matthews, D.H., 2014. Life Cycle Assessment: Quantitative Approaches for Decisions That Matter. Green Design Institute, Carnegie Mellon University, Pittsburgh.

McDowell, G., Lim, W.L., Collop, A., Armitage, R.J., and Thom, N., 2005. Laborarartory simulation of the effects of train loading and tamping on ballast. In: Proceedings of the Institution of Civil Engineers. 89–95.

McDowell, G.R., Harireche, O., Konietzky, H., Brown, S.F., and Thom, N., 2006. Discrete element modelling of geogrid-reinforced aggregates. Proceedings of the ICE - Geotechnical Engineering, 159 (1), 35–48.

McMichael, P., 1986. Stone blowing from theory to practice. In: Third International Heavy Haul Conference. Vancouver, Canada.

McMichael, P., 1998. The Stoneblower comes of age. Development, testing and operating of a new track maintenancesystem. In: ICE.

McMichael, P. and McNaughton, A., 2003. The Stoneblower-Delivering the Promise: Development, Testing and Operation of a New Track Maintenance System. In: Transportation Research Board annual meeting. Washington, D.C.

McMichael, P. and Strange, P.R., 1992. BR Adopts New Maintenance Process. International Railway Journal.

Merheb, A., Motta, R., Bernucci, L., Moura, E., Costa, R., Bessa, I., Vieira, T., and Sgavioli, F., 2014. Railway Ballast Load Analysis using Small-Scale Cylindrical Triaxial Test. In: J. Pombo, ed. Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance,. Stirlingshire, Scotland: Civil-Comp Press, 1–12.

Michas, G., 2012. Slab Track Systems for High-Speed Railways. Royal Institute of Technology (KTH), Stockholm, Sweden.

Milford, R.L. and Allwood, J.M., 2010. Assessing the CO2 impact of current and future rail track in the UK. Transportation Research Part D: Transport and Environment, 15 (2), 61–72.

Momoya, Y., Nakamura, T., Fuchigami, S., and Takahashi, T., 2016. Improvement of Degraded Ballasted Track to Reduce Maintenance Work. International Journal of Railway Technology, 5 (3), 31–54.

Moreno-Martinez, E., 2016. Survey.

Moreno-Navarro, F., Sol-Sánchez, M., Jiménez del Barco-Carrión, A., and Rubio-Gámez, M.C., 2015. Analysis of the influence of binder properties on the mechanical response of bituminous mixtures. International Journal of Pavement Engineering, 8436 (September), 1–10.

Moreno-Navarro, F., Sol-Sánchez, M., Martin, J., Pérez, M., and Rubio-Gámez, M.C., 2013. The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation. Materials and Design, 47, 272–280.

Morley, S., 2017. http://inflation.stephenmorley.org/ [online].

Nakamura, T. and Muramoto, K., 2010. Repair Method for Ballasted Track by Composite Filling Material Track Consisting of Water Glass and Polymer Water. Railway Technical Research Institute, 51 (2), 55–59.

Nakamura, T., Muramoto, K., Yoshihiko, Y., and Nomura, K., 2015. Development of repair method using polymer for ballasted tracks with high-mixture ratio of fine particles. In: The 15th Asian Regional conference on Soil Mechanics and Geotechnical Engineering.

Nassar, A.I., Mohammed, M.K., Thom, N., and Parry, T., 2016. Characterization of High Performance Cold Bitumen Emulsion Mixtures for Surface Courses. International Journal of Pavement Engineering.

National Roads Authority (NRA), 2014. NRA Interim Advice Note 10 / 14 NRA Specification for Road Works Series 900 Road Pavements – Bituminous Materials. Dublin, Ireland.

Naziur, M.S.M., 2017. Effect of Particle Size Distribution and Packing Characteristics on Railroad Ballast Shear Strength: a Numerical Study Using the Discrete Element Method. Boise State University.

Needham, D., 1996. Developments in bitumen emulsion mixtures for roads. University of Nottingham, UK.

Nelder, L., England, C., Armitage, R., Brough, M., Fleming, P., and Frost, M., 2008. A comparison of trackbed design methodologies: a case study from a heavy haul freight railway. In: Proceedings of the International Conference on Advances in Transportation Geotechnics. 135–142.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., and Olsson, L., 2007. Categorising tools for sustainability assessment. Ecological Economics, 60 (3), 498–508.

Nimbalkar, S. and Indraratna, B., 2016. Improved Performance of Ballasted Rail Track Using Geosynthetics and Rubber Shockmat. Journal of Geotechnical and Geoenvironmental Engineering, (April), 04016031.

NR/L2/TRK/001/mod12, 2015. Track Geometry - Maintenance design requirements.

Nurmikolu, A., 2005. Degradation and Frost Susceptibility of Crushed Rock Aggregates Used in Structural Layers of Railway Track. Tampere University of Technology, Tampere.

Nurmikolu, A., 2012. Key aspects on the behaviour of the ballast and substructure of a modern railway track: research-based practical observations in Finland. Journal of Zhejiang University SCIENCE A, 13 (11), 825–835.

Ojum, C.K., 2015. The Design Optimisation of Cold Asphalt Emulsion Mixtures. The University of Nottingham.

Ozbay, K., Parker, N.., Jawad, D., and Hussain, S., 2003. Guidelines for Life Cycle Cost Analysis. FHWA-NJ-2003-012.

Pires, J., 2016. Integrated maintenance model for heavy haul tracks. Ecole Polytechnique federale de Lausanne.

Pires, J. and Dumont, A.G., 2015. Railway ballast degradation. In: 15th Swiss Transport Research Conference. Ascona.

Pirozzolo, L., Sol-Sánchez, M., Moreno-Navarro, F., Martínez-Montes, G., and Rubio-Gámez, M.C., 2017. Evaluation of bituminous subballast manufactured at low temperatures as an alternative for the construction of more sustainable railway. Materiales de Construcción, (Accepted in-press).

du Plooy, R., Gräbe, P.J., and Turner, C., 2017. Laboratory characterisation of rigid polyurethane foam reinforced ballast. In: Proceedings of the 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields. Athens, Greece, 1851–1858.

Powrie, W. and Le Pen, L., 2016. A Guide to Track Stiffness.

Profillidis, V.A., 2000. Railway Engineering. Ashgate.

Profillidis, V.A., 2016. Railway Management and Engineering: Fourth Edition. Fourth Edi. New York, USA: Routledge.

Raymond, G.P., 1985. Research on railroad ballast specification and evaluation. Transportation Research Record, (1006).

Raymond, G.P. and Bathurst, R.J., 1987. Performance of Large-scale Model Single Tie/ballast Systems. In: Transportation Research Record. 7–14.

Raymond, G.P. and Bathurst, R.J., 1994. Repeated-load response of aggregates in relation to track quality index. Canadian Geotechnical Journal, 31 (4), 547–554.

Raymond, G.P. and Gaskin, P.N., 1975. Selection and performance of railroad ballast. In: Proc. of a symposium held at Princeton Univ. Railroad Track Mechanics and Technology, 369–385.

Raymond, G.P. and Ismail, I., 2003. The effects of geogrid reinforcement on unbound aggregates. Geotextiles and Geomembranes, 21 (6), 355–380.

Raymond, G.P. and Williams, D.R., 1978. Repeated load triaxial tests on a dolomite ballast. Journal of the Geotechnical Engineering Division, ASCE, 104 (GT7), 1013–1029.

Read, D. and Li, D., 2006. Research Results Digest 79. In: Transit Cooperative Research Program, Sponsored by the Federal Transit Administration. Washington, D.C.

Road Emulsion Associated Ltd (REAL), 2006. REAL Technical Data Sheet No 8 - Patching and Grouting Introduction.

Rose, J.G. and Anderson, J.S., 2006. Long-term performance of asphalt underlayment trackbeds for special trackbed applications. In: American Railway Engineering and Maintenance-of-Way Association. Louisville, USA.

Rose, J.G. and Bryson, L.S., 2009. Hot mix asphalt railway trackbeds: Trackbed materials, performance evaluations ans significant implications. International Conference on Perpetual Pavements, 7326, 19.

Rose, J.G., Li, D., and Walker, L.A., 2002. Tests and evaluations of in-service asphalt trackbeds. In: American Railway Engineering and Maintenance-of-Way Association. Washington, D.C., USA.

Rose, J.G. and Souleyrette, R., 2014a. Hot-Mix Asphalt (Bituminous) Railway Trackbeds: In-Track Tests, Evaluations, and Performances - A Global Perspective -- Part I -Introduction to Asphalt Trackbeds and International Applications and Practices. 3rd International Conference on Transportation Infrastructure.

Rose, J.G. and Souleyrette, R., 2014b. Hot-Mix Asphalt (Bituminous) Railway Trackbeds: In-Track Tests, Evaluations, and Performances - A Global Perspective -- Part II -United States Asphalt Trackbed Applications and Practices. 3rd International Conference on Transportation Infrastructure.

Rose, J.G., Teixeira, P.F., and Veit, P., 2011. International Design Practices , Applications , and Performances of Asphalt / Bituminous Railway Trackbeds. Georail, 1–23.

Rostler, F.S., White, R.M., Nair, K., Hicks, R.G., and Newton, J.W., 1966. Study of Methods of Stabilizing Conventional Ballast Using Polymers. Oakland, CA.

RT/CE/C/006, 2002. Design, Installation & Maintenance of lineside drainage.

Salim, W., 2004. Deformation and degradation aspects of ballast and constitutive modelling under cyclic loading. University of Wollongong.

Salomon, D.R., 2006. Asphalt emulsion technology. Transportation Research Board, Washington, D.C.

Schafer, D.H. and Barkan, C.P.L., 2008. A prediction model for broken rails and an analysis of their economic impact. In: Proceedings of the AREMA 2008 Annual Conference. Salt Lake City, UT, USA.

Schilder, R., 2006. USP-Under Sleeper Pads. Applications and Benefits of Elastic Elements in Ballasted Tracks. Paris.

Schlake, B.W., Barkan, C.P.L., and Edwards, J.R., 2012. Train Delay and Economic Impact of In-Service Failures of Railroad Rolling Stock. Transportation Research Record: Journal of the Transportation Research Board, 2261, 124–133.

Schultze, E. and Coesfeld, G., 1961. Elastic properties of ballast. In: 5th International Conference on Soil Mechanics and Foundation Engineering. Paris, France: Dunond Publishers, 323–327.

Selig, E.T. and Waters, J.M., 1994. Track Geotechnology and Substructure Management. T. Telford.

Semmelink, C.J., 1991. Use of the DRTT K-mould to determine the elastic and shear properties of pavement materials. South Africa.

Sevi, A.F., 2008. Physical modeling of railroad ballast using the parallel gradation scaling technique within the cyclical triaxial framework. Missouri University of Science and Technology.

Shenton, M.J., 1975. Deformation of railway ballast under repeated loading conditions. In: Proc. of a symposium held at Princeton Univ. Railroad Track Mechanics and Technology, 387–404.

Shenton, M.J., 1984. Ballast deformation and track deterioration. In: Proc. of a Conf. organized by the Inst. of Civil Engineers and held at the Univ. of Nottingham. Nottingham: Track Technology, 242–252.

Shenton, M.J., 1985. Ballast deformation and track deterioration. Derby, UK.

Shimatake, M., 1997. A track maintenance model for high-speed rail: a system dynamic approach. Massachusetts Institute of Technology, USA.

Shin, E.C., Kim, D.H., and Das, B.M., 2002. Geogrid-reinforced railroad bed settlement due to cyclic load. Geotechnical and Geological Engineering, 20 (3), 261–271.

SMARTRAIL, 2014. Optimized Whole Life Management of Rail Infrastructure Elements [online]. Available from: http://smartrail.fehrl.org/?m=1.

Sol-Sánchez, M., Moreno-Navarro, F., Martínez-Montes, G., and Rubio-Gámez, M.C., 2017. An alternative sustainable railway maintenance technique based on the use of rubber particles. Journal of Cleaner Production, 142 (4), 3850–3858.

Sol-Sánchez, M., Moreno-Navarro, F., and Rubio-Gámez, M., 2014a. The Use of Deconstructed Tires as Elastic Elements in Railway Tracks. Materials, 7, 5903–5919.

Sol-Sánchez, M., Moreno-Navarro, F., and Rubio-Gamez, M.C., 2014. Viability analysis of deconstructed tires as material for rail pads in high-speed railways. Materials and Design, 64, 407–414.

Sol-Sánchez, M., Moreno-Navarro, F., and Rubio-Gamez, M.C., 2015. The use of elastic elements in railway tracks: A state of the art review. Construction and Building Materials, 75 (1), 293–305.

Sol-Sánchez, M., Moreno-Navarro, F., and Rubio-Gámez, M.C., 2014b. Viability of using end-of-life tire pads as under sleeper pads in railway. Construction and Building Materials, 64, 150–165.

Sol-Sánchez, M., Moreno-Navarro, F., and Rubio-Gámez, M.C., 2015. The use of deconstructed tire rail pads in railroad tracks: Impact of thickness. Materials and Design, 58, 198–208.

Sol-Sánchez, M., Moreno-Navarro, F., and Rubio-Gámez, M.C., 2016a. An Analysis of the Performance of Deconstructed Tires for Use as Pads in Railroad Tracks. Journal of Civil Engineering and Management, 22, 739–746.

Sol-Sánchez, M., Moreno-Navarro, F., and Rubio-Gámez, M.C., 2016b. Analysis of ballast tamping and stone-blowing processes on railway track behaviour: the infuence of using UPS's. Geotechnique, 66 (6), 481–489.

Sol-Sánchez, M., Pirozzolo, L., Moreno-Navarro, F., and Rubio-Gamez, M.C., 2015. Advanced characterisation of bituminous sub-ballast for its application in railway tracks: The influence of temperature. Construction and Building Materials, 101 (July).

Sol-Sánchez, M., Pirozzolo, L., Moreno-Navarro, F., and Rubio-Gámez, M.C., 2016. A study into the mechanical performance of different configurations for the railway track section : A laboratory approach. Engineering Structures, 119, 13–23.

Sol-Sánchez, M., Thom, N., Moreno-Navarro, F., Rubio-Gámez, M.C., and Airey, G.D., 2015. A study into the use of crumb rubber in railway ballast. Construction and Building Materials, 75, 19–24.

Soleimanmeigouni, I., Ahmadi, A., and Kumar, U., 2016. Track geometry degradation and maintenance modelling: A review. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.

Spielmann, M. and Scholz, R.W., 2005. Life cycle inventories of transport services. The International Journal of Life Cycle Assessment, 10 (1), 85–94.

Steenbergen, M., 2009. Efficient long-term track design: energy flux optimisation. In: 8th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems. Firenze.

Su, B., 2005. Effects of Railroad Track Structural Components and Subgrade on Damping and Dissipation of Train Induced.

Sugrue, W., 2013. Permanent Way for High Speed Lines. In: 9 th Training on High Speed Systems Permanent Way for High Speed Lines. UIC - Paris.

Sun, Q.D., Indraratna, B., and Nimbalkar, S., 2010. Deformation and Degradation Mechanisms of Railway Ballast under High Frequency Cyclic Loading. Journal of Geotechnical and Geoenvironmental Engineering, 142 (1).

Sussmann, T.R., Ebersohn, W., and Selig, E.T., 2001. Fundamental nonlinear track load-deflection behavior for condition evaluation. Transportation Research Record, 1742, 61–67.

Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.L., Ciroth, A., Brent, A.C., and Pagan, R., 2011. Environmental life-cycle costing: A code of practice. International Journal of Life Cycle Assessment, 16 (5), 389–391.

Teixeira, P.F., 2003. Contribucion a la reduccion de los costes de matenimiento de vias de alta velocidad mediante la optimizacion de su rigidez vertical. PhD Thesis, 268.

Teixeira, P.F., 2009. State-of-the-Art on the Use of Bituminous Subballast on European High- Speed Rail Lines. In: Congress of Bearing Capacity of Roads, Railways and Airfiels. Barcelona, Spain.

Teixeira, P.F., Ferreira, P.A., Lopez Pita, A., Casas, C., and Bachiller, A., 2009. The use of bituminous subballast on future high-speed lines in Spain: structural design and economical impact. International Journal of Railway, 2 (1), 1–7.

Thom, N. and Brown, S.F., 1988. 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.

Thom, N., Cooper, A., Grafton, P., Walker, C., Wen, H., and Sha, R., 2013. A New Test for Base Material Characterisation. In: 2nd MESAT Conference on Sustainable Asphalt Pavements in the Middle East, MESAT-055.

Thom, N.H., 2008. Principles of pavement engineering. London, UK: Thomas Telford.

Thom, N.H., 2009. Rail traffic testing. In: Jubilee Symposium on Polymer Geogrid

Reinforcement. Institute of Civil Engineering. London, UK, 61–66.

Thomson, D.R. and Woodward, P.K., 2004. Track Stiffness Management Using the XiTrack Geocomposite. Journal of the Permanent Way Institution, 122 (3), 1–12.

Tillman, A.-M., 2000. Significance of decision making for LCA methodology. Environmental Impact Assessment Review, 20, 113–123.

Tutumluer, E., Dombrow, W., and Huang, H., 2008. Laboratory Characterization of Coal Dust Fouled Ballast Behavior. In: Proc., AREMA 2008 Annual Conf. Lanham, MD: American Railway Engineering and Maintenance-of-Way Association (AREMA), 21–24.

Tutumluer, E., Staplin, D., Trosino, M., Smak, J., and Tomas, M., 2015. Stone Blowing as a Remedial Measure Mitigating Differential Settlement at Bridge Approaches. In: 94th Annual Transportation Research Board, meeting. Washington, D.C., USA.

UIC, 2009. Railway applications/Track - Concrete sleepers and bearers - Concrete sleepers and bearers with under sleeper pads.

UIC, 2011. Code 719-1 Recommendations for the use of under ballast mats.

UIC, 2013. USP recommendations. Under Sleeper Pads, Recommendations for Use.

UIC, 2016. Web page [online]. Available from: http://www.uic.org [Accessed 20 Jun 2016].

UK Department of Energy and Climate Change, 2011. A brief guide to the carbon valuation methodology for UK policy appraisal.

Vallerga, B.A., Monismith, C.L., and Granthem, K., 1957. A study of some factors influencing the weathering of paving asphalts. In: Assoc Asphalt Paving Technol Proc.

Vandanjon, P.O., Coiret, A., Paslaru, B.M., Fargier, A., Bosquet, R., Dauvergne, M., Jullien, A., Francois, D., and Labarthe, F., 2012. Practical guidelines for Life Cycle Assessment applied to railways project. International Symposium on Life Cycle Assessment and Construction: Civil Engineering and Buildings, 144–152.

Veit, P., 2006. Track quality – luxury or necessity? RTR Special, 57 (12), 32–37.

Westin, J. and Kågeson, P., 2012. Can high speed rail offset its embedded emissions? Transportation Research Part D: Transport and Environment, 17 (1), 1–7.

Whateley, M.K. and Barrett, W.L., 2009. Cliffe Hill Quarry, Leicestershire-development of aggregate reserves. Introduction to Mineral Exploration.

Wilson-Fahmy, R.F. and Koerner, R.M., 1993. Finite element modelling of soil-geogrid interaction with application to the behaviour of geogrids in a pullout loading condition. Geotextiles and Geomembranes, 12, 479–501.

Winters, O., 2009. Investigating the use of a new test for road materials. The University of Nottingham.

Witt, S., 2008. The Influence of Under Sleeper Pads on Railway Track Dynamics. In: Proceeding of Linköping University, Department of Management and Engineering, Division of Solid Mechanics. Sweden.

Woodward, P.K., Kacimi, A. El, Laghrouche, O., Medero, G., and Banimahd, M., 2012. Application of polyurethane geocomposites to help maintain track geometry for high-speed ballasted railway tracks. J Zhejiang Univ-Sci A (Appl Phys & Eng), 13 (11), 836–849.

Woodward, P.K., Kennedy, J., Laghrouche, O., Connolly, D.P., and Medero, G., 2014. Study of Railway Track Stiffness Modification by Polyurethane Reinforcement of the Ballast. Transportation Geotechnics, 1 (4), 214–224.

Woodward, P.K., Kennedy, J., and Medero, G., 2009. Three dimensional track reinforcement using polymer geocomposites. In: Proceedings of the American Railway Engineering and Maintenance of Way Association (AREMA). Chicago, Illinois, USA.

Woodward, P.K., Kennedy, J., Medero, G., and Banimahd, M., 2011a. Maintaining absolute clearances in ballasted railway tracks using in situ three-dimensional polyurethane GeoComposites. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 226 (3), 257–271.

Woodward, P.K., Kennedy, J., Medero, G.M., and Banimahd, M., 2011b. Application of in situ polyurethane geocomposite beams to improve the passive shoulder resistance of railway track. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 226, 294–304.

Woodward, P.K., Thompson, D., and Banimahd, M., 2007. Geocomposite technology: reducing railway maintenance. In: Proceedings of the ICE - Transport 160. 109–115.

World Bank Group, 2017. http://data.worldbank.org/indicator/AG.LND.PRCP.MM [online].

X-Rates, 2017. http://www.x-rates.com [online]. Available from: http://www.x-rates.com/average/?from=GBP&to=EUR&amount=1&year=2017.

Xiangwu, Z., 2005. Rubber-Modified Asphalt Concrete for High-Speed Railway

Roadbeds. Innovations Deserving Exploratory Analysis Programs.

Xiao, H., Huang, L.W., and Hu, F., 2015. Analysis on mechanical properties of railroad ballast bed enhanced by polyurethane material. Materials Research Innovations, 19 (S10), S10-59-S10-63.

Yuliestyan, A., Cuadri, A.A., García-Morales, M., and Partal, P., 2016. Binder Design for Asphalt Mixes with Reduced Temperature: EVA Modified Bitumen and its Emulsions. Transportation Research Procedia, 14 (December), 3512–3518.

Zaremsbki, A.M. and Newman, G.R., 2008. Comparative Technical and Economic Analysis Of Stoneblowing vs. Tamping. In: AREMA 2008 Annual Conference and Exposition. Salt Lake City.

Zoorob, S.E., Hassan, K.H., and Setyawan, A., 2002. Cold mix, cold laid semi-flexible Grouted Macadams, mix design and properties. In: Performance of Bituminous and Hydraulic Materials in Pavements. Lisse.