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Evaluating Different Track Sub-Ballast Solutions Considering Traffic Loads and Sustainability

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Abstract: The railway industry is seeking high-performance and sustainable solutions for sub-ballast materials, particularly in light of increasing cargo transport demands and climate events. The meticulous design and construction of track bed geomaterials play a crucial role in ensuring an extended track service life. The global push for sustainability has prompted the evaluation of recycling ballast waste within the railway sector, aiming to mitigate environmental contamination, reduce the consumption of natural resources, and lower costs. This study explores materials for application and compaction using a formation rehabilitation machine equipped with an integrated ballast recycling system designed for heavy haul railways. Two recycled ballast-stabilised soil materials underwent investigation, meeting the necessary grain size distribution for the proper compaction and structural conditions. One utilised a low-bearing-capacity silty sand soil stabilised with recycled ballast fouled waste (RFBW) with iron ore at a 3:7 weight ratio, while the second was stabilised with 3% cement. Laboratory tests were conducted to assess their physical, chemical, and mechanical properties, and a non-linear elastic finite element numerical model was developed to evaluate the potential of these alternative solutions for railway sub-ballast. The findings indicate the significant potential of using soils stabilised with recycled fouled ballast as sub-ballast for heavy haul tracks, underscoring the advantages of adopting sustainable sub-ballast solutions through the reuse of crushed deteriorated ballast material.

Keywords: recycled ballast; ballast waste; numerical modelling

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1. Introduction

Railway track efficiency can be improved mainly by increasing the track's service life, allowing it to resist additional loads over time and reducing maintenance cycles, track interruptions, and greenhouse gas emissions [1].

The sub-ballast layer plays a crucial role in a railway track's life cycle. As outlined in [2], it serves to protect the subgrade from traffic loads and prevent mud from pumping into the ballast layer by providing separation and drainage for rainwater or groundwater. Numerous studies by researchers [3–17] have explored sustainable solutions related to geotechnical layers in railway tracks, such as ballast and sub-ballast, with their objectives including (i) enhancing the load-bearing capacity of the railway track, (ii) reducing strains from traffic loads, (iii) repurposing waste materials, (iv) proposing alternative materials, and (v) minimising ballast breakage.

Regarding the ballast layer, Indraratna and Salim [8] and Indraratna et al. [9] examined the stress–strain behaviour and the degradation of recycled ballast with geosynthetics, comparing it with clean ballast. Their aim was to reduce the amount of discarded ballast, maintenance costs, and environmental impact. The studies revealed that reinforced recycled ballast with geosynthetics showed promising potential to improve railway track resilience and reduce maintenance costs. Indraratna et al. [4] investigated the potential of using geogrids and recycled rubber in the ballast layer to enhance the track performance. Giunta [10] evaluated different recycled waste materials as potential solutions to improve the ballast behaviour.

Concerning the sub-ballast layer, Ebrahimi and Keene [5] investigated the possibility of rehabilitating the substructure and replacing the sub-ballast with alternative materials derived from a mixture of recycled ballast with recycled pavement materials (RPM), with or without industrial by-products (fly ash), to improve its mechanical behaviour (stabilised fouled ballast). They found that the use of fly ash mixed with RPM resulted in lower values in terms of permanent deformations, while the application of RPM alone provided behaviour similar that of conventional granular sub-ballast. Saborido Amate [11] assessed a novel alternative of recycled aggregates derived from blast furnace slag, known as SFS-Rail, for use in sub-ballast layers. The authors concluded that this type of recycled aggregate exhibits high quality in terms of durability, hardness, and resistance to abrasion, while also contributing to a reduction in environmental impacts. Giunta [10] also discussed various modern railway engineering sub-ballast sustainable solutions, including the use of alternative materials like cement-reinforced soils and asphalt binder for sub-ballast applications. Indraratna et al. [8] investigated the use of recycled rubber tires mixed with gravel as a sub-ballast layer. The authors found that this solution has the potential to reduce ballast degradation due to its damping characteristics, decrease the track's modulus in the case of rigid substructures, and enhance lateral confinement and the track's structural behaviour. Qi et al. [12] introduced two methods for stabilising railway substructure materials by blending waste materials such as blast furnace slag, washed coal, and rubber crumbs for use as sub-ballast materials. The authors showed that the proposed solutions can increase particle interlocking to provide proper shear strength as well as higher absorbing characteristics than traditional materials. In summary, the mentioned research focused mainly on improving the strength, load-bearing capacity, and durability of the sub-ballast layer by reusing recycled materials in a sustainable way.

However, limited research exists on recycled ballast fouled with iron ore, despite ongoing investigations into alternative and sustainable materials. Railways transporting iron ore often generate significant ballast waste, requiring extensive cleaning [18,19]. Ebrahimi and Keene [5] advocate for the cost-effective and sustainable practice of reusing materials obtained from ballast cleaning to construct a new sub-ballast layer, as opposed to disposal, which incurs additional expenses. The inclusion of iron ore as a fouling material may enhance the hydro-mechanical behaviour by improving interparticle contact, filling voids, and increasing stiffness, as observed in [19,20].

Schilder and Piereder [21], Auer et al. [22], and Mundrey [23] stated that the Rail-mounted Formation Rehabilitation Machine (RMFRM) can improve railway tracks' structural behaviour by constructing and rehabilitating a new sub-ballast layer in recycling, reusing, and mixing the used ballast waste with different alternative materials, such as the subgrade soil itself. This process has higher productivity, less track disruption, and lower carbon emissions compared to conventional earthwork methods.

Nonetheless, the material originated from the integrated recycling process should satisfy the design specifications to be applied as sub-ballast to contribute to the proper mechanical behaviour. In recent decades, the analysis and design of railway components have been performed using various numerical modelling methods, notably the Finite Element Method (FEM). Many authors have studied complex railway problems through the development of 2D plane strain numerical models, applying the FEM due to its low computational effort requirements and computation times and greater simplicity in terms of the number of required parameters. Punetha et al. [24] developed a 2D numerical model to investigate the structural behaviour in bridge–track and track–bridge transition zones by considering the influence of a moving train, applying dynamic loads. The authors studied techniques that can increase the track stiffness and reduce track displacements at these critical zones. Indraratna and Nimbalkar [25] developed a 2D FEM numerical model to evaluate different scenarios and configurations of a cyclic triaxial chamber developed in the laboratory to simulate a railway multi-layer system stabilised using geosynthetics. The authors obtained important results regarding the stresses and deformations at the sleeper–ballast and ballast–sub-ballast interfaces. Jiang and Nimbalkar [26] developed a 2D FEM railway track model to predict the structural behaviour of the track's substructure by simulating a geogrid reinforced ballast layer. The authors obtained relevant insights regarding vertical strains and tensile forces in geogrid and ballast settlement and justified that the method is convenient and economical for this purpose. Ramadan et al. [27] evaluated the influence of subgrade settlement on stresses for different loads and boundary condition scenarios. All of these mentioned works could reproduce different railway structural problems through the simplification of 2D plane strain FEM numerical models, as well as achieving important and accurate results.

The main objective of this paper is to evaluate the structural performance of alternative material solutions composed of recycled material from a ballast cleaning process and subgrade soil stabilised, or not, with cement for application as a sub-ballast layer using a RMFRM. This investigation aimed to analyse the structural conditions of the materials and their influence on the track performance in terms of displacements, strains, and stresses.

2. Formation Rehabilitation

2.1. The Sub-Ballast Layer

The sub-ballast is located underneath the ballast layer and has as its main function providing a better load distribution from the ballast to the subgrade, protecting it against possible high stress magnitudes and strains, being an essential part of the track for heavy haul operational conditions [2,28,29].

Li et al. [30] emphasise that the grain size distribution of sub-ballast material is a critical parameter, as it significantly influences separation, filtration, drainage, and strength. It should ideally contain a specific percentage of fine material passing through a 0.075 mm sieve to prevent mud pumping from the subgrade soil [31,32]. However, this percentage should be balanced to avoid increasing the water susceptibility and plastic deformation and hindering drainage [2,33,34]. As a result, many researchers and technical specifications recommend a well-graded material for the sub-ballast layer to meet these criteria, including Mundrey [23] and AREMA [34].

Different materials can be employed as sub-ballasts, such as well-graded crushed rock [2,35], hot mix asphalt underlayment [36,37], and lateritic tropical soils from quarries [20,38]. Regarding the latter, Castro et al. [20] and Guimarães et al. [38] explain that these types of soils contribute to better railway track behaviour as sub-ballasts because their clay fraction contains minerals from the kaolinite group and hydrated iron and aluminium oxides, which are considered stable in the presence of water and can bind their particles. Studies on stabilising local soils with recycled ballast fouled with iron ore or binder, such as cement, to improve their strength and deformability characteristics are still scarce, so further exploration may be interesting from an environmental and economical point of view.

2.2. Ballast Recycling Using a Formation Rehabilitation Machine

According to Esveld [39] and Klotzinger [40], ballast cleaners are employed when ballast particles with dimensions smaller than 22 mm constitute more than 30% of the total ballast volume. Profillidis [41] also states that the equipment removes all ballast particles smaller than 35 mm to a depth of 0.25 m in a layer next to the sleeper.

A RMFRM has been developed to rehabilitate railway infrastructure by integrating different processes performed into a single machine, including ballast cleaning and subgrade rehabilitation through the construction of sub-ballast using different materials, such as the ballast waste from the cleaning process.

Some railways have employed the RMFRM in their rehabilitation processes, as reported by Schilder and Piereder [21], Auer et al. [22], Mundrey [23], and Fu et al. [42]. According to Schilder and Piereder [20] and Auer et al. [21], the RMFRM can save up to 50% of the amount of new material required. However, the excavated materials should meet the specifications, as previously mentioned.

Schilder and Piereder [21] and Auer et al. [22] stated that the compaction energy applied in studies conducted in Austria, regarding the RMFRM for passenger railway tracks, was the Standard Proctor, followed the European specification BS EN 13286-2 [43]. However, Brazilian specifications use a reference minimum compaction energy for sub-ballast layers of heavy haul tracks between the Standard and the Modified Proctor, named the Intermediate Proctor. Hence, chemical stabilisation materials may be necessary if material compaction in the field is ineffective or inefficient. However, the compaction efficiency of the RMFRM is not the focus of this work and will not be addressed.

3. Materials and Methods

3.1. Site Characteristics and Material Sampling

The methodology employed in this study aimed to investigate and propose different materials for compaction using a RMFRM by mixing recycled ballast with a low-bearing-capacity subgrade soil stabilised, or not, with cement for heavy haul tracks. The railway under investigation was the Carajás railway (EFC), located in Northern Brazil, which primarily transports iron ore using trains consisting of 330 wagons with 32.5 t/axle. The railway features the following main characteristics: (i) TR-68 (RE 136) rail; (ii) stiff rail pads; (iii) concrete sleepers averaging 2.80 m in length, 0.27 m in thickness, and 0.23 m in depth; (iv) a ballast layer with a depth of 0.30 m; (v) a sub-ballast layer initially 0.25 m thick, with plans to increase it to 0.30 m; (vi) a track gauge of 1.60 m; (vii) Pandrol fastenings; and (viii) sleepers spaced 0.61 m apart.

Firstly, the studied materials were collected from quarries and in the vicinity of the railway, where maintenance and rehabilitation works were being carried out: (i) Itapeti soil identified as a soft silty sand soil from Mogi das Cruzes city; (ii) São Pedro da Água Branca (SPAB) soil from km 650 + 560, characterised as a stiff subgrade soil; (iii) recycled fouled ballast waste 1 (RFBW 1) from km 554 + 000; and (iv) recycled fouled ballast waste 2 (RFBW 2) from km 15 + 000, in Bacabeira city. Some of the characteristics of these materials were obtained from the study conducted by Saico et al. [44]. Figure 1 depicts the piles of RFBW.

(**a**) (**b**)

Figure 1. Photos of piles of fouled ballast in EFC Carajás. (**a**) Pile 1, reference code: RFBW 1; (**b**) pile 2, reference code: RFBW 2.

3.2. Laboratory Tests

3.2.1. Physical–Chemical Characterisation and Dosage

Initially, the studied materials underwent investigation to determine their grain size distribution and classification, assessing their suitability as sub-ballast materials according to ASTM D6913 [45]. The particle size distribution and characterisation of the fouled ballast waste material followed ASTM C136–06 [46] and ASTM C702 [47]. In addition, it was assumed that the particle size distribution curve of the sub-ballast material should meet the specifications of a well-graded material, satisfying the criteria for filtering, separation, drainage, compaction, and stiffness, outlined by AREMA [34], Mundrey [23], Selig and Waters [2], and Auer et al. [22].

The particle size distribution of the resulting coarse-grained material was evaluated based on the Brazilian specifications DERSA ET-DE-P006 [48] and DERSA ET-DE-P00/008 [49], which are applied to well-graded road pavement base materials and aggregate. Table 1 shows the characteristics and properties of the investigated soil materials.

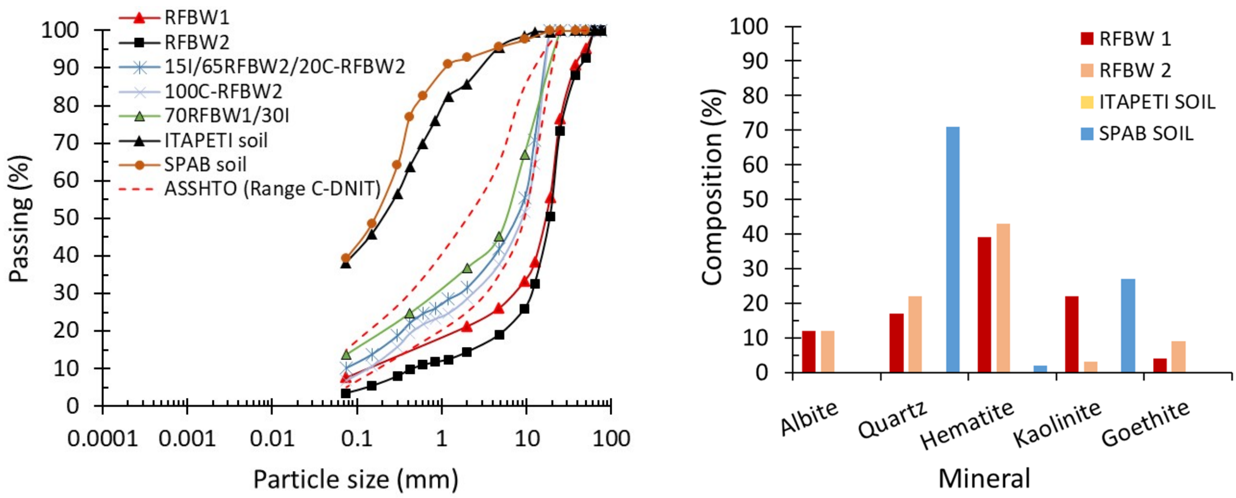
Table 1. Characteristics and properties of the investigated soil materials.

Characteristics and Properties	**Soil Materials**	
	Itapeti (Soft Soil)	**SPAB (Stiff Soil)**
Sand fraction (%)	57.2	56.3
Silt and clay fraction (%)	38.3	39.4
Gs	2.790	2.720
LL (%)	41	34
PL (%)	29	19
PI (%)	12	15
γ_d^{max} (kg/m^3)	1730	1950
w_{opt} (%)	16.9	12.2
HRB soil classification	A-7-5	A-6
MCT tropical soil classification	NS′-NG′	LA′-LG′

The soils were further assessed in terms of their physical characteristics and properties. As the soft subgrade soil (Itapeti) did not meet the design requirements individually and faced the possibility of ineffective compaction using a RMFRM, the material was stabilised with RFBW and 3% cement. Previous studies have highlighted the positive potential of a low percentage of cement to improve the hydro-mechanical properties, compaction, and stabilisation of pavement materials [50–54]. On the other hand, the stiff subgrade soil SPAB, while suitable for subgrade applications, did not require stabilization.

Thus, the chosen soil–aggregate mixtures were (i) 30% soil and 70% RFBW 1, assuming a proportion that leads to higher load-bearing capacity values, in accordance with ABNT NBR 12053 [55], and (ii) a combination of 15% soil, 65% RFBW 2 passing through the 19 mm sieve, and 20% crushed ballast material (C–RFBW). The details about the RFBW 2 mixture have been well described by Saico et al. [44]. The chosen mixture dosages followed the maximum and minimum limits of Range C from DNIT 141 [56]. Figure 2 shows the grain size distribution and the mineralogical composition of the studied materials.

It was noticed that Itapeti soil requires granulometric stabilisation to increase its strength and resilient modulus (RM) and to meet sub-ballast specifications. In addition, the mineralogical composition data showed that it was not possible to determine the true quantity of clay minerals present in the Itapeti soil, which is why Itapeti data do not appear in Figure 2b. The XRD technique depends on the crystallinity of its compounds. Clays, in general, have low crystallinity, and when stabilised with highly crystalline minerals, the quantification method becomes less precise, potentially leading to significant errors in quantification.



(**a**) (**b**)

Figure 2. (**a**) Grain size distribution; (**b**) mineral composition of the materials.

Regarding the SPAB soil, it contains almost 30% kaolinite and 2% hematite, which can contribute to better mechanical behaviour compared to Itapeti soil. Furthermore, 40% hematite or iron ore and presence of kaolinite clay mineral could be observed in the fouled ballast waste materials, possibly originating from material falling off the wagon during transport and/or from existing sub-ballast/subgrade materials.

3.2.2. Mechanical Characterisation

For the mechanical behaviour assessment of the materials for the subgrade and sub-ballast layers, their resilient modulus (RM) values were determined following AASHTO T 307-99 [57]. The specimens were compacted in their optimal moisture content and maximum density conditions.

The RM of the ballast material was determined using a large-scale triaxial test, in accordance with the methodology outlined in detail by Costa et al. [58] and Merheb et al. [59] to prepare the specimen and to perform the test, which can be summarised as (i) fixing a latex membrane in a steel base; (ii) separating and inserting different homogenised portions of the material into the membrane; (iii) compacting the resulting material with a vibratory plate at a frequency of 20 Hz; and (iv) applying a pre-determined confining pressure with a deviatoric stress.

The laboratory test results underwent nonlinear regression analysis using nonlinear constitutive models for the different geotechnical materials (Equations (1) and (2)), in accordance with their prevailing response to confining and deviatoric stresses. This analysis, following the methodologies of Liu [60] and Delgado et al. [13], yielded regression parameters used as input in the numerical model. Tables 2 and 3 present the regression coefficients and compaction conditions of the tested specimens, respectively.

$$MR = k_1 \times {\sigma_d}^{k_2} \quad (1)$$

$$MR = k_1 \times {\sigma_3}^{k_2} \times {\sigma_d}^{k_3} \quad (2)$$

$$k_1' = k_1 \times 10^{[\alpha(1-k_2)]} \quad (3)$$

where k_1, k_2, and k_3 are the material-specific nonlinear regression coefficients obtained in the RM test, and α = 6 was used to convert the regression parameter k_1 unit obtained in MPa into Pa.

Table 2. RM constitutive model and regression coefficients of the materials.

Material	RM Non-Linear Constitutive Model	$k_{1'}$ (Pa)	k_2	k_3	R^2
Ballast	$MR = k_1 \sigma_d^{k_2}$	6,096,877	60.1	-	0.94
Itapeti soil	$MR = k_1 \sigma_3^{k_2} \sigma_d^{k_3}$	8,727,494	0.48241	−0.29736	0.84
SPAB soil		33,728,634	0.3969	−0.2814	0.74
RFBW 1 + ITA + CEM		76,445,929	0.27569	−0.00503	0.97
RFBW 2 + ITA + CEM		224,523,318	0.21365	−0.08193	0.91
RFBW 1 + ITA		2,229,317	0.43700	−0.04401	0.94
RFBW 2 + ITA		52,787,363	0.06871	0.02779	0.20

Table 3. Compacted conditions of the studied materials.

Material	γ_{dmax}	γ_d	w_{opt}	w	Degree of Compaction (D_{Pr})
	(kg/m^3)		(%)		(%)
ITAPETI soil	1730	1720	16.2	16.9	99
SPAB soil	1950	1973	12.0	12.2	101
RBFW 1 + ITA + CEM	2110	2143	9.4	9.1	102
RBFW 2 + ITA + CEM	2293	2293	6.5	6.7	100
RBFW 1 + ITA	2110	2181	9.4	8.0	103
RBFW 2 + ITA	2240	2218	8.7	8.1	99

3.3. Numerical Modelling of the Railway Track

3.3.1. Geometry, Meshing, Boundary Conditions, Load, and Materials

The mechanical response of the proposed materials was evaluated using the ABAQUS/CAE software using a 2D FEM numerical model developed for railway applications. A Fortran UMAT subroutine code, developed by Vargas [61] for road application, was employed in this research. In summary, the constitutive model is represented as a stress–strain relationship or Jacobian Matrix, in which the elastic modulus, or RM magnitude, depends on the stress state of the structure. More details regarding the UMAT processes and programming implementation can be found in Vargas [61].

To determine the most cost-efficient mesh that could provide accurate results while maintaining computational feasibility, a mesh convergence analysis was conducted. This involved varying the mesh settings to increase the number of elements and comparing the stress and displacement results for different configurations. The resulting mesh and geometry characteristics are depicted in Figure 3 and summarised in Table 4.

The boundary conditions were set with restrained vertical and free horizontal degrees of freedom (DOF) at the bottom of the model, while restrained horizontal and free vertical DOF were applied at the lateral edges. The operational conditions of the track under study, in terms of speed and rolling stock geometry, were simulated using a dynamic impact factor of 1.4558, corresponding to a wagon with a static load of 32.5 t/axle, a maximum allowable speed of 22.2 m/s, and a wheel diameter of 0.9144 m, resulting in an equivalent dynamic load of 23.6 t/wheel. The equation for calculating the impact factor was obtained from AREMA [34]. The interfaces between the track components were assumed to be completely bonded for simplification. The material characteristics of the geotechnical layers were assumed to be the RM constitutive models outlined in Table 5.

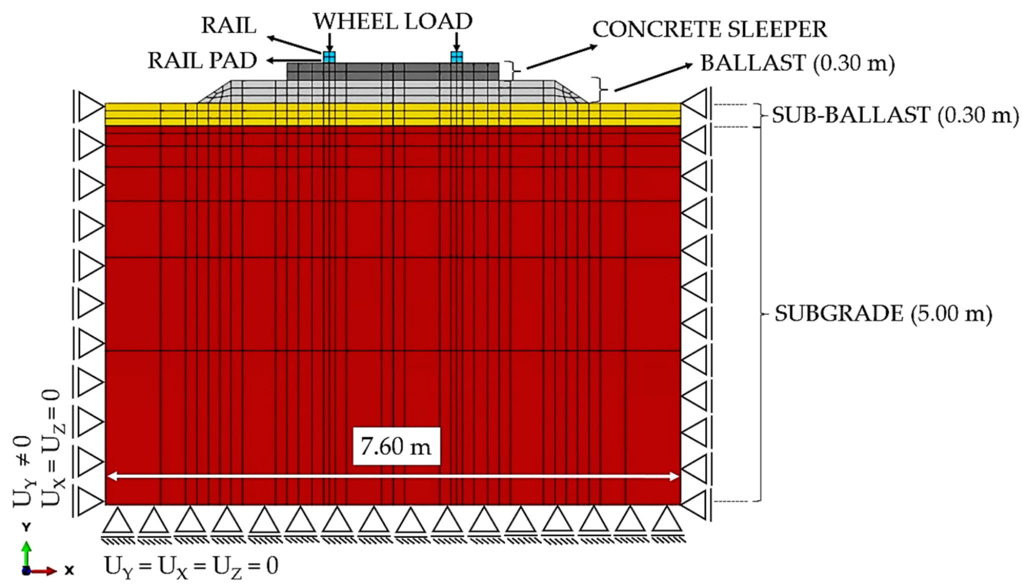


Figure 3. Mesh configuration and geometric characteristics of the developed 2D model.

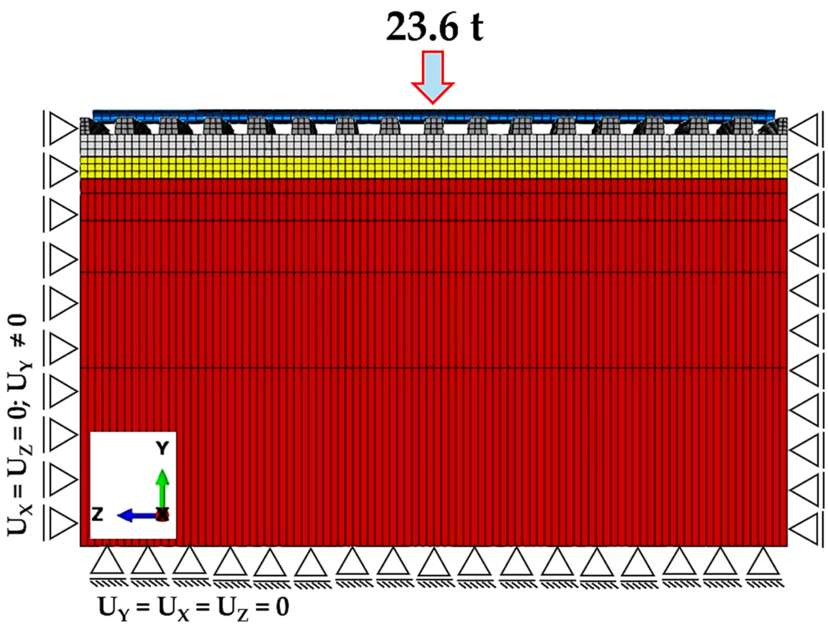
Table 4. Meshing characteristics of the developed numerical model.

Railway Track Component	Number of Elements	Element Type	Element Shape	Technique
Rail	4	CPE8R	Quad-dominated	Structured
Rail pad	2			
Concrete sleeper	16			
Ballast	41			
Sub-ballast	51			
Subgrade	119			

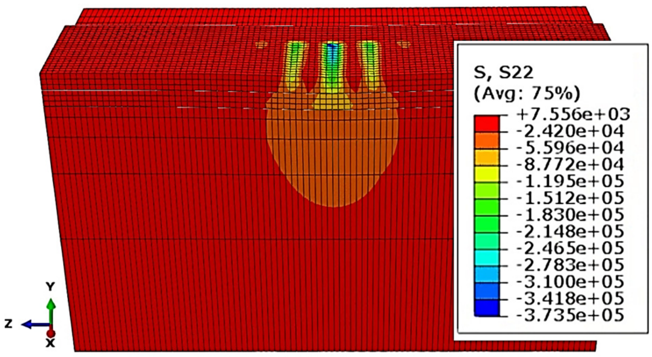
Table 5. Constitutive model and input parameters of the materials applied in the numerical model.

Track Component	Material Type	Constitutive Model	Model Type	Young's Modulus (MPa)	Poisson's Ratio (υ)	$k_{1'}$	k_2	k_3
Rail	Steel	$MR = E$	Linear elastic	210,000	0.30		Table 2	
Rail pad	Elastomer			135.5	0.01			
Sleeper	Reinforced concrete			32,000	0.20			
Ballast	Crushed rock	$MR = k_1 {\sigma_d}^{k_2}$	Non-linear elastic	-				
Sub-ballast	RFBW 1/ITA/CEM	$MR = k_1 {\sigma_3}^{k_2} {\sigma_d}^{k_3}$		-	0.30			
	RFBW 2/ITA/CEM			-	0.30			
	RFBW 1 + ITA			-	0.30			
	RFBW 2 + ITA			-	0.30			
Subgrade	Itapeti soil			-	0.35			
	SPAB soil			-	0.35			

Considering a plane strain numerical model of this study, it was assumed that only 40% of the wheel load would be transferred to the single main sleeper, in accordance with Profillidis [41]. Additionally, a linear elastic 3D FEM numerical model developed by Castro et al. [62] was employed to validate this assumption, considering the same railway track characteristics. Therefore, the material properties outlined in Table 5 were applied in the analysis, including the rail, rail pad, and concrete sleeper mechanical characteristics. Figure 4 illustrates the stress distribution through the sleepers under a single wheel load of 23.5 t, as calculated in this study.



(a)



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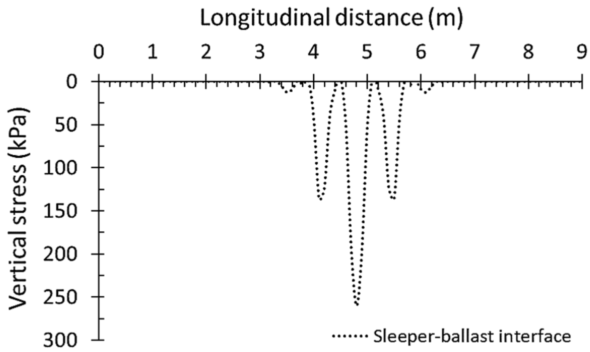

(c)

Figure 4. Mesh configuration and geometric characteristics of the 3D model developed by Castro et al. [62]: (**a**) general configuration of the model; (**b**) vertical stress contours, S_{22} (in Pa); (**c**) vertical stress at the sleeper-ballast interface.

3.3.2. Validation and Calibration

In terms of the model calibration, the track structure was simulated using the linear elastic configuration within ABAQUS and compared to other simulations using the UMAT subroutine with the equivalent elastic properties. ABAQUS software requires the input of the elastic or Young's modulus, density, and Poisson's ratio, while the UMAT subroutine requires the constitutive equation, regression coefficients obtained through laboratory tests, and Poisson's ratio. The displacement values obtained from both analyses were consistent. Table 6 presents a comparison of the different model scenarios for calibration.

Furthermore, additional numerical simulations were conducted using the data from Table 6 as the input parameters, employing the UMAT subroutine. These simulations were carried out to compare the results with field instrumentation and monitoring data obtained from various studies in the literature.

Table 6. Model scenarios for the UMAT subroutine calibration and application to railway tracks.

Model Scenario	Railway Track Component	ABAQUS Built-In Linear Model	UMAT Subroutine				Poisson's Ratio
		Young's Modulus (MPa)	Constitutive Model	k_1 (Mpa)	k_2	k_3	
ABAQUS built-in linear model	Rail	210,000	$MR = E$	-	-	-	0.20
	Rail pad	135.5		-	-	-	0.25
	Concrete sleeper	32,000		-	-	-	0.01
	Ballast	-	$MR = k_1\sigma_d^{k_2}$	208	0	-	0.20
	Sub-ballast	-	$MR = k_1\sigma_3^{k_2}\sigma_d^{k_3}$	300	0	0	0.30
	Subgrade	-		70	0	0	0.35
UMAT subroutine	Rail	210,000		-	-	-	0.20
	Rail pad	135.5		-	-	-	0.25
	Concrete sleeper	32,000		-	-	-	0.01
	Ballast	208		-	-	-	0.20
	Sub-ballast	300		-	-	-	0.30
	Subgrade	70		-	-	-	0.35

4. Results and Discussions

Figures 5–8 show the results of the 2D model calibration and validation analyses.

Different analyses were performed to evaluate the structural potential of the sub-ballast solutions in protecting the subgrade soil foundation from the traffic loads. Figures 9–11, along with Table 7, present the results on the displacements, strains, and stresses in the subgrade and rails when different sub-ballast alternative solutions with RFBW were applied over soft subgrade soil.

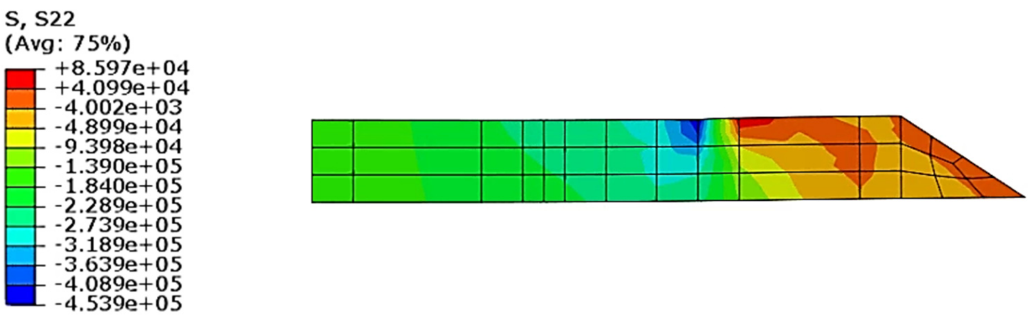

Figure 5. Vertical stresses, denoted as S_{22} [Pa], within the ballast layer, in a transverse cross-section (X-Y) aligned with the axle load.

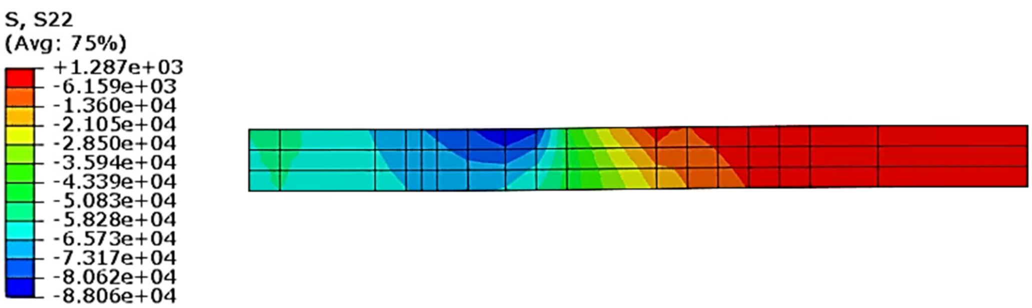

Figure 6. Vertical stresses, denoted as S_{22} [Pa], within the sub-ballast layer, in a transverse cross-section (X-Y) aligned with the axle load.

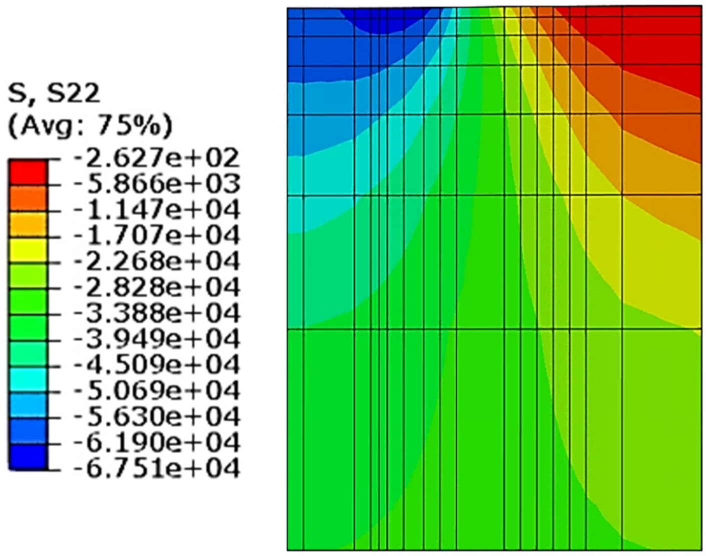

Figure 7. Vertical stresses, denoted as S_{22} [Pa], within the subgrade, in a transverse cross-section (X-Y) aligned with the axle load.

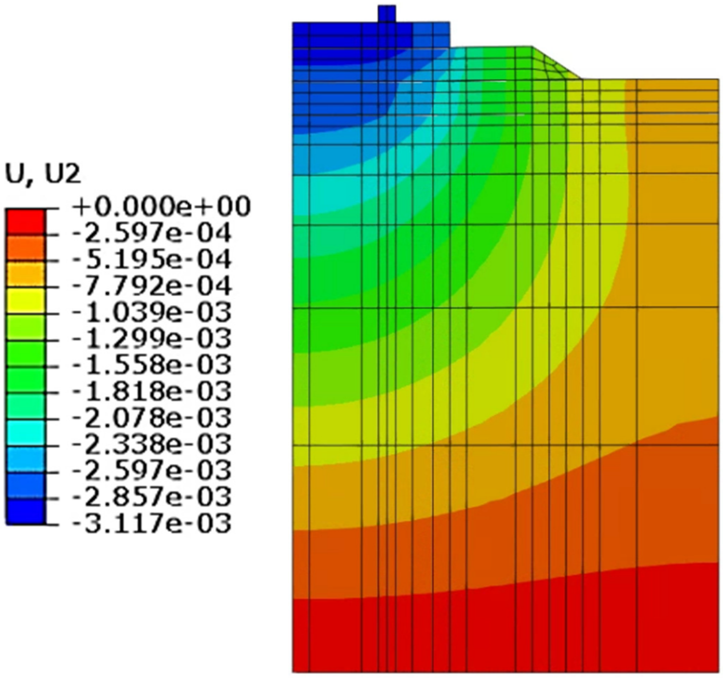

Figure 8. Vertical displacements, denoted as U_2 [m], in the track structure, in a transverse cross-section (X-Y) aligned with the axle load.

In terms of the results on the stresses and displacements obtained during the second calibration analysis, reasonable values were observed. Studies by Indraratna et al. [9] and Costa et al. [58] reported similar values, with vertical stresses around 280, 75, and 60 kPa at the sleeper–ballast, ballast–sub-ballast, and sub-ballast–subgrade interfaces, along with track vertical displacements of approximately 3 mm. The material characteristics and load conditions applied in the numerical model were also comparable with the field investigations and monitoring studies of Indraratna and Nimbalkar [25] and Wang and Markine [63]. The results on the stresses at the sleeper–ballast, ballast-sub–ballast and sub-ballast–subgrade interfaces and track displacements showed that the developed 2D modelling was effectively calibrated.

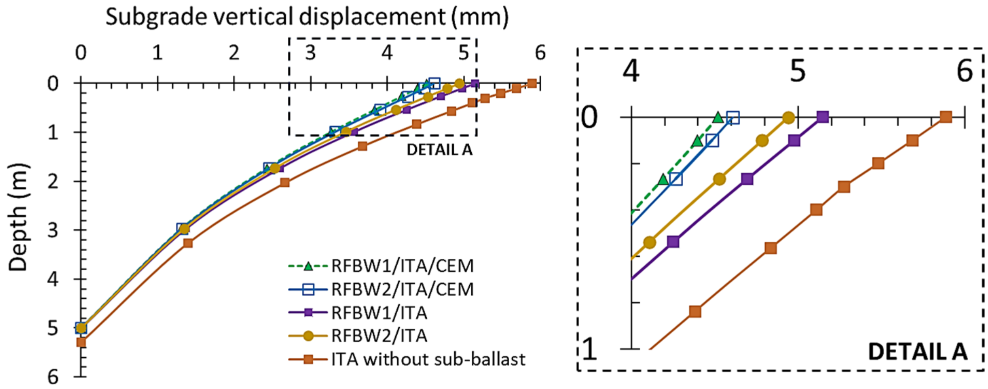

Figure 9. Displacements with depth in the subgrade (over 5 m depth).

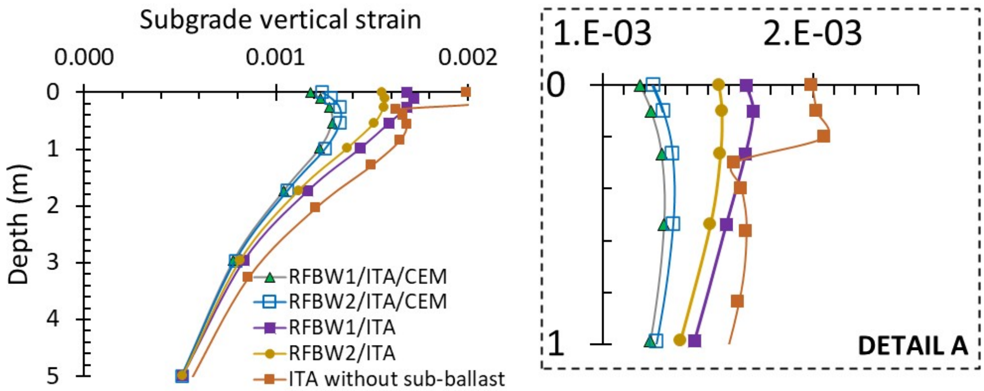

Figure 10. Peak strains with depth in the subgrade (over 5 m depth).

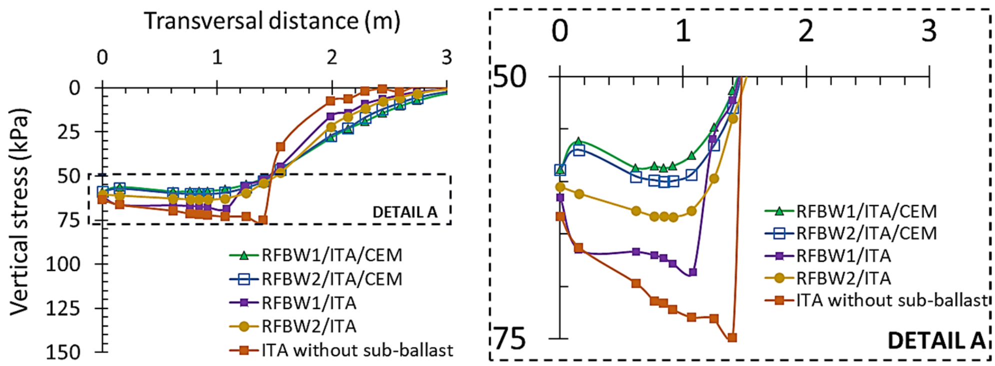

Figure 11. Peak stresses in the subgrade top at 5 m from the bottom vs. transversal distance.

Table 7. Summary of the vertical displacements (U_2), strains (ε_{22}), and stresses (S_{22}) for the Itapeti subgrade scenario.

Subgrade Scenario	Sub-Ballast Solution	Top of the Subgrade (Depth = 0 m)			Rail
		U_2	ε_{22}	S_{22}	U_2
		mm	%	kPa	mm
Itapeti soil	Itapeti soil without sub-ballast	5.9	0.199	72.2	6.5
	RFBW 1 + ITA	5.1	0.168	66.1	6.1
	RFBW 2 + ITA	4.9	0.155	62.6	5.7
	RFBW 1/ITA/CEM	4.5	0.118	57.8	5.1
	RFBW 2/ITA/CEM	4.6	0.124	59.1	5.2

Regarding the peak subgrade vertical displacements, it was noticed that the scenarios without stabilisation with RFBW and/or cement resulted in approximately 5.9 mm. However, these values decreased to 5.1 and 4.9 mm when stabilised solely with RFBW1 or RFBW2, respectively. This difference may be attributed to the higher amount of hematite and quartz in the RFBW2 material. The incorporation of 3% cement further reduced the displacements to 4.5 mm and 4.6 mm for RFBW1 and RFBW2, respectively. This reduction may be attributed to the more homogeneous mixture achieved with cement stabilisation.

These values align with the peak rail displacements, which corresponded to 6.5, 6.1, 5.7, 5.1 and 5.2 mm, for the same scenarios, respectively. The high displacement values observed can be attributed to the heavy haul operational conditions simulated, characterised by heavy axle loads. These conditions differ from the typical conditions found in Western Europe, where the axle loads are generally lower. Additionally, the relatively high dynamic amplification factor assumed, under the assumption of well-maintained track and trains, further contributed to these elevated displacement values.

In terms of strains, it can be noted that the vertical strain at the top of the subgrade decreased from 0.199% to 0.155% with the application of the sub-ballast layer stabilised with RFBW and to 0.118% with chemical stabilisation using 3% cement. Stabilisation with the RFBWs also contributed to a decrease in the vertical stresses at the top of the subgrade from 72.2 kPa to 66.1 and 62.6 kPa for RFBW1 and RFBW2, respectively. Further stress reduction is achieved with 3% cement stabilisation, resulting in stresses of 57.8 and 59.1 kPa for RFBW1 and RFBW2, respectively. These values align with the findings from Trevizo [64], Li [65], and Xu et al. [66].

It Is important to note that the scenario under evaluation assumed soft (highly deformable) subgrade soil. The significant influence of the subgrade on track displacements is widely acknowledged. To verify this assertion, further numerical simulations were conducted, substituting the soft Itapeti subgrade soil with a stiff SPAB subgrade soil. Figures 12–14, along with Table 8, illustrate the outcomes of the displacement, strain, and stress in the subgrade and rails when various sub-ballast alternative solutions with RFBW are applied over stiff subgrade soil.

The observed trends in the latter scenarios indicate lower track and subgrade displacements for all the investigated scenarios, as anticipated. The rail displacements reduced from 3.3 mm without a sub-ballast layer to 2.9 mm, with a sub-ballast stabilised using RFBWs and 3% cement. The difference between the values obtained for each material solution was also lower than in the last case. In other words, a higher load-bearing-capacity subgrade soil provides a stiffer foundation, which contributes to a better track mechanical performance, with or without sub-ballast gradation or chemical stabilisation. Consequently, the contribution of RFBW sub-ballast stabilisation proves more effective for soft track subgrade soils. In addition, the alternative RFBW solutions could decrease the strain values at the top of the subgrade from 0.074% to 0.070%.

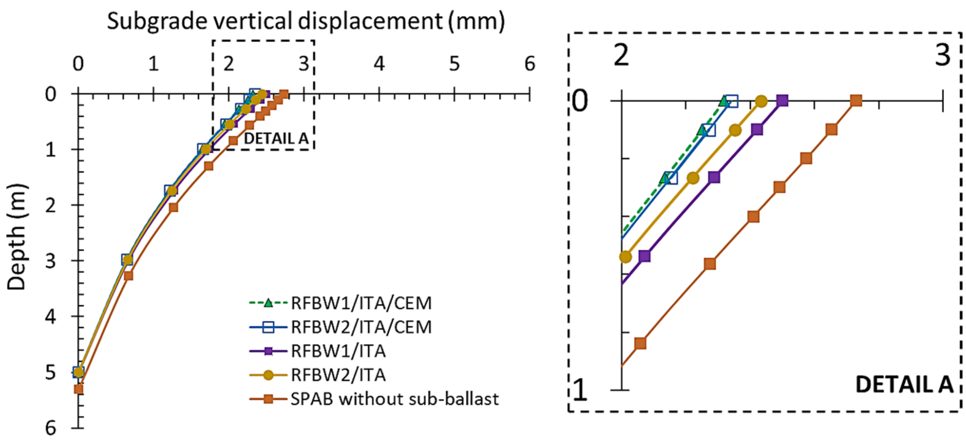

Figure 12. Displacements with depth in the subgrade (over 5 m depth).

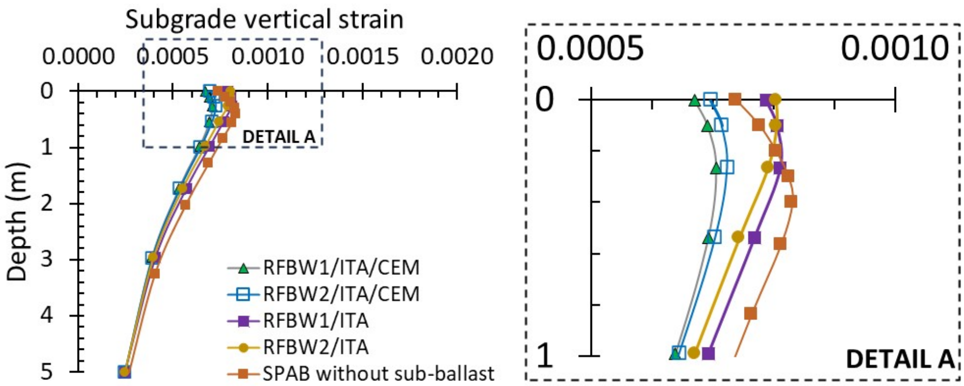

Figure 13. Peak strains with depth in the subgrade.

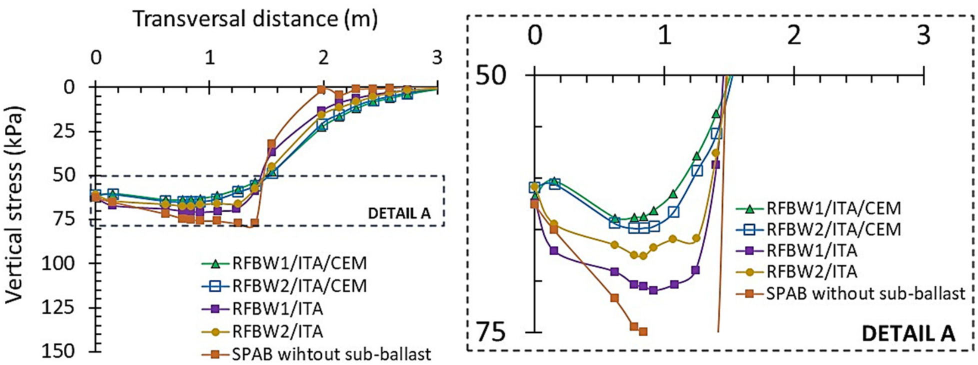

Figure 14. Peak stresses in the subgrade top at 5 m from the bottom vs. transversal distance.

Table 8. Summary of the vertical displacements (U_2), strains (ε_{22}), and stresses (S_{22}) for the SPAB subgrade scenario.

Subgrade Scenario	Sub-Ballast Solution	Top of the Subgrade			Rail
		U_2	ε_{22}	S_{22}	U_2
		mm	%	kPa	mm
SPAB soil	SPAB soil without sub-ballast	2.7	0.074	75.0	3.3
	RFBW 1 + ITA	2.5	0.079	70.5	3.4
	RFBW 2 + ITA	2.4	0.080	67.6	3.2
	RFBW 1/ITA/CEM	2.3	0.067	63.8	2.9
	RFBW 2/ITA/CEM	2.3	0.070	64.8	3.0

The resulting mixture demonstrated potential for use as sub-ballast, especially when stabilised with a low percentage of cement (3%). The use of cement can be advantageous mainly when there are not local materials meeting the specifications for the construction of a new sub-ballast layer and when the maintenance is being performed with a RMFRM which may not compact the sub-ballast layer efficiently.

In other words, utilising a small amount of cement can still offer greater sustainability compared to transporting suitable soils over long distances from quarries or deposits to the construction site. Additionally, alternative binders like lime, bio-binders, or bio-asphalts, as well as binders from reclaimed asphalt mixtures, present lower carbon CO_2 emissions during manufacturing and offer enhanced performance when applied in road and railway infrastructure [3,5,14,67].

The mixture potential is also attributed to the presence of stable minerals such as hematite, kaolinite, and goethite, which are relevant to sub-ballast layer applications, as reported by Castro et al. [20] and Guimarães et al. [38]. Additionally, the coarse grains contribute to a higher stability and stiffness and better interlocking within the material. The RFBW materials also demonstrated a potential to mitigate peak rail displacement, ensuring the limits of 6.35 mm set by AREMA [34] were not exceeded. The grain size distribution prescribed for the use of RMFR machinery ensured a better behaviour of the track structure as recommended and in agreement with the studies conducted by Schilder and Piereder [19], Auer et al. [22], Mundrey [23], and Fu et al. [42].

According to Mundrey [23], it is common to encounter poor subgrade conditions along railway tracks requiring extensive maintenance, such as replacing the sub-ballast material or constructing a new sub-ballast layer. However, soil deposits, aggregate stone crushing, or asphalt mixture plants are not always readily available to meet the demand in the field.

The results in this paper highlight the characteristics of alternative materials and the possibility of recycling and reusing degraded ballast from tracks mixed with local soils for subgrade rehabilitation. This can be accomplished using traditional earthwork machinery or advanced RMFRMs, thereby reducing environmental impacts and the costs for the railway operator. This alternative solution holds particular interest for heavy haul tracks transporting iron ore, as it has the potential to increase the load-bearing capacity of the track structure and influence the track modulus, thereby mitigating rail displacements. The developed modelling approach effectively captures the observed trends and results concerning stress, displacements, and strains, aligning with some studies found in the literature presenting track field monitoring, instrumentation data, and numerical modelling results, particularly on the stresses at the top of the subgrade and rail displacements [50].

Thus, despite the analysis being conducted in a plane strain state (2D), which neglected the stress and strain contributions from the components along the z-axis (the direction of the track), such as adjacent sleepers and the rail, the developed numerical model provided accurate insights into the mechanical behaviour of the railway track when applying a sub-ballast layer with RFBW alternative materials. These findings can assist in the design, construction, and maintenance of the track.

5. Conclusions

Mixtures incorporating RFBW material demonstrate significant potential for use as sub-ballast due to their mineralogical composition, including iron ore, kaolinite, and quartz. However, chemical stabilisation with 3% cement can further enhance the structural conditions of the track. However, the solutions proved to be more efficient for soft subgrade soil than on a stiffer soil foundation.

Despite the fact that the use of cement is not commonly sustainable, it may become more sustainable when there are no available materials near the construction site, which would otherwise demand higher carbon emissions from the dump trucks used to transport materials over long distances. In addition, cement may be replaced with different binders such as lime, bio-binders, bio-asphalts, or binders from reclaimed asphalt mixtures, considering the well-known lower carbon CO_2 emissions in their manufacture and reuse and the acceptable behaviour they provide when applied in pavements and railways.

The physical and chemical analyses of the RFBW material revealed its pre-dominant composition of quartz, albite, and hematite. This not only signifies the presence of iron ore but also indicates the presence of fine material resulting from the breakdown and wear of ballast particles.

The developed 2D numerical model effectively assesses the non-linear behaviour of these materials by applying parameters derived from laboratory cyclic triaxial tests for the ballast, sub-ballast, and subgrade with a lower computational cost than a 3D numerical model. The stress, strain, and displacement trends aligned well with the characteristics of the materials evaluated. The magnitudes of the stresses and displacements were considered realistic, despite not considering the rail longitudinally and adjacent sleepers using this numerical approach.

This study contributes to proposing alternative sub-ballast materials through the recycling and reuse of fouled ballast waste, focusing on more productive and efficient rehabilitation methods such as the use of RMFRM equipment. It could be concluded that the combined application of both solutions has a high potential to enhance the sustainability of railway transportation.

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