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Use of bitumen-stabilised ballast for improving railway trackbed conventional maintenance

G. D'ANGELO*, M. SOL-SÁNCHEZ†, F. MORENO-NAVARRO‡, D. LO PRESTI* and N. THOM*

Despite its many advantages, ballasted track needs frequent maintenance to ensure an adequate quality of service. However, tamping, traditionally used to correct geometry, causes ballast degradation and loosening of the already compacted ballast layer, which quickly returns the track to its pre-maintenance position. Then, other maintenance techniques such as stoneblowing, as well as diverse solutions that reinforce trackbed, have been developed to reduce ballast settlement and particles degradation. Given the need to further advance research in this field, bitumen-stabilised ballast (BSB) has started to be investigated by the authors as a feasible solution thanks to its easy and quick applicability and relatively low cost of the bonding agent. Nonetheless, more in-depth laboratory full-scale tests are necessary to prove the effectiveness of this solution before its application in real trial sections. This paper focuses on investigating the effect of BSB application during tamping and stoneblowing, on trackbed performance. Various scenarios are analysed to evaluate the effectiveness of this technology when applied at different stages of ballast service (clean and fouled). The results show that the use of BSB could improve the effectiveness of maintenance, particularly in the case of tamping and at the early stage of ballast life.

KEYWORDS: full-scale tests; laboratory tests; settlement; soil stabilisation; stiffness

INTRODUCTION

Traditional ballasted tracks, used worldwide, are often preferred by railway administrations and engineers because of their low initial costs and extensive construction experience; also appropriate drainage and damping capacity are achieved, as well as maintainability and good response to noise and vibrations (Blanco-Lorenzo *et al.*, 2011; Manzo-Constanzo *et al.*, 2015). However, one of the main issues associated with the unbound nature of ballast is the settlement of the trackbed (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 also determines trackbed durability. Fine material progressively produced by abrasion is, in fact, the main contribution (around 70%) (Huang *et al.*, 2009) to ballast void filling, a phenomenon known as 'fouling' that 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, despite the possible improvement of track design by including innovative elastic elements (Sol-Sánchez *et al.*, 2014a, 2015a), frequent maintenance interventions are also required during the service life of 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 & Dumont, 2015) due to its aggressiveness during the introduction and vibration of the tines. Furthermore, this process leads to the loosening of the already compacted ballast layer, which rapidly returns the track to its pre-maintenance position, a phenomenon known as 'ballast memory' (Selig & Waters, 1994; Anderson & Fair, 2008). In addition, all of these disadvantages are accentuated with the ever-growing demands of traffic speed and loads, as well as track quality requirements, which cannot help but increase maintenance costs (almost 30% of annual maintenance costs are related to ballast) and material consumption, further decreasing the durability of the trackbed itself. An alternative maintenance technique is stoneblowing, developed and principally used in the UK. This process 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 & McNaughton, 2003; D'Angelo *et al.*, 2015; Tutumluer *et al.*, 2015; Sol-Sánchez *et al.*, 2016). However, other studies have highlighted how in some cases the stoneblower fails to meet expected performance in terms of post-maintenance settlement (Fair, 2003) or that it can lead to trackbed stiffening and a consequent reduced damping capacity, which is one of the main functions of ballast (Sol-Sánchez *et al.*, 2016, 2017). These points suggest the need for further investigation before the use of stoneblowing becomes widespread.

In order to mitigate these problems associated with ballasted track and its conventional maintenance, diverse solutions, addressing both layer structure and maintenance effectiveness, have been developed (Woodward *et al.*, 2007; Lakušic *et al.*, 2010; Rose, 2013; Manzo-Constanzo *et al.*, 2015), with the main objective of reducing ballast settlement and particle degradation. In this regard, given the need to develop solutions to increase the durability and geometric quality of ballasted tracks while reducing costs associated with their maintenance, bitumen-stabilised ballast (BSB) has recently been investigated by D'Angelo *et al.* (2016, 2017a,

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Discussion on this paper is welcomed by the editor.

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2017b) as a feasible solution because of its easy and quick applicability and the relatively low cost of the bonding agent. These characteristics would allow this technology to be applied during a routine maintenance operation in order to improve ballast layer resistance to permanent deformation and degradation, and therefore to reduce maintenance frequency (D'Angelo *et al*., 2017a). Nonetheless, more in-depth laboratory full-scale tests need to be completed to prove the effectiveness of this solution before its application in real trial sections.

In particular, the aim of this paper is to study the ability of this technology to improve the effectiveness of conventional maintenance operations widely used all around the world. Thus, the paper focuses on investigating the effect of BSB application tamping or stoneblowing on trackbed performance, looking for the optimum solution in terms of type and dosage of bitumen emulsion used in the BSB process. For this purpose, various scenarios are contemplated (clean or fouled ballast, corresponding to the early life and a degraded state, respectively) in order to analyse the effect of BSB at different stages of the service life of ballasted track, in reference to conventional ballasted track. The aim of this analysis is to define the most appropriate stage in trackbed life to carry out this innovative solution.

MATERIALS AND METHODS

Materials

The field conditions were simulated using a ballast box 440 mm wide, 750 mm long and 500 mm deep. Perpendicularly to the length of the box, a piece of concrete sleeper with the base dimensions of 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 tyres (Sol-Sánchez *et al*., 2014b, 2015b)) were used to transmit the load to the ballast layer, as in Fig. 1(a) (Sol-Sánchez *et al*., 2016).

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

Two ballast gradations, 'clean' and 'fouled' ballast, were formulated by combining ophite aggregate of different sizes. A more detailed description of this material can be found in Sol-Sánchez *et al*. (2016). In particular, the clean ballast is compliant with European standards (BS EN 13450 (BSI, 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 Fig. 2, 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).

To reproduce in the laboratory the stoneblowing maintenance process, the small stones employed to restore the original position of the sleeper–rail system were sized

Fig. 1. (a) Specimen set-up in the ballast box; (b) stoneblowing; (c) tamping; (d), (e) simulation and bitumen stabilisation; (f) fouled ballast after stoneblowing

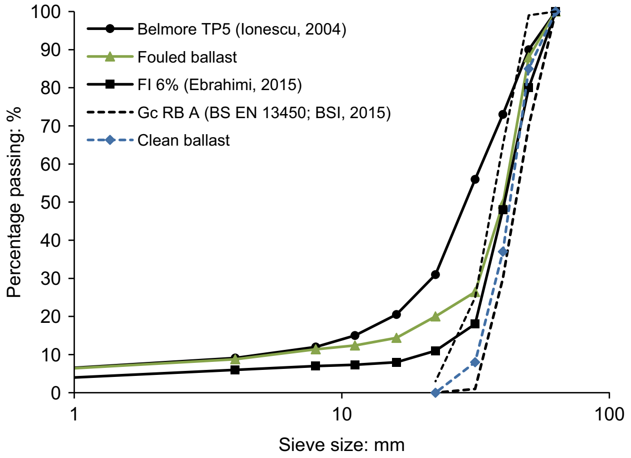

Fig. 2. Particle size distribution of clean ballast and fouled ballast used in this study

between 14 and 20 mm, which is the size recommended on actual track to avoid any possible drainage problem (Fair & Anderson, 2003; D'Angelo *et al.*, 2015; Sol-Sánchez *et al.*, 2016). These stones were marked with a different colour (Fig. 1(b)) to distinguish them from the 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 *et al.*, 2016) (Fig. 1(b)).

Stabilisation (Figs 1(d) and 1(e)) was carried out using two bitumen emulsions (referred as BE I and BE II), which differed mainly with regard to binder content and bitumen properties (as shown in the last three rows of Table 1). The influence of binder content (strictly related to the emulsion viscosity) on flowability is particularly strong (D'Angelo *et al.*, 2017b), since the higher the binder content is, the lower is the flowability. In addition, the presence of softer or harder bitumen could also have an effect on bitumen emulsion percolation at ambient temperature through ballast particles.

Methods

The main objectives of this study were the evaluation of the efficiency of the stabilisation method, the influence of BSB on post-maintenance trackbed performance and the most appropriate stage of trackbed life at which to carry out this technique. For this purpose, full-scale laboratory tests were developed to measure the ability of the bitumen emulsion to percolate through and stabilise the ballast layer and to evaluate the effectiveness of bitumen emulsion stabilisation during maintenance operations for clean and fouled ballast, analysing also the influence of ballast degradation. These steps are summarised in Table 2.

Initially, a full-scale flowability test was carried out in order to define the type of bitumen emulsion to be used in successive stages, proving as well the suitability of the dosage selected in previous studies for application in BSB. For both bitumen emulsions (type I and II), based on previous studies (D'Angelo *et al.*, 2017b), a dosage of 1·44% by weight (considered an optimum for full-scale ballast to improve performance while minimising the amount of material lost due to percolation toward the sub-ballast layer) was poured over a 300 mm deep ballast layer after stoneblowing (which add a layer of stones with higher potential to retain bitumen emulsion). 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 can be seen in Fig. 3. Once the ballast was poured and compacted, stoneblowing was simulated in order to recover 15 mm of permanent deformation. Afterwards, the bitumen

Table 1. Bitumen emulsions (I and II) main properties

Property	Standard	BE I	BE II
Particle surface electric charge	—	Positive	Positive
Binder content: %	EN 1428 or EN 1431	67	70
Breaking behaviour: s	EN 13075-1	< 110	< 110
Penetration (dam)	EN 1426	160–220	45
Softening point: °C	EN 1427	40	70
Type of modifier	—	Styrene-butadiene-styrene polymer modified	Styrene-butadiene-styrene polymer modified

Q32

Table 2. Testing plan

Variables	Material tested	Properties tested	Test	Main parameters
Influence of bitumen emulsion properties and dosage on technology application				
Bitumen emulsion dosage Bitumen emulsion type	BE I BE II	Flowability of bitumen emulsion	Flowability test	Quantity of bitumen emulsion lost
Effectiveness of bitumen emulsion stabilisation during maintenance operations at the early life of ballast layer				
Maintenance strategies • Tamping • Tamping + BSB • Stoneblowing • Stoneblowing + BSB	Clean ballast	Ballast layer behaviour	Full-scale ballast box	Vertical settlement Vertical stiffness Dissipated energy Ballast deterioration
Effectiveness of bitumen emulsion stabilisation during maintenance operations at a degraded state of ballast layer life				
Maintenance strategies • Tamping • Tamping + BSB • Stoneblowing • Stoneblowing + BSB	Fouled ballast	Ballast layer behaviour	Full-scale ballast box	Vertical settlement Vertical stiffness Dissipated energy

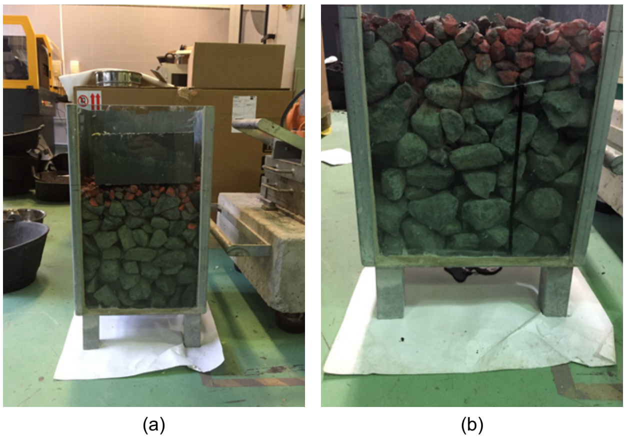

Fig. 3. Visual appearance of permeameter (a) after stoneblowing and (b) after bitumen emulsion stabilisation

emulsion was poured uniformly over the surface within 15–20 s. After 20 min (when the stabilisation process could be considered complete) the ballast was removed and the amount of bitumen collected at the bottom was considered as the bitumen emulsion loss (which should be avoided in order to save material and not to contaminate the granular sub-layers). Based on this test, the bitumen emulsion type to be used for dynamic load tests was chosen. The best bitumen emulsion was used also after tamping, to evaluate the influence of the maintenance operation used.

Having selected the most appropriate type and proven the optimal dosage of bitumen emulsion, the second objective was to evaluate the effect of stabilisation of fresh ballast during a routine maintenance operation. To achieve this, four series of dynamic tests, including tamping and stoneblowing simulations (with and without stabilisation with bitumen emulsion), were carried out in a ballast box where the track section was reproduced, comparing the results for the different solutions in terms of mechanical performance. In addition, to assess the influence of each maintenance strategy considered on ballast degradation, the ballast specimen gradation was measured before and after each series. These maintenance processes (tamping and stoneblowing) were selected due to their wide application to recover track geometry, while they also present the best opportunity to apply the proposed technique (BSB) on in-service railway tracks.

In order to understand the most appropriate stage, in terms of ballast life, at which to apply this technology, the same series of tests was also carried out for fouled ballast.

The series of tests carried out in the ballast box 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. 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 *et al.*, 2016). All series of tests were carried out twice, exhibiting good repeatability.

The stabilisation process was carried out immediately after tamping or stoneblowing by blowing uniformly, at room temperature (approximately 20°C), the calculated amount of bitumen emulsion over the ballast/sleeper contact area. After a curing time of approximately 3 h (quick-setting bitumen emulsion), the dynamic test was resumed.

Table 3. Flowability test results

	Stoneblowing + BE II	Tamping + BE II	Stoneblowing + BE I
Bitumen emulsion lost: g	9·1	26·3	46·9

The parameters evaluated during the dynamic ballast box test were: the vertical settlement (to analyse the effect of BSB to reduce the geometrical track degradation, which is one of the main issues in ballasted tracks); vertical stiffness and dissipated energy (to determine the mechanical behaviour of each solution, and its effect on track response under train passage); and the degradation of ballast (only in the cases of clean ballast in order to analyse the ability of BSB to reduce particle deterioration, and then to increase its durability before becoming fouled).

RESULTS AND DISCUSSION

Influence of bitumen emulsion properties and dosage on technology application

Results of the flowability test in terms of bitumen emulsion lost are reported in Table 3. This parameter represents the quantity of material 'lost' (not working) during the stabilisation process. It can be observed that, for the same maintenance operation (stoneblowing), BE II provided the best results in terms of material lost (five times lower), which could be attributed to the higher viscosity (higher bitumen content in the emulsion) compared to BE I. These results indicate that BE II leads to better ballast stabilization, because less material percolates to the bottom of the ballast layer, giving a more homogeneous material composed of bitumen emulsion 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 II 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 bitumen emulsion lost was almost three times lower than that measured after tamping (which consists of dilating the granular layer, obtaining a higher volume of air voids between ballast particles while no small particles with higher specific surface are included). Therefore, the amount of bitumen emulsion employed during track maintenance will be conditioned to the type of technique employed to restore the original position of the railway track, which requires earlier studies to select the optimal dosage of bitumen emulsion to be used. Nonetheless, in this study the BE II dosage was the same for both processes in order to obtain a comparative analysis between the effectiveness of BSB after each maintenance technique.

Influence of bitumen emulsion stabilisation on trackbed post-maintenance behaviour for clean ballast (early life of ballast layer)

Figure 4 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 bitumen emulsion

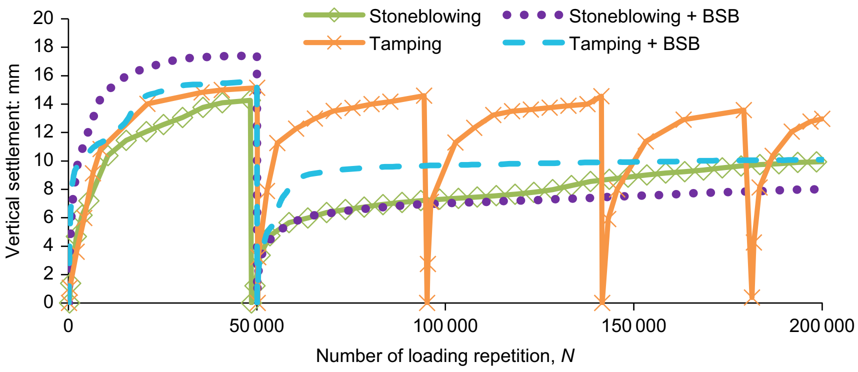

Fig. 4. Vertical settlement: influence of bitumen emulsion stabilisation when applied during tamping and stoneblowing for clean ballast

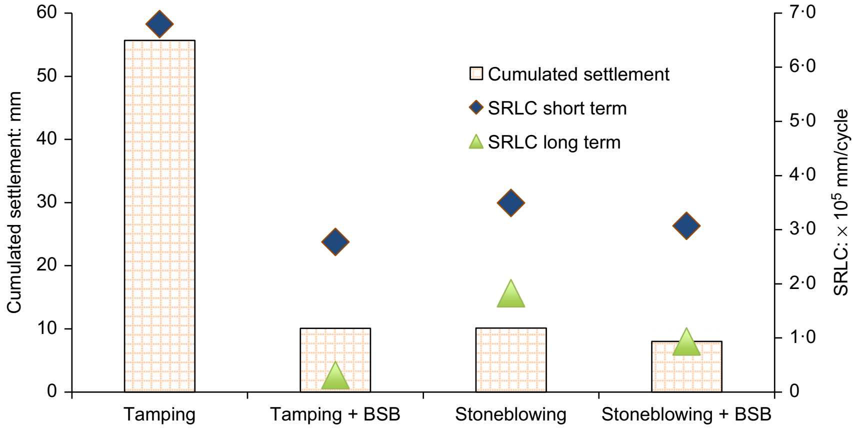

Fig. 5. Final cumulative vertical settlement, short-term and long-term SRLC for clean ballast series

for ballast stabilisation), when level of settlement had reached approximately 14–15 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). Fig. 5 displays the cumulative permanent deformation together with the short- and long-term deformation rate.

It can be noted that the tamping series exhibited a higher settlement than 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 (D'Angelo *et al.*, 2015; Sol-Sánchez *et al.*, 2016). This phenomenon became quicker after each maintenance operation, confirming that tamping progressively reduces in effectiveness over time (Selig & Waters, 1994; McMichael & McNaughton, 2003; Aursudkij, 2007). However, the addition of bitumen emulsion provided a much better resistance to permanent deformation so that, after an initial lower re-compaction, no further maintenance intervention was needed. This improvement is even more evident when the settlement rate per load cycle (SRLC), Q2 calculated as in Sol-Sánchez *et al.* (2014a, 2014b), is analysed in the short (60 000–100 000 cycles) and long term (160 000–200 000) (Fig. 5).

Both stoneblowing series, however, exhibited a lower final settlement, due presumably to a lower post-maintenance re-compaction (Anderson & Key, 2000), presenting apparently lower bitumen emulsion effectiveness since the stoneblowing process already allows for a more stable track behaviour (Anderson & Key, 2000; D'Angelo *et al.*, 2015; Tutumluer *et al.*, 2015; Sol-Sánchez *et al.*, 2016). Nevertheless, despite the decrease in the influence of bitumen emulsion after this maintenance technique, results indicate that the stabilisation process contributed to increase performance, especially in the long term, where the SRLC value for stoneblowing alone was double that for stoneblowing with BSB. 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 required. Studies reported by Selig & Waters (1994) and Berggren (2009), reveal that, excluding the initial settlement just after maintenance, the standard deviation of track irregularities (as a convenient measure of quantifying the quality of geometry of a track section) grows almost proportionally to track settlement. Thus, frequency of maintenance activities could be related, in a first approximation, to the SRLC calculated from ballast box tests. Based on these considerations, intervals between maintenance could be doubled by using BSB. However, initial economic studies reveal that coupling the stabilisation process with a routine maintenance operation would increase the cost by approximately 30%. Thus, considerable economic savings could be obtained by using BSB alongside the environmental benefits associated with the ballast lifespan. Nonetheless, in this regard, a more in-depth life-cycle cost analysis would be needed in further studies.

According to these results, it can be asserted that bitumen stabilisation can improve trackbed post-maintenance performance 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.

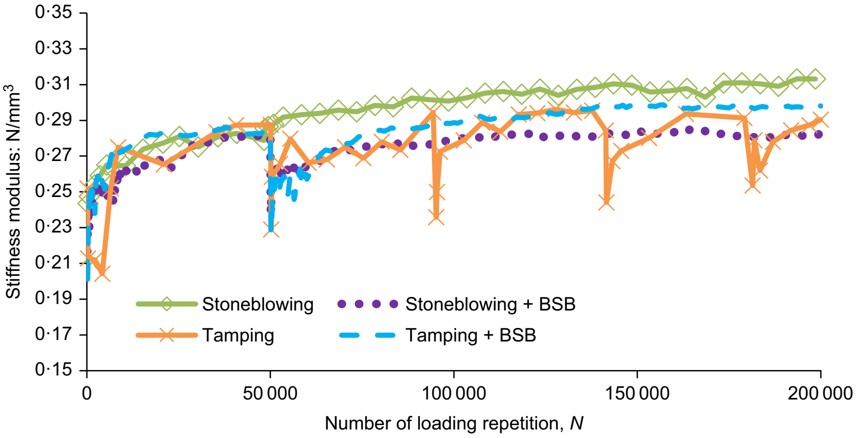

Fig. 6. Influence of maintenance and bitumen emulsion stabilisation on vertical stiffness and curve slope for clean ballast

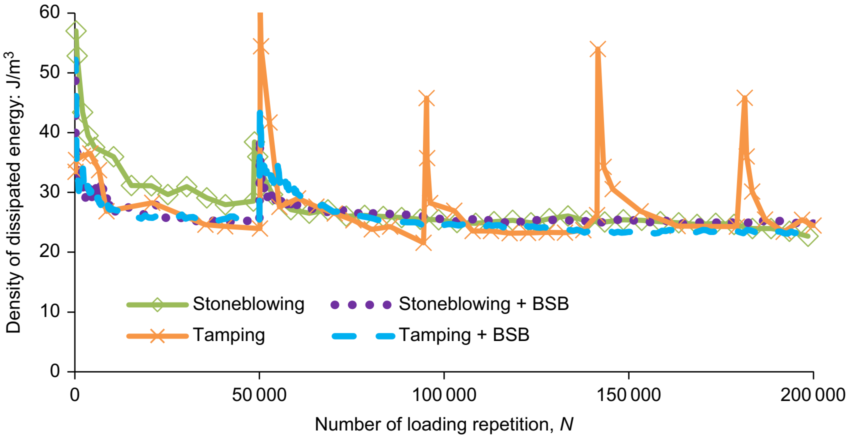

Fig. 7. Influence of maintenance and bitumen emulsion stabilisation on trackbed density of dissipated energy and curve slope for clean ballast

Figures 6 and 7 show the evolution of mechanical performance of the ballast layer in terms of stiffness and energy dissipation per cycle for these scenarios and for clean ballast. Vertical stiffness values were calculated as stress amplitude over the resilient deformation per cycle, whereas the dissipated energy was assessed by way of the hysteresis loop (strain–stress diagram) per cycle (D'Angelo *et al*., 2016; Sol-Sánchez *et al*., 2016).

It can be observed that stoneblowing can induce a stiffening of the track, which could lead to abrupt changes with reference to adjacent sections where this maintenance process is not carried out (Sol-Sánchez *et al*., 2016). This contrasts with the application of BSB, as this leads to lower values of stiffness, which could be related to the inclusion of a softer material between the contacts of ballast particles. Looking at the tamping series, stabilisation provided an increasingly stable behaviour over the test, reducing the abrupt changes in stiffness and dissipated energy just after the maintenance process, which is very desirable to avoid differential settlement (Sussmann *et al*., 2001).

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 Fig. 8. This parameter is essential for clean ballast in order to know the speed of particle degradation, and the consequent reduction in service life resulting in fouled ballast.

It can be seen that the series with tamping only was the one that generated 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 the 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 reinforcing techniques (Indraratna & Salim, 2003; Dersch *et al*., 2010; Fischer *et al*., 2015).

Nonetheless, it must be recognised that the effectiveness of bitumen emulsion to reduce ballast degradation is lower in the case of stoneblowing, because this technique already gives an important decrease in particle breakage and wear (Sol-Sánchez *et al*., 2016) 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 because the granular layer is not disturbed during the maintenance process.

Effect of stabilisation on fouled ballast behaviour (degraded stage of ballast layer life)

Figure 9 shows the cumulative settlement for fouled ballast following the different techniques studied in this paper, as well as the rate of settlement in the short and long term (Sol-Sánchez *et al*., 2014a) after maintenance. It may be noted that, overall, all fouled series exhibited permanent

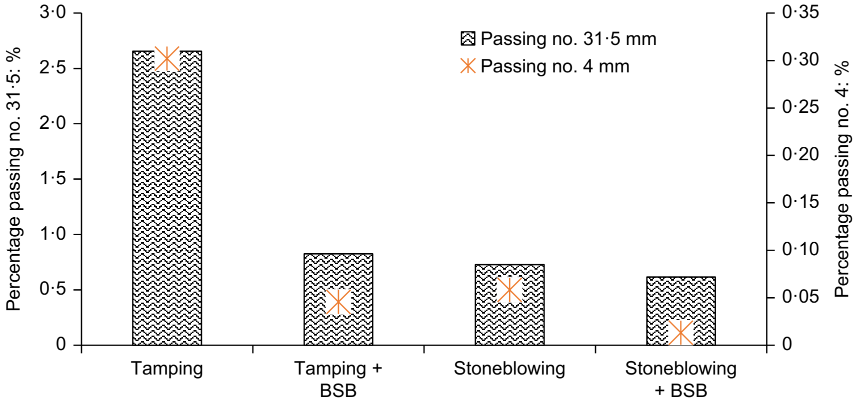

Fig. 8. **Influence of maintenance and bitumen emulsion stabilisation on trackbed durability: increase in the percentage of particles with size lower than 31·5 mm and 4 mm**

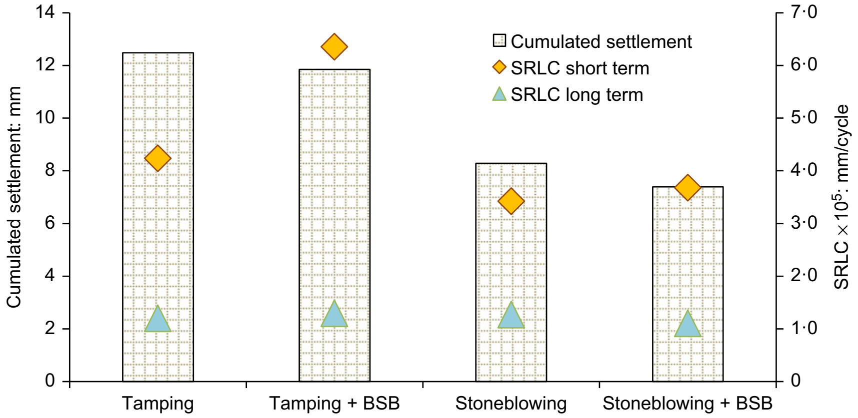

Fig. 9. **Final cumulative vertical settlement, short-term and long-term SRLC for fouled ballast series**

deformations lower than those of clean ballast, which can be associated with the reduction in air voids volume due to the content of fines. This result is in agreement with the findings of Ionescu *et al.* (2016), where desert sand was used to contaminate the ballast. Also in this case, the use of mineral fouling provided an increased resistance due to an increased contact surface area. It is also possible to observe a slightly lower deformation rate for the non-stabilised series (compared to clean ballast), which can be attributed to the improved load transmission and lower degradation of the already deteriorated ballast particles (Ionescu *et al.*, 2016) while fine particles occupy the air voids.

It is important to highlight that in this case the influence of BSB on fouled ballast permanent deformation is very low for both the stoneblowing and tamping series: reductions of 5–10% are observed for the final settlement, whereas insignificant differences are noted in the long-term deformation rate. This result can be related to the lower air void content, and thus lower capacity for layer compaction with reduced ability of bitumen emulsion to permeate into the fouled ballast.

Nonetheless, it should be noted that these results show that stabilisation by bitumen for this type of fouled ballast appears to be less effective in comparison with the findings of D'Angelo *et al.* (2016, 2017b) for granite ballast. In this case, indeed, a cementation process due to the type of fine particles used appeared to weaken the gluing effect of bitumen, while the reduced air voids prevented a homogeneous stabilisation of the ballast layer. This means 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 case, probably the use of a less viscous bitumen emulsion could present a more penetrating effect of the binder into the fouled layer in order to facilitate a more homogeneous stabilised layer. Thus, further studies focused on the development of BSB as a solution to improve track durability when the ballast is fouled should take these parameters into consideration to define the optimal situation in which to use bitumen emulsion.

In Figs 10 and 11, the mechanical performance in terms of stiffness and energy dissipation for the fouled ballast series is 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 equations (1) and (2)

$$\text{Rate of stiffness modulus} = \frac{S_N - S_0}{N} \tag{1}$$

$$\text{Rate of dissipated energy} = \frac{D_N - D_0}{N} \tag{2}$$

where N is the number of cycles considered, and S_N, D_N and S_0, D_0 represent the stiffness and dissipated energy values at the end and the beginning of the range considered, respectively.

It can be observed again here that the influence of bitumen emulsion stabilisation is very low and that the slight effect provided depends on the maintenance task applied. At this stage of ballast life, the key factors influencing the mechanical behaviour are the amount of fouling, the type of

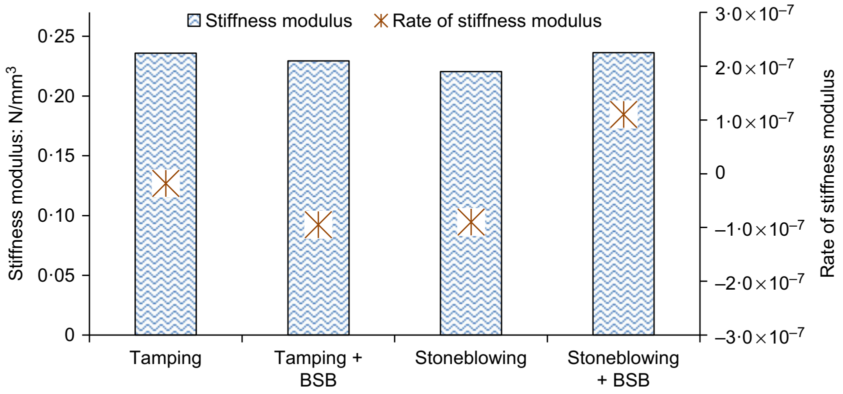

Fig. 10. Influence of maintenance and bitumen emulsion stabilisation on vertical stiffness and curve slope for fouled ballast

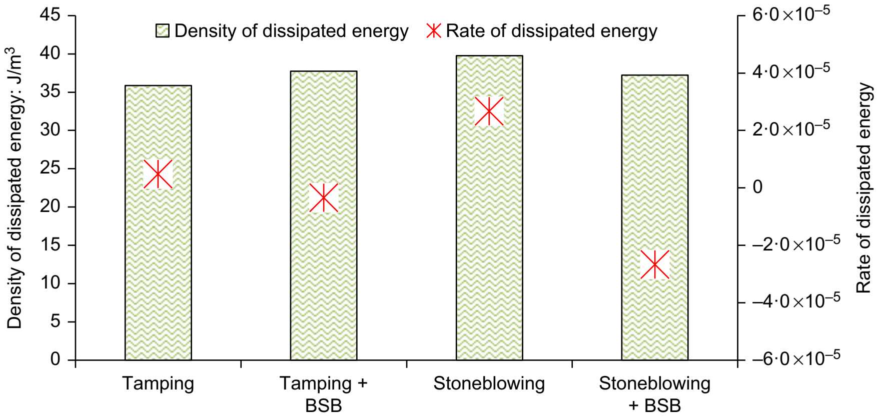

Fig. 11. Influence of maintenance and bitumen emulsion stabilisation on density of dissipated energy and curve slope for fouled ballast

material, the presence of water and the void ratio. Therefore, the addition of a stabiliser such as bitumen emulsion does not have any clear influence on results. In this regard, more in-depth research varying the above-mentioned parameters is needed. In particular, since the arrangement and structure of the fouled ballast layer play a relevant role on the stabilisation process and consequently on BSB behaviour, X-ray or gamma-ray techniques could help to obtain the pore size distribution and, thereby, provide a better understanding of the bitumen emulsion flowability through the specific ballast gradation.

CONCLUSIONS

This paper has focused on the influence that bitumen stabilisation of a ballast layer can have on trackbed performance when coupled with conventional maintenance operations such as tamping and stoneblowing. The analysis of various scenarios has allowed evaluation of the effectiveness of such technology when applied at different stages of ballast service (clean and fouled) in terms of mechanical behaviour. The main findings are as follows

(*a*) Properties of bitumen emulsion such as viscosity (related to binder content) and bitumen properties as well as gradation of the granular layer can significantly influence the flowability of bitumen emulsion through that layer. For a fresh coarse-sized ballast layer, high-viscosity bitumen emulsion (approximately 70% binder content) is suggested 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 bitumen emulsion.

(*b*) In order to increase ballast durability, bitumen stabilisation appears to be much more effective when applied at an early stage of ballast life.

(*c*) 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 a sensible reduction in the frequency of such maintenance.

(*d*) The effects of stabilisation carried out after stoneblowing on settlement were lower. Nonetheless, a long-term improvement was observed as well as a contrasting effect on the stiffening of the track.

(*e*) In this regard, results indicate also that bitumen emulsion can have an importance influence on track stiffness variations 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.

(*f*) 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 stoneblowing series, the increasing shear strength due to the cohesion component could reduce abrasion between particles and therefore fines production.

(*g*) The effectiveness of BSB is drastically reduced for fouled ballast as a consequence of the reduced air voids, which prevented a homogeneous stabilisation. A minor improvement was observed in the final value of settlement. In this regard, the reduced effectiveness obtained compared to other types of ballast encourages further studies on stabilisation of fouled ballast, particularly by using innovative X-ray or gamma-ray techniques that could facilitate the understanding of pore size distribution, and thereby, the flowability of bitumen emulsion into the ballast layer.

By defining the most appropriate bitumen emulsion properties and maintenance practice, and the stage of ballast service life at which to stabilise, it is possible to appreciably reduce the need for maintenance and increase trackbed durability, which could lead to important economic and environmental benefits. In this regard, future work will focus on the assessment of the costs and environmental savings that the use of this technology could bring. Nonetheless, in order to improve the readiness of this technology before trial application, more variables such as temperature effects, BSB permeability, application method, as well as amount of volume stabilised, among others, need to be investigated in future studies.

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