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Optimisation of bitumen emulsion properties for ballast stabilisation

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ABSTRACT: Ballasted track, while providing economical and practical advantages, is associated with high costs and material consumption due to frequent maintenance. More sustainable alternatives to conventional ballasted trackbeds should therefore aim at extending its durability, particularly considering ongoing increases in traffic speed and loads. In this regard, the authors have investigated a solution consisting of bitumen stabilised ballast (BSB), designed to be used for new trackbeds as well as in reinforcing existing ones. This study presents the idea behind the technology and then focuses on a specific part of its development: the optimisation of bitumen emulsion properties and dosage in relation to ballast field conditions. Results showed that overall bitumen stabilisation improved ballast resistance to permanent deformation by enhancing stiffness and damping properties. Scenarios with higher dosage of bitumen emulsion, higher viscosity, quicker setting behaviour, and harder base bitumen seem to represent the most desirable conditions to achieve enhanced in-field performance.

KEYWORDS: Aggregate; Characterization; Permeability; Deformation; Durability

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RESUMEN: *Optimización de las propiedades de emulsión de betún para la estabilización de balasto.* El balasto proporciona ventajas económicas y prácticas, sin embargo se asocia con altos costos y consumo de materiales. Las alternativas más sostenibles deben tener como objetivo extender la durabilidad del balasto, sobre todo teniendo en cuenta los actuales incrementos en la velocidad y las cargas del tráfico. Los autores presentan una solución que consiste en estabilizar el balasto con betún. Este estudio describe la tecnología y se centra en la optimización de las propiedades de la emulsión bituminosa y su dosis en función de las condiciones del balasto. Los resultados muestran que la estabilización con betún mejora la resistencia a la deformación permanente mediante la modificación de la rigidez y las propiedades de amortiguación. Pruebas con mayor dosis de emulsión bituminosa, mayor viscosidad, fraguado rápido y betún base más duro, representan las condiciones más deseables para lograr un mejor rendimiento en la vía.

PALABRAS CLAVE: Áridos; Caracterización; Permeabilidad; Deformación; Durabilidad

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1. INTRODUCTION

The railway system represents one of the most attractive modes of transportation worldwide because of its high efficiency, speed, capacity and low environmental impact compared to other systems. These factors lead to continuously increasing demand on train speed and load transported, which represents an important challenge especially for the infrastructure. In this regard, ballasted track, which is by far the most widely-used track form due to its economical and practical advantages, is particularly affected by deterioration and the need for maintenance (1).

The ballast layer contributes significantly to these problems. Typically, 50–70% of trackbed settlement is thought to be due to permanent deformation in the ballast layer (2). Particle degradation and breakage, which are related to the settlement mechanism (3), contribute significantly to material consumption (4). Furthermore, when ballast degradation reaches a high level (fouled ballast), this can compromise the mechanical performance of the track and accelerate degradation of geometry. In addition, frequent maintenance (tamping), needed to restore track geometry, contributes significantly to ballast degradation, leading to a vicious circle (4).

To reduce ballast-related maintenance costs (approximately 30% of annual maintenance expenditure (5)) and increase railway system sustainability, recent decades have seen growing interest in new solutions for ballast layer design/maintenance that modify the trackbed structure and offer better resistance to permanent deformation and particle degradation. Track deterioration and maintenance are, in fact, related to track stiffness and its ability to dissipate energy (and their variability along the track) (1, 6–10). On the one hand low levels of stiffness can lead to higher trackbed settlement as well as flexural deformation and consequently increased track deterioration by fatigue of its component elements (6, 10). In addition a significant decrease in track stiffness, despite providing a higher damping effect, could also lead to a significant increase in rolling resistance (10). On the other hand, increasing track stiffness, while providing better resistance to permanent deformation and reducing flexural stresses in the superstructure, could also lead to higher dynamic loads. These, if not adequately damped, could speed up track component deterioration as well as increasing noise and vibration (6; 9; 10). In this regard, various authors have proposed optimum ranges of stiffness that take into account degradation rate (1), maintenance frequency and service costs (8, 11).

Solutions towards trackbed substructure modification, such as elastic elements, geosynthetics, ballast stabilisation by polymers or resins among others, aim to provide a balanced level of stiffness and damping properties especially in railway hotspots and transition areas where a smooth variation of these properties (1) can significantly reduce the need for maintenance (10, 12–22).

In this regard, bitumen stabilised ballast (BSB) is an alternative solution, relatively economic and easy to apply, proposed for either newly constructed track or track requiring maintenance (23). This technique consists of blowing bitumen emulsion onto ballast, over the sleeper/ballast contact area, in order to increase shear strength and resistance to permanent deformation by modifying the stiffness and damping properties of the ballast layer. The potential of this technology for improving ballast durability has been highlighted by D'Angelo et al. (23). However, properties of the bitumen emulsion (BE) used in that study, in terms of solid content and breaking behaviour, allowed a significant part of the material to be lost by drainage.

This study aims to further develop this solution by optimising bitumen emulsion characteristics in relation to bitumen type, proportion, breaking behaviour and dosage, in terms of their influence on its flowability through the ballast layer and on BSB performance (for both clean and degraded ballast states).

2. MATERIALS AND METHODS

2.1. Materials

For this study three different bitumen emulsions were selected (Table 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 setting speeds; and different types of bitumen.

Table 1. Physical and rheological properties of bitumen emulsions used

Property	Standard	N1	N2	R1
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

N1 is a high performance BE typically used for pavement surface courses (24). N2 and R1 were selected for their quick setting, high viscosity and suitability for this new application (25). All of them are cationic emulsions with affinity to a wide range of mineral aggregates and promote adhesion of bitumen to ballast particles.

The ballast used for this study was granite aggregate sourced from Bardon Hill quarry in Leicestershire, United Kingdom (23, 26). Due to the dimensions of the test apparatus, two scaled (approximately one third scale) gradations (clean and fouled ballast) were used as described in previous studies (23, 27, 28).

2.2. Methods

Bitumen emulsion dosage and properties (29), as well as the aggregate gradation used, can potentially affect the quantity of BE achieved during the application 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, a series of laboratory tests were carried out: (i) Flowability tests and (ii) Confined compression tests using the Precision Unbound Material Analyser (PUMA) apparatus.

The three different emulsions selected with two dosages and two different gradations for ballast (clean and fouled) were combined to give a total of 12 BSB configurations and compared with two unbound materials (clean and fouled), used as reference. The dosing ranges of the bitumen emulsions were selected based on the authors' previous work in this domain (23). Table 2 summarises the work carried out.

2.2.1. Flowability test

One of the most important factors influencing BSB application is the viscosity of the bitumen emulsion (BE), since the 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 but should minimise the percentage of material that reaches the interface with underlying materials. Variables involved are the bitumen content in the emulsion (the higher the bitumen content the more viscous the BE), the dosage and the breaking behaviour (25).

Thus, a specific test, similar to the determination of penetration power of bituminous emulsion (30), was set-up to evaluate the ability of BE to penetrate a specific aggregate mix. The apparatus used for the test consisted of a transparent tube with an inner diameter of 120mm and height of 240mm having in the base a porous metal plate with a pore size of 1mm, as shown in Figure 1. The test was carried out under normal laboratory conditions, at room temperature of approximately 20°C. It consisted of pouring a quantity of BE corresponding to 2% or 3% by weight into a cylindrical aggregate volume with a height of 150 mm within approximately 20-30s. The test duration was 1200s, during which the process was recorded photographically and the emulsion draining through the layer was collected at the bottom of the apparatus so that the percentage of material lost could be evaluated. Two key parameters were measured to evaluate flowability: (i) the penetration time, i.e. the time for the emulsion to completely penetrate into the aggregates, expressed

TABLE 2. Testing plan

Variables	Material tested	Properties tested	Test	Main parameters
Dosage	Clean BSB (N1)	Flowability of BE	Flowability test	Penetration time
BE Viscosity	Clean BSB (N2)			Quantity of BE lost
BE breaking behavior	Clean BSB (R1)			Flowability Index
Ballast gradation	Fouled BSB (N1)			
	Fouled BSB (N2)			
	Fouled BSB (R1)			
Dosage	Clean ballast	BSB mechanical behaviour	Confined compression test (PUMA)	Plastic strain
Bitumen type	Clean BSB (N1)			Plastic strain rate
Ballast gradation	Clean BSB (N2)			Resilient Modulus
	Clean BSB (R1)			Dissipated Energy per cycle
	Fouled ballast			
	Fouled BSB (N1)			
	Fouled BSB (N2)			
	Fouled BSB (R1)			

FIGURE 1. Flowability test apparatus and specimen set up.

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. In order to calculate a specific desirability function for this property, these two parameters were combined, obtaining a flowablity index (FI) as in equation [1]:

$$FI = \left(1 - \%BE\ lost\right) \cdot \left(test\ duration - penetration\ time\right) \qquad [1]$$

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 start setting.

2.2.2. *Confined compression test*

In order to assess the mechanical properties of BSB, a dynamic confined compression test (PUMA) was used. This test consists of the application of a repeated compression load and records the resulting vertical displacement as described in (23, 31, 32). Figure 2 illustrates the frame and the apparatus used. Each specimen was compacted using a standard vibrating hammer and then loaded on its top surface by a circular platen.

The test conditions were the same as in D'Angelo et al. (23): cyclic load was applied as a 5Hz haversine, bell-shaped loading pulse with peaks (200kPa) and rest loads (11.7kPa) for 200,000 repetitions, as these conditions can be considered representative of those experienced by ballast in real track (33). For each BSB specimen, before pouring the emulsion, 2% by weight of water was added in order to lubricate the aggregate and activate the surface charges on the aggregate particles (34). All tests were carried out twice and good repeatability was obtained.

2.2.3. *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 in this study had to be established. 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 whereas 1 means the most desirable properties (35). Two types of DF were proposed by Derringer & Suich (36): 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%, a value intended to represent that at which a maintenance intervention is likely to be needed (33). 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 (1, 6, 8). Finally dissipated energy ranged from 0 J/m^3 to 20J/m^3 (37–39). Almost all these limits and optimum values are

FIGURE 2. PUMA frame and loading apparatus (after Thom et al. (31)).

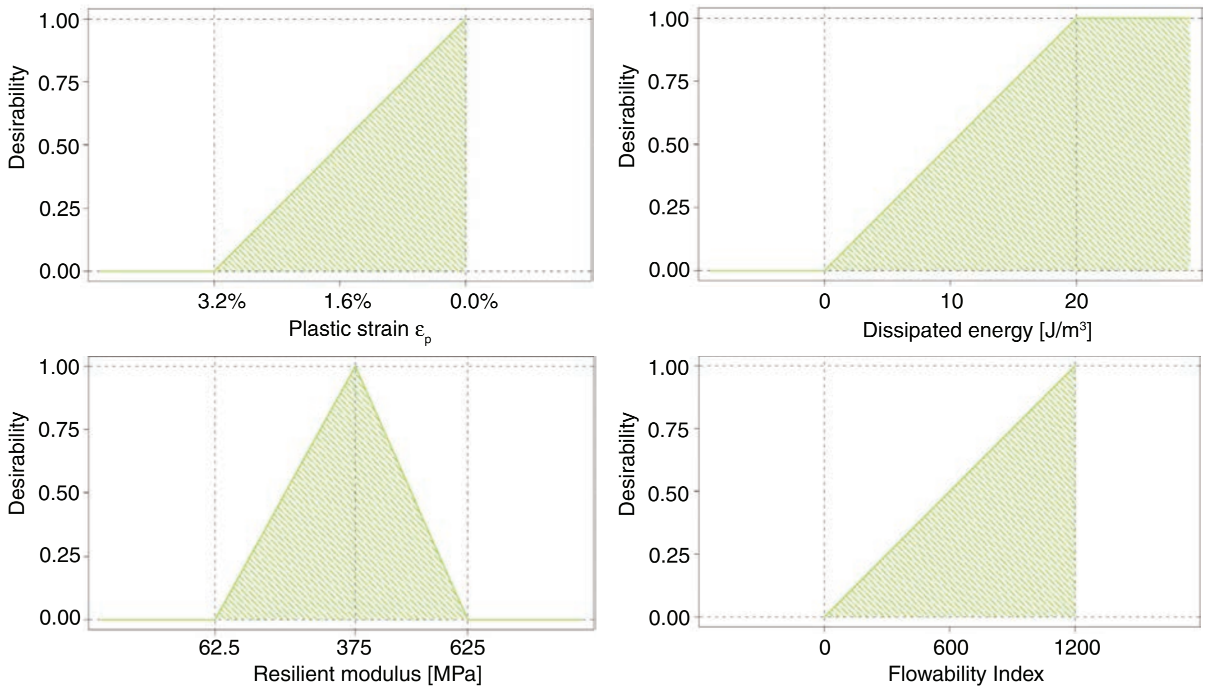

FIGURE 3. Derringer's desirability functions for the selected BSB properties.

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 study are presented in Figure 3.

For each BSB configuration, applying the DFs to the parameters under investigation provides a set of desirability values (DVs) which, being now homogenous, can be used to compare all the configurations by means of any specified method, for example the geometrical mean. In this study a desirability index (DI) was used that valued all the properties equally, as in equation [2]:

$$DI = \sqrt[4]{DV_{FI} \cdot DV_{PS} \cdot DV_{RM} \cdot DV_{DE}} \qquad [2]$$

where the subscripts stand for flowability index, plastic strain, resilient modulus and dissipated energy, respectively.

This index allows for a straightforward comparison of the different BSB configurations. It should be noted that if even one of the DVs is zero then the DI comes to zero, disqualifying any configuration that does not meet the established requirements.

3. RESULTS AND DISCUSSION

3.1. Influence of gradation and BE properties on flowability

Table 3 shows results of the flowability tests, indicating penetration time, quantity and percentage of BE lost, and flowability index as determined by equation [1]. It can be observed that viscosity and breaking behaviour played the most important roles. In fact, passing from low binder content (60%) and slow setting (N1) to high binder content (70%) and fast setting (R1) (with an intermediate situation for N2) the percentage of material lost dropped drastically. The gradation had an important influence on the results to the extent that passing from a more open graded (clean ballast) to a well graded (fouled ballast) there was a 20–75% reduction in material lost, depending on the BE used. In the case of BE N2 the effect of dosage was also relevant: an increase from 2% to 3% BE led to an approximately tenfold increase in material lost. This analysis shows that, depending on field conditions, properties of BE such as viscosity, breaking behavior and dosage can be optimized to reach a desired penetration depth.

Results also show that, for the specific materials analysed, BE R1 had the best scores in terms of flowability index.

3.2. Influence of BE properties on ballast mechanical behaviour

Figure 4 shows the plastic strain after 200,000 repetitions in the confined compression test (PUMA) for the 12 BSB configurations and 2 reference materials. Results indicate an overall improvement in resistance to permanent deformation (up to 3 times) for stabilised specimens compared to the unbound reference materials, in agreement with other studies on ballast stabilisation (33, 40, 41). It can be noted that gradation had an important influence on results since in almost every case clean ballast specimens (both stabilised and unbound) exhibited a lower plastic strain than their fouled counterparts. This result is in agreement with Keene et al. (33).

TABLE 3. Flowability test results

Gradation	**Clean**						**Fouled**					
BE	**N1**		**N2**		**R1**		**N1**		**N2**		**R1**	
Dosage	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 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	10.58	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

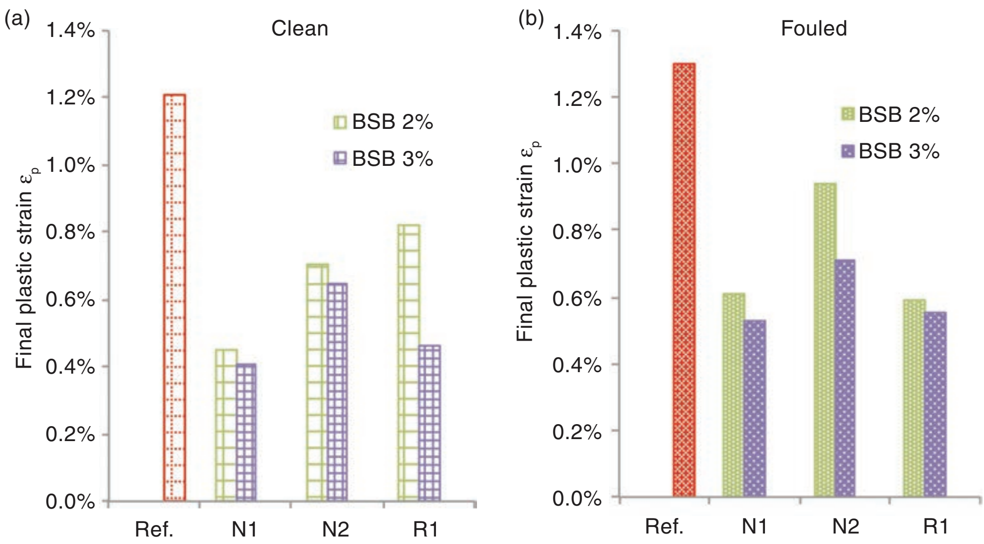

FIGURE 4. Final plastic strain after 200,000 repetitions in the PUMA test for clean (a) and fouled (b) ballast.

The dosage of BE also influenced results to the extent that increasing %BE led to a lower final plastic strain, confirming the findings of D'Angelo et al. (23). Also the type of bitumen had a significant influence: almost all BSB specimens with harder bitumen (N1 and R1, Table 1) exhibited lower plastic strain than those with softer bitumen (N2).

With the aim of analysing the influence of BE on long-term ballast behaviour, Table 4 shows plastic strain rate (PSR) values calculated over the last 20,000 cycles as in (23). It can be observed that in general 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.

These results confirm the potential of this technology to improve trackbed resistance to geometry degradation and consequently to reduce the need for maintenance due to ballast settlement (23).

Figure 5 illustrates the influence of bitumen stabilisation on ballast resilient modulus (stress amplitude over the resilient strain) and its ability to dissipate energy (hysteresis loop area per cycle), averaged over the last 20,000 cycles. It can be observed that stabilisation typically provided an increase in resilient modulus of approximately 25% with respect to the reference cases without BE. At the same time the stabilisation process improved the ability of ballast to dissipate energy. BSB specimens dissipated on average 40% and 30% more energy than clean and fouled reference materials, respectively. In addition, with the exception of 2% BSB (N1), it can be noted that fouled specimens dissipated a higher quantity of energy, even if by a relatively small margin, than their clean counterparts. It is also interesting to highlight that a small increase in bitumen content (BE from 2% to 3%) corresponded for almost all BSB specimens to a small increase in dissipated energy, confirming the important role played by this variable. The influence of gradation and BE content was however less marked in the case of the resilient modulus values.

TABLE 4. Influence of BE stabilisation on long-term behaviour (PSR) of clean and fouled ballast

PSR: *10^9 [mm/cycle]													
Clean							Fouled						
	N1		N2		R1			N1		N2		R1	
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

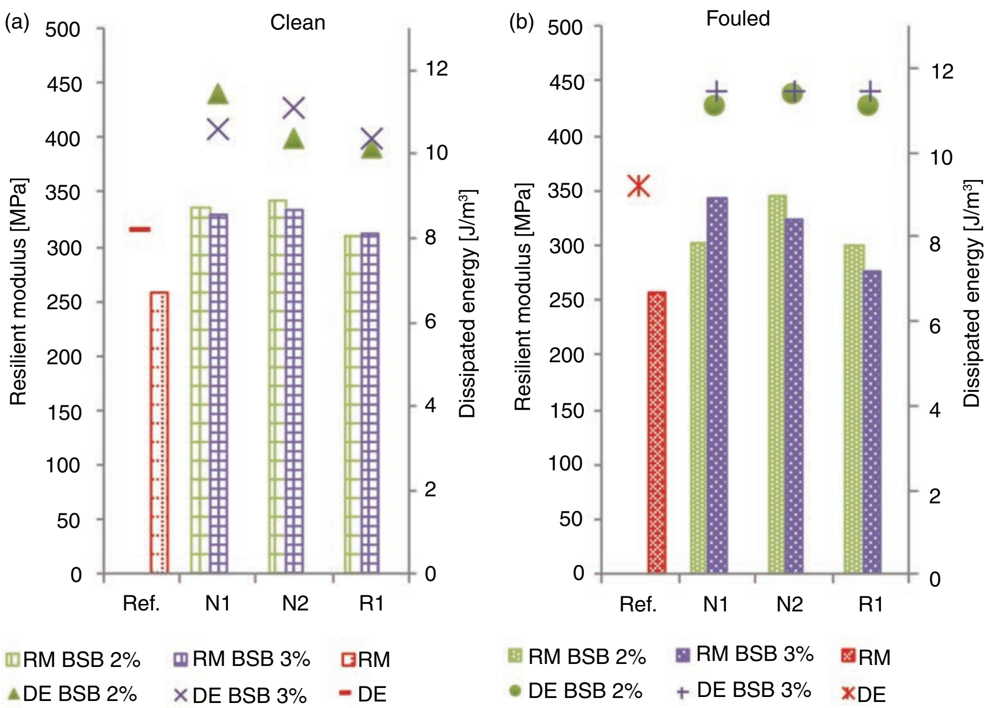

FIGURE 5. Influence of stabilisation on resilient modulus (RM) and dissipated energy per cycle (DE) for clean (a) and fouled ballast (b).

These results jointly suggest the potential of BSB for reducing track deterioration and maintenance costs: a relatively small increase in stiffness could be beneficial for reducing fatigue and deterioration of track components when dynamic loads are adequately damped (6, 10). Nevertheless it is worth noting that these results may be partly a function of the confined conditions of the test used.

3.3. Desirability of the different BSB configurations

In the sections above 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 2.6. 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 reflect some of the most important objectives to be achieved by this new technology for its application in a railway.

Table 5 and 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 the corresponding desirability index is obtained for each configuration. Figure 6 summarises these values for clean and fouled BSB.

In can be observed that the best scores, ranging from 0.72 to 0.75, were obtained by N2 and R1, regardless of the gradation considered. BE N1, in contrast, reached noticeably lower values, especially in the case of clean ballast; despite 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 had, in fact, the highest impact on the optimisation process. This suggests that a more viscous BE is preferred for stabilisation of ballast having a relatively low level of degradation.

Table 5. Detailed desirability values of flowability index, plastic strain, resilient modulus, dissipated energy and resulting desirability index for all BSB configurations

Gradation	**Clean**						**Fouled**					
BE	**N1**		**N2**		**R1**		**N1**		**N2**		**R1**	
Dosage	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 3%**	**BSB 2%**	**BSB 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**

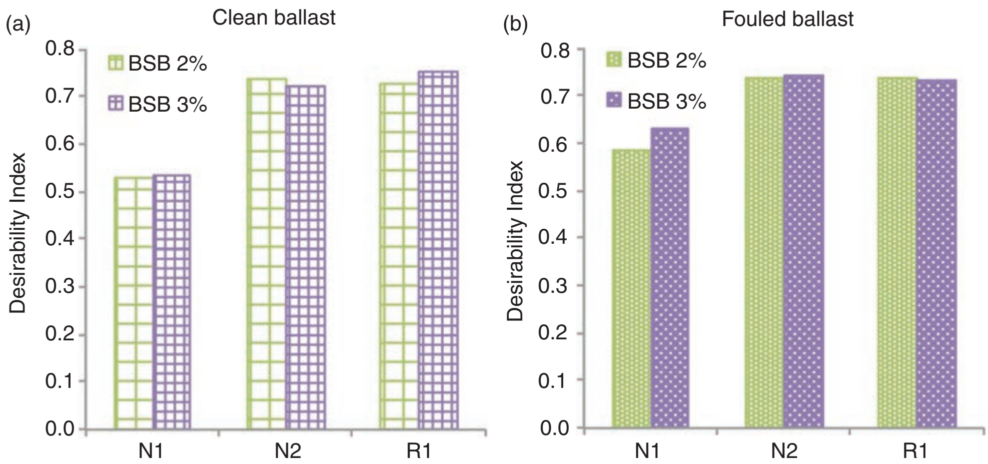

Figure 6. Desirability index results of (a) clean and (b) fouled stabilised specimens as a function of BE dosage and type.

4. CONCLUSIONS

The present paper provides an insight into the optimisation of BSB. Different solutions 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 effectiveness of BE application. From the analysis carried out in this study, the following conclusions can be drawn:

- Overall, bitumen stabilisation improved ballast properties in terms of plastic strain and plastic strain rate (long-term behaviour), confirming the potential of the technology for enhancing ballast layer mechanical performance, in a similar way to other stabilisation technologies (18, 33, 41, 42). In this regard, the modified stiffness and damping properties could be beneficial for track component lifecycles and noise and vibration reduction, with associated reduced economic and environmental costs.
- The type of emulsion and its dosage seem 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 stabilising behaviour. Nevertheless, depending on the field application and ballast depth to be stabilised, a specific BE could be designed to fulfil specific requirements.
- Ballast gradation is another important factor to take into account: results showed that overall clean specimens exhibited better performance than fouled ones. Nevertheless, it has to be noted that this study was carried out using a scaled grainsize distribution.
- Comparison of all BSB configurations, with the optimisation method used, indicates that configurations with N2 and R1 emulsions, which obtained the highest desirability values, are likely to mark the path to follow for further development of this new technology.

The results obtained give important guidance on the influence of the factors studied here, but further investigation of full-scale BSB is still needed to support the results obtained in this study and provide a better understanding of the potential of this new technology.

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