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Railway ballast stabilising agents: Comparison of mechanical properties

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HIGHLIGHTS

- Four additives are investigated in the laboratory as railway ballast stabilisers.
- Repeated load triaxial tests assess the mechanical properties of stabilised ballast.
- The stabilisers enhance resilient modulus and resistance to permanent deformation.

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ABSTRACT

Expensive and time-consuming maintenance operations are routinely performed to preserve the ballast mechanical properties in railway lines. Binding agents are used for ballast stabilisation. Four different additives based on bitumen, organosilane, lignosulphonate and polyurethane are investigated in the laboratory by means of repeated load triaxial tests. The parameters that are directly relevant for use in railway structures are assessed. Each binder type significantly influences both the resilient modulus and the resistance to permanent deformation of the treated specimens. The ballast mechanical properties can be conveniently modified, thus being beneficial to track stability and railway maintenance programme.

1. Introduction

Ballast is the granular material that distributes the cyclic loads induced by trains to the underlying track structure. The size of the aggregates is usually comprised between 20 and 62 mm [1]. Ballast is commonly adopted as the primary load bearing component and represents the track form most used in Norway [2].

Ballast aggregates undergo wearing and crushing under the train traffic action; the process entails the formation of fine particles (a main cause of ballast fouling) [3]. A higher content in fines engenders a decrease in support stiffness, lateral stability and resistance against permanent deformation [4,5]. This situation can lead to augmented maintenance costs and, if neglected, even train accidents [1].

The transition zones along the track are associated with abrupt variation in support rigidity [6]. They exist in correspondence of change from conventional track to slab track, at bridge approaches and ends, level crossings and railway turnouts [7,8]. The change in the support stiffness of these zones causes high dynamic loads, leading to ballast quality deterioration and consequently generation of fine particles [9,10].

Maintenance operations are frequently performed (i.e. ballast tamping or renewal) in order to comply with the track geometric requirements. The European yearly maintenance costs amount to a significative quantity (30,000–100,000 euros per kilometre) entailing, among the others, disruption to traffic and environmental issues [11,12]. Reducing maintenance expenses while still having a high-quality ballast layer can contribute to huge savings.

The research investigates the improvement of ballast mechanical properties associated to the use of binding agents. The use of additives should aim at satisfying as many as possible of the following needs: 1) provide three-dimensional reinforcement across the track 2) ensure drainage property 3) accomplish a relatively quick treatment 4) decrease the frequency of maintenance operations 5) represent a cost-effective and environmentally friendly technology. The most suitable stabilising solution among the

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available ones can be chosen upon each project's contingencies and priorities.

Four types of stabilising agents based on bitumen, organosilane, lignosulphonate and polyurethane were investigated in the laboratory to assess the structural performance of treated ballast. Bitumen and polyurethane were chosen to expand and possibly buttress the existing positive experience [13–17]. Organosilane and lignosulphonate were investigated since recent applications to coarse aggregates for pavement constructions showed promising results [18,19].

Repeated Load Triaxial Tests (RLTTs) characterise the stiffness and the resistance against permanent deformation of untreated and treated ballast samples. The systematic comparison of the additives by means of RLTTs represents the innovative content of the research. The existing literature solely and partly covers the application of bitumen [14–16,20] and polyurethane [13,17]: these agents were investigated by means of different testing methodologies. In addition, previous triaxial tests (not cyclic ones as RLTTs) were performed on ballast [21–24] without comprising any additive.

2. Stabilising agents

The tested material was collected from a railway section close to Trondheim (Norway) in cooperation with the Norwegian National Railway Administration - Bane NOR SF. The material was partly worn, making the shape more rounded than newly produced ballast. The main rock type is fine-grained greenstone, verified by petrographic thin-section analysis, and metagabbro. The stabilising agents adopted in the investigation are described in the following sections and the main physical and chemical properties are reported in Table 1.

2.1. Bitumen

Bitumen Stabilised Ballast (BSB) refers to the application of bituminous emulsion directly sprayed onto the ballast layer along the track. Even if this binder can be sometimes used in railway asphalt concrete tracks [25–27], there is very limited research applied to railway ballast stabilisation [8,14]. Different types of bituminous emulsions and use percentages were previously investigated and showed promising results [15,16]. Due to a lack of local availability of bitumen emulsion, this research applies traditional bitumen instead. However, after the evaporation of water has taken place, the rheological and mechanical properties of bitumen emulsion become similar to the ones of traditional bitumen [28]. The investigation applies two types of binder commonly used in Norway for road construction, one has penetration 70/100 (referred to as BSB1) and one has penetration 160/200 (referred to as BSB2).

2.2. Organosilane

Organosilane Stabilised Ballast (OSB) is based on organosilane, which is a nanoscale agent resistant to ultraviolet radiation and temperature variation [29–31]. The additive is based on two components here referred to as C1 and C2: they are an acrylic copolymer emulsion based on acetic acid and methanol and a polymeric dispersion composed of propylene glycol and alkoxy-alkyl silyl, respectively. The components promote the formation of an impermeable nanolayer of alkyl siloxanes on the surface of the rocks. The available limited results are promising, but they are mainly connected to clay and silt examined in the laboratory [32–34] and in the field [35]. Recently, its application to coarse crushed rocks has showed positive outcomes [18,19]. The safety data sheets of the product do not report any environmental hazard [36,37].

2.3. Lignosulfonate

Lignosulfonate Stabilised Ballast (LSB) refers to the application of lignosulfonate, namely a sustainable agent obtained in industries involving papermaking operations. Lignosulfonate is a water-soluble organic substance that is not toxic and does not cause corrosion [38,39]. The current results related to the improvement of mechanical properties of aggregates are connected to clay and silt tested both in the laboratory [38–42] and in the field [43–45]. As in the case of organosilane, the recent application of lignosulfonate to coarse crushed rocks has shown positive outcomes [18,19]. Since lignosulfonate is water soluble, it is important to ensure water drainage, i.e. by virtue of good transversal profile.

2.4. Polyurethane

Polyurethane Stabilised Ballast (PSB) is a stabilisation technology based on isocyanate compounds [13,17,46]. Two types of products have been mainly investigated in previous researches, one based on isocyanate [47,48] and one based on isocyanate and resins [49,50]; a rigid-foam version has also been tested [51]. By controlling the polymer rheology, the curing time (gel-time) can be adjusted as well as the strength of the bonding between the aggregates contact points [52]. Special precautions should be adopted when handling the product, as it is harmful if inhaled and causes skin irritation.

3. Experimental methodology

3.1. Sample preparation

The tested particle size distribution (PSD) is displayed in Table 2, each sample consisted of 5100 g of dry ballast material. The tested PSD is a downscaled version of railway ballast by factor 0.5: the

Table 1
Main physical and chemical properties of the stabilising agents.

Additive	Penetration (0.1 mm @ 25 °C)	Dynamic viscosity (cP @ 60 °C)	Fraass point (°C)	Softening point (°C)
bitumen 70/100	70–100	≥90,000	≤−10	46–54
bitumen 160/220	160–220	≥30,000	≤−15	35–43
	Density (kg/m^3)	Dynamic viscosity (cP @ 30 °C)	Freezing point (°C)	Boiling point (°C)
organosilane C1	1010–1030	200–600	<−5	188
organosilane C2	1000–1020	20–200	0	100
lignosulfonate	1250	550	5	100
polyurethane	1090	780	<10	>200

Table 2
Particle size distribution (PSD) of ballast material.

Sieve Size (mm)	22.4–25	25–31.5
Ballast Passing (%)	70	30

maximum particle size to be tested is recommended to be one fifth of the sample diameter 150 mm as indicated by the code [53]. Even if the downscaling process has an impact on the measured mechanical responses [54], this does not hinder the general research purpose of assessing and comparing the ballast stabilised by means of different agents.

The BSB specimens were added 3% of bitumen by weight, both binder 70/100 (BSB1) and binder 160/220 (BSB2) were tested; the aggregates and the bitumen were heated up to 160 °C for three hours before mixing. The material pre-heating is not necessary when using a bituminous emulsion [25–27]. The OSB, LSB and PSB samples were created at room temperature (22 °C) by adding 1.5%, 0.65% and 1.5% of organosilane, lignosulfonate and polyurethane binders by weight, respectively. In order to blend properly the stabilising agents and the aggregates, OSB, LSB and PSB samples were carefully mixed inside plastic bags and BSB samples inside a steel bowl. The operator successively compacted each specimen inside a steel mould by using a vibratory hammer (frequency 25–60 Hz, amplitude 5 mm, total weight 35 kg), the compaction time was 30 s. Finally, each sample was covered by latex membranes. Further information about curing time, curing temperature and bulk density [55] is reported in Table 3. The conditioning of the LSB samples comprised 50 °C for 48 h and then 22 °C (room temperature) for five days; in this fashion the lignosulfonate could adhere properly to the ballast aggregates [39–41]. Table 3 also shows an approximate price per kg of each stabilising agent. It is important to stress that the amount of additive has not been optimised for performance and cost, but it was chosen after some trial and error tests. Fig. 1 displays the appearance of the treated samples.

The diameter and the height of the tested specimens were 150 mm and 176–188 mm, respectively. The variation in height was connected to the compaction of the coarse particles of the samples. According to the code requirements, the height to diameter proportion should be 2:1 [53]. Nevertheless, previous research proved that this ratio has limited influence on the measured mechanical properties [56]. The samples were added end-platens, hose clamps and rubber O-rings before testing. Two replicate specimens were investigated for every RLTT.

3.2. Repeated load triaxial test

Repeated Load Triaxial Test (RLTT) investigated the mechanical properties of the aggregates, namely stiffness and resistance against permanent deformation [57,58]. The device exerts two kinds of external actions on the sample: a uniform confining pressure (σ_3, triaxial or confining stress) thanks to pressurised water and a vertical dynamic pressure (σ_d, deviatoric stress) by means of a hydraulic jack. The application of σ_d follows the selected sinusoidal pattern and gradually augments with different intensities of σ_3. The performed RLTT complies with the multi-stage low stress level (MS LSL) scheme, characterised by five different σ_3 values; moreover, six σ_d values constitute every sequence [53]. The MS LSL loading is depicted in Fig. 2 considering σ_d and the bulk stress θ ($\theta = \sigma_1 + \sigma_2 + \sigma_3$). The maximum value of σ_d = 600 kPa adequately simulates the train traffic [14,59]. Each test is formed by 30 steps comprising 10,000 pulses applied at 10 Hz. Three Linear Variable Differential Transducers (LVDTs) measure and record the axial permanent displacement every 5 pulses (0.5 s). A sequence is stopped if the axial permanent deformation reaches 0.5% [53]. Fig. 3a shows the RLTT equipment used in the investigation and Fig. 3b displays the test rig [60]. The values of the deviatoric stress σ_d and the load frequency applied are appropriate as they correspond to the order of magnitude generated by a common railroad car travelling at the speed of 200 km/h with total weight of 40,000 kg, length of 25 m and two two-axle bogies with 2.5 m wheelbase; cement concrete sleepers are 2.6 m wide and 0.3 m long [2]. The generated load frequency is approximately comprised between 3 Hz and 30 Hz, and the pressure under the sleeper varies between 300 kPa and 500 kPa taking the Dynamic Amplification Factor (DAF) into consideration [61].

3.3. Results interpretation

Given a constant triaxial stress σ_3, the resilient modulus M_R connected to a variation in the dynamic deviatoric stress σ_d^{dyn} is determined as

$$M_R = \frac{\Delta\sigma_d^{dyn}}{\varepsilon_a^{el}} \tag{1}$$

where ε_a^{el} is the axial resilient strain. There are many equations that describe the relationship between M_R and θ [57]. The k-θ model which is mostly used to interpret experimental results is provided by Hicks & Monismith [62]

$$M_R = k_{1,HM}\sigma_a\left(\frac{\theta}{\sigma_a}\right)^{k_{2,HM}} \tag{2}$$

where σ_a is a reference pressure (100 kPa) and $k_{1,HM}$, $k_{2,HM}$ are regression parameters. Moreover, Uzan model establishes a relationship between three parameters, namely M_R, θ and σ_d [63]

$$M_R = k_{1,UZ}\sigma_a\left(\frac{\theta}{\sigma_a}\right)^{k_{2,UZ}}\left(\frac{\sigma_d}{\sigma_a}\right)^{k_{3,UZ}} \tag{3}$$

where $k_{1,UZ}$, $k_{2,UZ}$, $k_{3,UZ}$ are regression parameters. Compared to Hicks & Monismith model, Uzan model has the advantage to take into consideration both bulk stress and deviatoric stress, enabling an useful representation in a three-dimensional plot.

The deformational response of the ballast can be described by two components: one is elastic (resilient) and the other one is

Table 3
Overview of tested samples: additive quantity, curing time, curing temperature, bulk density and additive price estimate.

Additive	Code	Additive content (%, weight)	Curing		Bulk density (t/m^3)	Price estimate (EUR/kg)
			Time (day)	Temperature (°C)		
untreated	UGM	–	–	–	1.68	–
bitumen 70/100	BSB1	3.0	2	22	1.73	0.4
bitumen 160/220	BSB2	3.0	2	22	1.73	0.4
organosilane	OSB	1.5	7	22	1.73	9.0
lignosulfonate	LSB	0.7	2 + 5	50 + 22	1.70	0.6
polyurethane	PSB	1.5	2	22	1.69	4.5

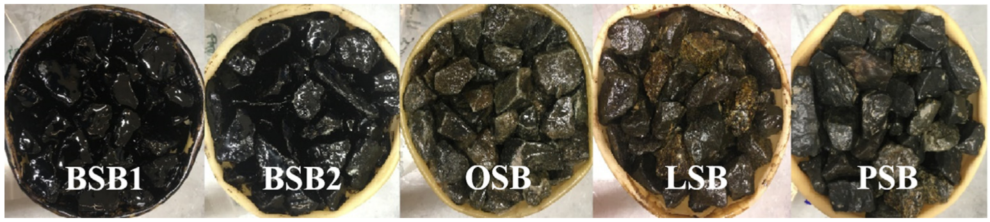

Fig. 1. Treated ballast samples.

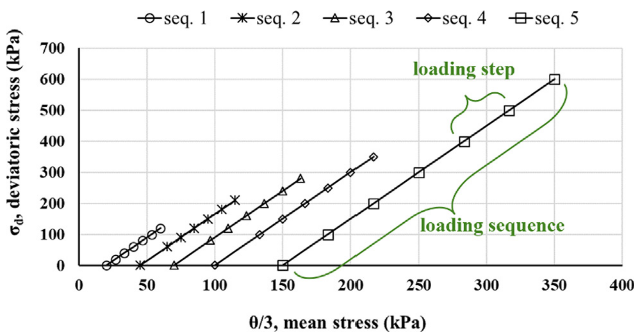

Fig. 2. RLTT loading sequences and steps.

plastic (permanent). The latter is the result of compaction, particle crushing or material migration; the plastic deformation is responsible for the long-term distresses [58]. Several models have been developed to illustrate the accumulation of vertical permanent deformation ε_{vp} as a function of different parameters. The experimental data corresponding to each step are fitted according to Hyde model [64], which establishes a relationship between the accumulated vertical permanent strain ε_{vp}, deviatoric stress σ_d and triaxial stress σ_3 as follows

$$\varepsilon_{vp} = a_{HY}\frac{\sigma_d}{\sigma_3} \quad (4)$$

where a_{HY} is the regression parameter. Hyde model is relatively simple, but sufficiently accurate for comparing the results of RLTTs.

4. Results and discussion

4.1. Resilient modulus

The experimental values of resilient moduli and their trends modelled according to Hicks & Monismith equation are displayed in Fig. 4. All the modelled resilient moduli are displayed together in Fig. 5a, the values of the regression parameters $k_{1,HM}$, $k_{2,HM}$ are reported in Fig. 5b.

All the additives except one significantly enhance the stiffness of the ballast. Furthermore, bitumen 70/100 achieves bigger M_R values than bitumen 160/220: a more viscous binder attains a major increase in stiffness [15]. Both organosilane and lignosulfonate augment the resilient modulus of the ballast, and the effect achieved by the latter proves to be the most significant among the investigated additives. In example, considering θ = 200 kPa, the M_R values for UGM, BSB1, BSB2, OSB and LSB are 460 MPa, 1935 MPa, 1612 MPa, 756 MPa and 2335 MPa, respectively. There is no previous experience regarding applications of organosilane and lignosulfonate in ballast, but the results are in good agreement with what previously found regarding coarse crushed rocks [18,19].

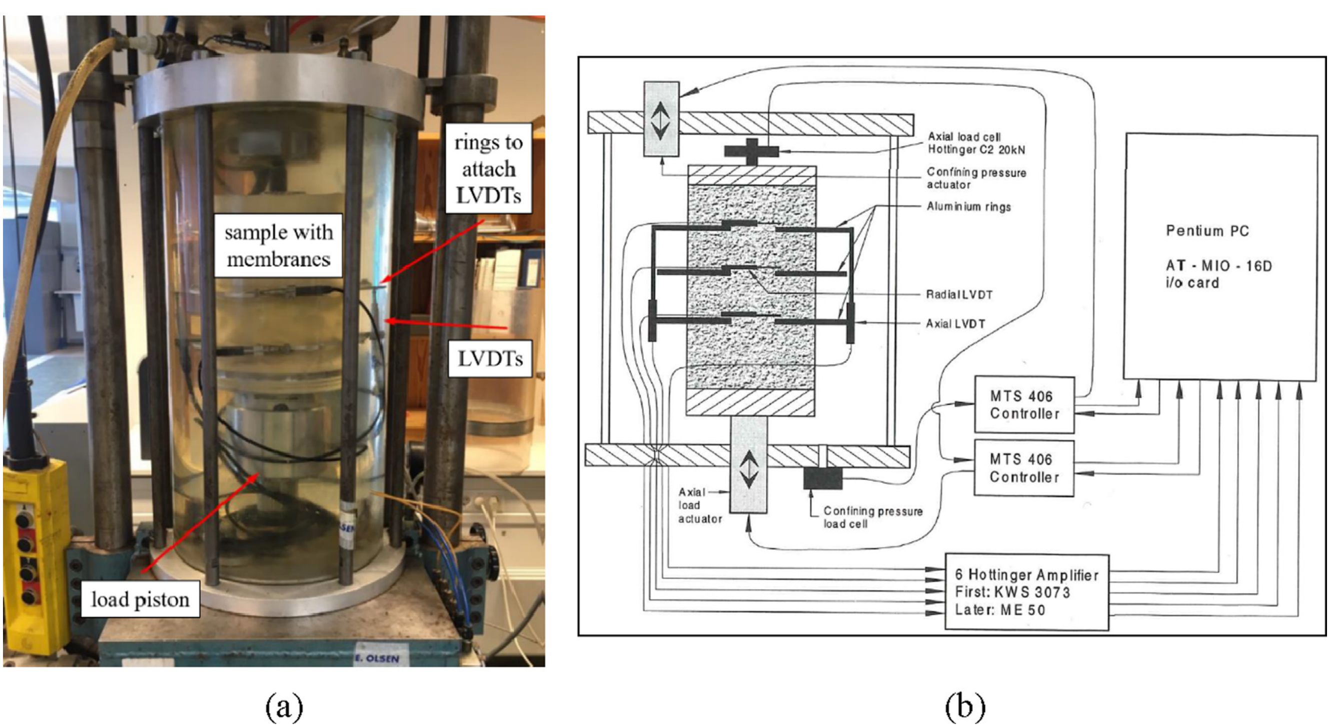

Fig. 3. RLTT equipment for the laboratory investigation (a) and test rig description [60] (b).

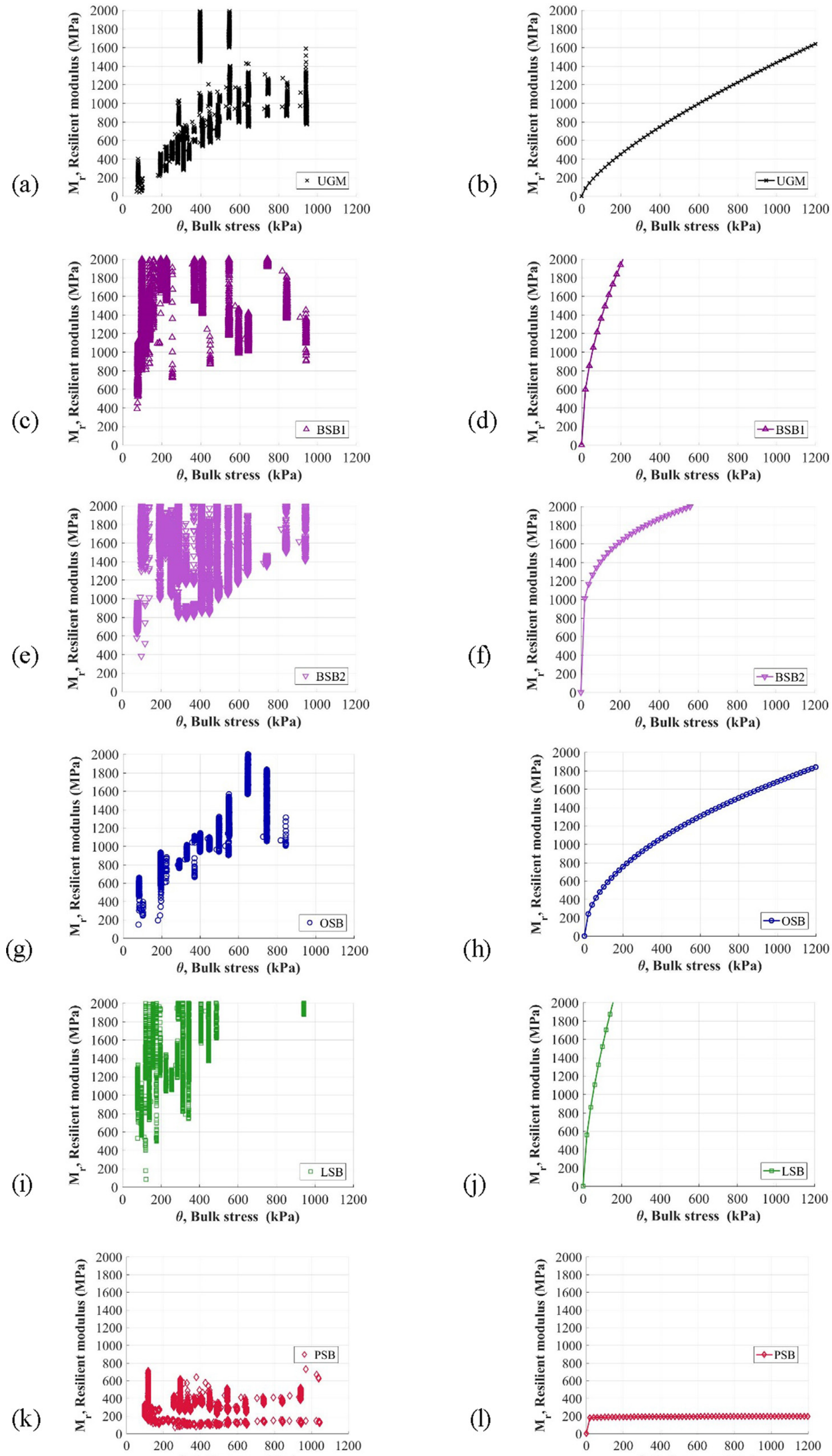

Fig. 4. Experimental data of resilient modulus and representation according to Hicks & Monismith model for UGM (a, b), BSB1 (c, d), BSB2 (e, f), OSB (g, h), LSB (i, j) and PSB (k, l) samples.

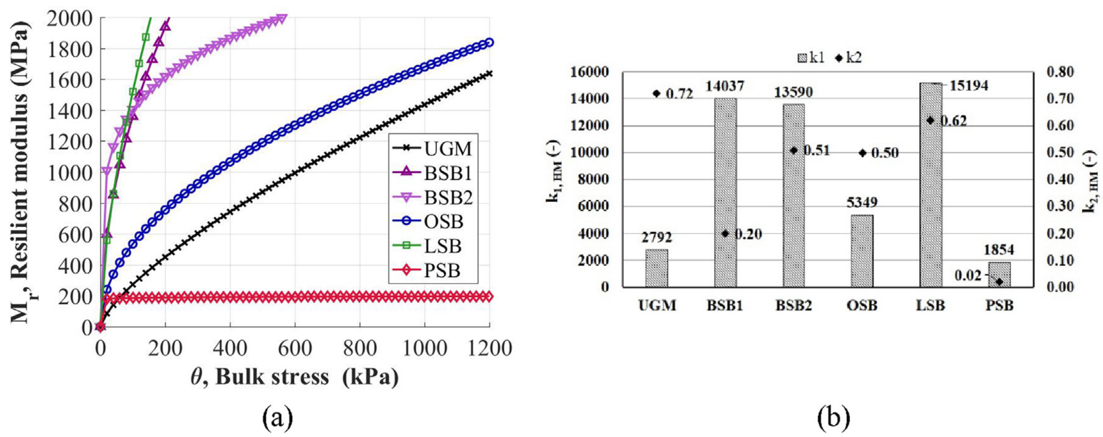

Fig. 5. Resilient moduli of tested samples according to Hicks & Monismith model (a) and regression parameters $k_{1,HM}$, $k_{2,HM}$ (b).

Polyurethane treated ballast behaved differently from the other additives, attaining the lowest value of resilient modulus, which is nearly constant (190 MPa) for any value of bulk stress θ. On the contrary, a previous experience performing triaxial load test (not cyclic) on PSB reported enhanced stiffness [65]. Furthermore, another laboratory investigation, but not based on triaxial tests, also found an increase in stiffness [66]. These discrepancies may be connected to the different testing methods, in particular the first mentioned experience applied uniaxial loads in a displacement-controlled mode [65].

In addition to the representation according to Hicks & Monismith model (Fig. 4l), the PSB resilient modulus can be also displayed in a three-dimensional plot according to Uzan model as reported in Fig. 6a: the polyurethane stabilised samples are not significantly dependent on either bulk or deviatoric stresses. All the M_R values are almost 190 MPa, as previously depicted in the two-dimensional representation (Fig. 5a). For comparison, Fig. 6b takes in consideration OSB resilient modulus to portray the general behaviour of ballast showing a clear dependency on both bulk and deviatoric stresses. Fig. 6c displays the model regression parameters. The elastic response of the PSB material deviates from the other investigated ballast materials: the main part of the load transfer is probably no longer in the rock skeleton but rather through the polyurethane.

A high stiffness of the track is usually positive as entails a decrease in deflections and a major resistance to train loads. Differently, an excessive high stiffness can augment the dynamic forces on the rail components, causing fatigue and wear issues. In some contexts, a lower track stiffness can be a desirable condition [67].

4.2. Resistance to permanent deformation

RLTT is composed of five loading sequences, the upper limit of axial permanent deformation in each sequence is 0.5% [53]. The accumulated vertical permanent deformation strains ε_{vp} corresponding to each sequence are represented in Fig. 7a, c, e, g, i and modelled according to Hyde formulation as displayed in Fig. 7b, d, f, h, j.

All the additives entail an improvement of the ballast in terms of resistance against permanent deformation [68]. The stabilising agents that display the best performance are organosilane, lignosulfonate and polyurethane. Nevertheless, the use of bitumen accomplishes a significative decrease in plastic strains. Considering i.e. the ratio $\varepsilon_{vp}/\sigma_d$ = 5, the values of the vertical permanent deformation ε_{vp} for UGM, BSB1, BSB2, OSB, LSB and PSB are 5.55, 1.40, 2.90, 4.10, 0.65, 0.50, respectively, during the first RLTT sequence and 3.50, 1.10, 0.70, 0.95, 1.75, 1.5, respectively, during the fifth RLTT sequence. With the progressive increase in the confining pressure, the trends of the vertical permanent deformation for the treated samples become more and more similar. For $\varepsilon_{vp}/\sigma_d$ = 6 in the first sequence, the difference between the highest and the lowest ε_{vp} values, corresponding to OSB and PSB, is 4.32. For the same $\varepsilon_{vp}/\sigma_d$ value in the fifth sequence, the difference assessed between the highest and the lowest ε_{vp} values, corresponding to LSB and BSB2, decreases to 1.26.

Fig. 8 displays the values of a_{HY} regression parameter for each loading sequence. The positive performance of stabilised ballast agree with what found in the previous researches investigating the deformation properties [14,17–19,69], even if different testing approaches were used.

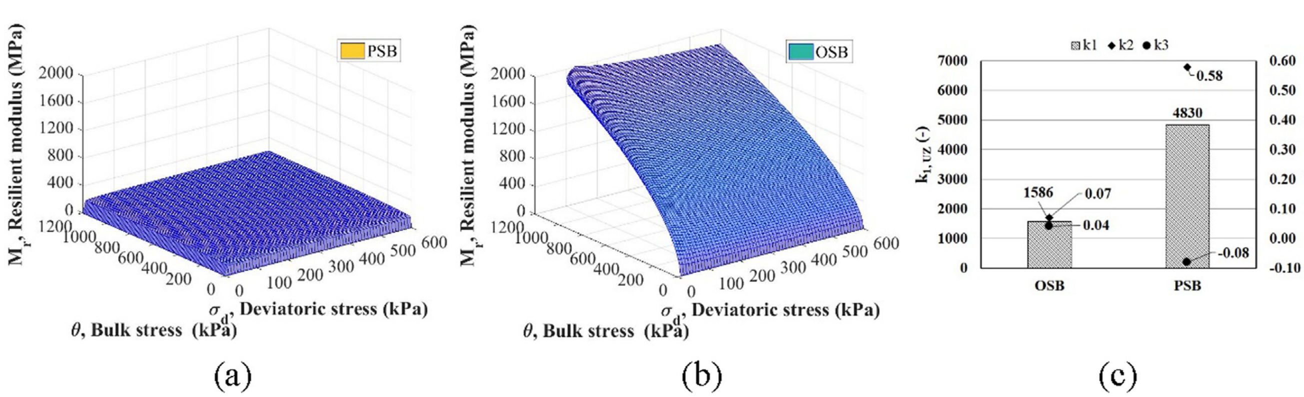

Fig. 6. Resilient modulus of PSB (a) and OSB (b) samples represented according to Uzan model with regression parameters $k_{1,UZ}$, $k_{2,UZ}$, $k_{3,UZ}$ (c).

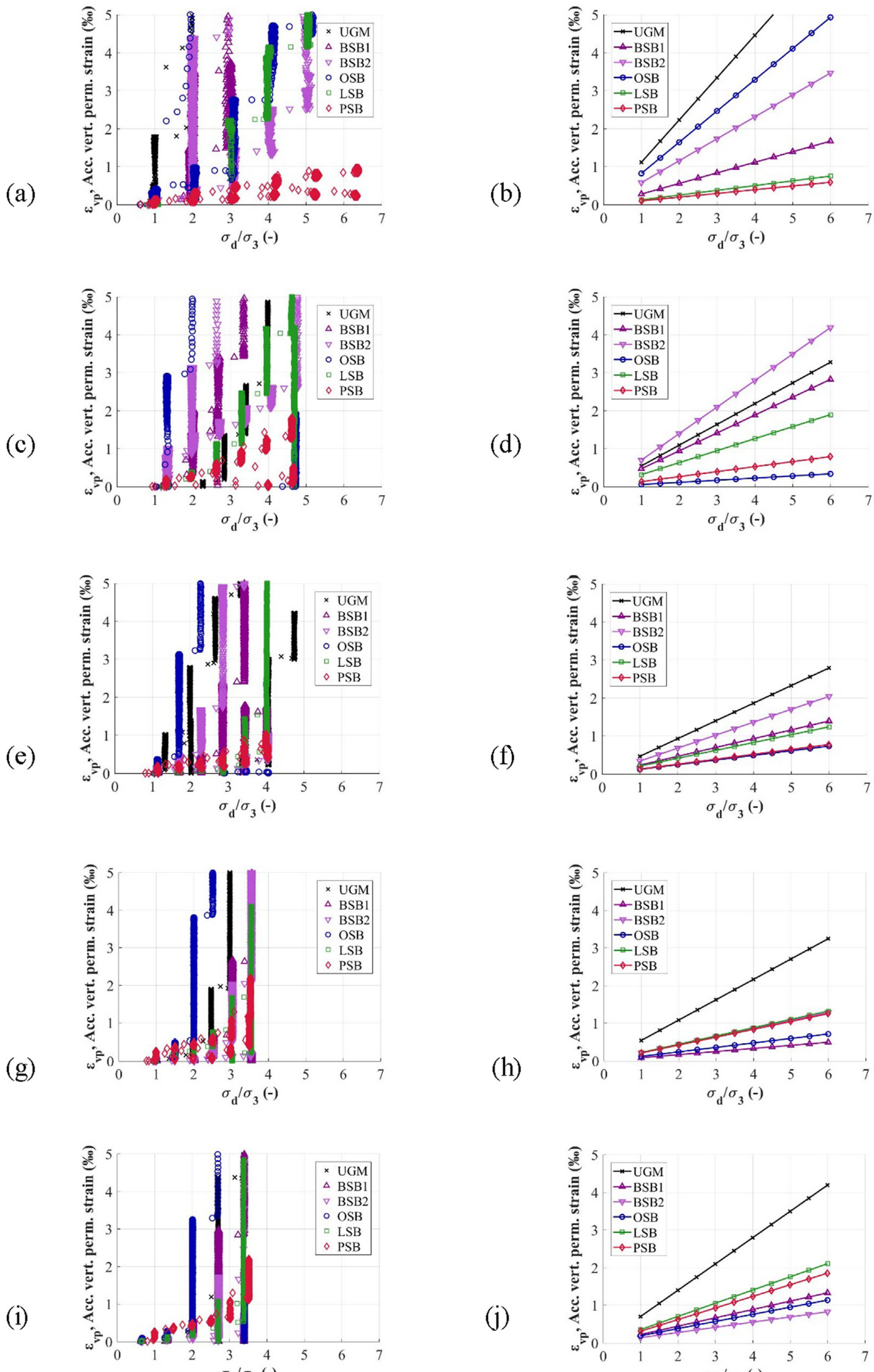

Fig. 7. Experimental and modelled accumulated vertical permanent strain corresponding to first (a, b), second (c, d), third (e, f), fourth (g, h) and fifth (i, j) RLTT loading sequence.

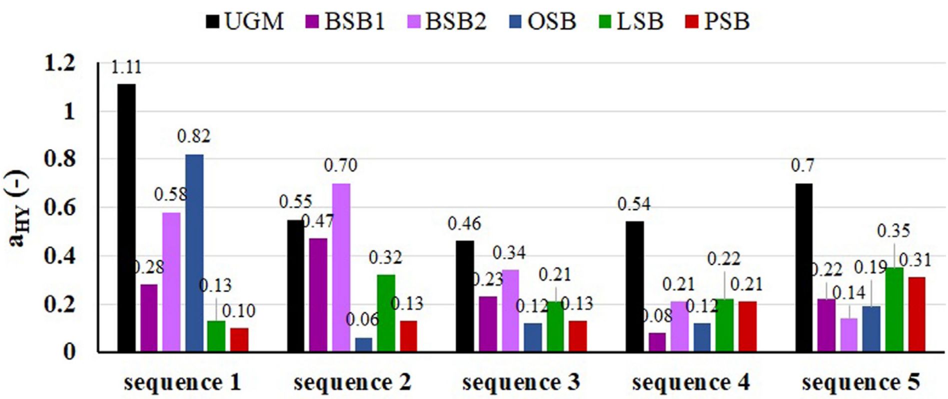

Fig. 8. Regression parameter a_{HY} for each RLTT loading sequence according to Hyde model.

5. Conclusions

The research scope was to characterise and systematically compare some additives that can be used as stabilisation agents for railway ballasts. They were composed of bitumen (Bitumen Stabilised Ballast, BSB), organosilane (Organosilane Stabilised Ballast, OSB), lignosulfonate (Lignosulfonate Stabilised Ballast, LSB) and polyurethane (Polyurethane Stabilised Ballast, PSB). The resilient modulus and the resistance against permanent deformation of both untreated and treated ballast were investigated in the laboratory by means of Repeated Load Triaxial Tests (RLTTs).

All the binding agents accomplished variation in ballast stiffness. Except for PSB, the resilient moduli of BSB, OSB and LSB increased compared to untreated ballast. In many cases this is beneficial to secure good load distribution to protect the layers under the ballast. Contrastingly, the resilient modulus of PSB was smaller than untreated ballast, and the stiffness of PSB was practically independent from both bulk stress and deviatoric stress. This indicates that there is a possibility to adjust rigidity in critical areas to reduce noise/vibration or to secure a uniform stiffness along the track irregularities.

Growing traffic volume, train speed and axle loads lead to recurring maintenance operations, which incurs significative expenses. All the additives enhanced the resistance to permanent deformation of ballast. OSB, LSB and PSB showed the most significant decrease in accumulated vertical permanent deformation.

The investigated technologies offer feasible solutions to mitigate ballast deterioration and track settlements; the additives represent promising options for improving ballast performance.

Nevertheless, there are some characteristics which may have impacted the research findings and their interpretation. Firstly, the optimization of the mixing proportions can contribute to identify the most suitable additive quantity for each practical case, focusing i.e. on mixing stability, flowability, and curing time. Furthermore, the tested particle size distribution was downscaled compared to real ballast; consequently, fulfilling a field test could contribute to buttress this research's findings. Moreover, the investigation has only dealt with one type of ballast: even if the results have been promising, the outcomes could be generalised even more by further testing of other rock types.

CRediT authorship contribution statement

Diego Maria Barbieri: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization, Project administration. **Marius Tangerås:** Conceptualization, Validation, Formal analysis, Investigation, Resources, Writing - original draft. **Elias Kassa:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Inge Hoff:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision, Project administration. **Zhuangzhuang Liu:** Writing - review & editing, Visualization, Supervision. **Fusong Wang:** Writing - review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.conbuildmat.2020.119041.

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