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Review Article

Roles and functions of asphalt sub-ballast in the modern maintenance of the European railways ☆

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ABSTRACT

The railway network is increasingly becoming central to the socio-economic development and the decarbonisation of transport, supporting its growth in compliance with the emission reduction targets set by the 2050 European Green Deal. Thus, several programmes for the major network renewals and the construction of safe, resilient and efficient high-speed lines have been implemented. In this scenario, some construction solutions have been introduced to enhance the durability and functionality of the railway infrastructure, particularly for the ballasted track one. Among these design techniques, the asphalt or bituminous sub-ballast has emerged as a proven technology capable of improving the railway performance and durability. Derived from the road construction approach, asphalt sub-ballast has been used in the European high-speed and high-capacity lines since the 1970s, providing both structural and functional benefits. This article offers a critical review of the current knowledge on the asphalt sub-ballast applications, highlighting its technical characteristics and long-term performances. Functional, structural and economic advantages have been assessed and analysed based on laboratory scale and on-field experiences. Experimental data indeed confirm the effectiveness of asphalt sub-ballast in improving the track stability and load distribution, in providing better water drainage and in reducing fatigue induced phenomena. These enhanced properties lead to lower maintenance costs and operations, particularly those related to ballast tamping, as well as to an extended service life of the whole infrastructure. From the circular economy perspective, the re-use or recycle of wastes and by-products in these mixes amplifies the cost-benefit ratio, also improving their sustainability.

Contents

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1. Introduction

Rail transport plays a key role in the overall policy of developing infrastructure and transport systems for sustainable mobility. It is once again at the centre of investment planning after the restrictions imposed on mass transit, including those applied during the Covid-19 pandemic, to promote economic and social cohesion, strengthen resilience and stimulate sustainable growth at European level (European Parliament, 2021). The environmental sustainability and climate neutrality objectives of the European Union's strategic initiatives by 2050, as outlined in the European Green Deal, assume that a significant part of the 75% of inland freight transport currently carried by road will have to be shifted to rail and inland waterways (European Commission, 2019). At the same time, the continental railways are moving towards maximum integration of existing systems and infrastructure, with major structural upgrades, increased safety in communications and greater reliability in asset management and maintenance planning. Increasingly complex and advanced infrastructure systems, such as railways, must therefore be inherently resilient in the face of expected future traffic growth and the inevitable exposure of linear works to exceptional catastrophic events. This can be achieved by adopting engineering solutions that can extend the service life and minimise the economic and environmental impact of maintenance interventions. Technological evolution in the rail vehicle sector has proceeded at different speeds, with exceptional acceleration for rolling stock, related control systems and traffic safety. The evolution is less obvious for the design and construction of the physical railway network, not only because of the lower technological content, but also for the caution with which large-scale construction and maintenance solutions for civil engineering works on the railway network can be reliably introduced. Several construction solutions, that have been introduced and widely adopted in recent decades, deserve a more thorough reassessment of the benefits they have brought to the durability and functionality of the railway infrastructure, particularly for ballasted tracks. These solutions include systems designed to improve the longevity of the railway infrastructure, involving both interventions in the superstructure, such use of elastic elements in the track (e.g. under sleeper pads and under ballast mats) or ballast stabilization (Prasad and Hussaini, 2022; Sol-Sánchez et al., 2015) and interventions aimed at enhancing the stability and load-bearing capacity of the substructure, such as the application of horizontal and vertical reinforcement elements (e.g. grouted micropiles) (Severino et al., 2022; Tiutkin et al., 2021, 2024).

Among these design solutions that have benefited the functionality of the track is the introduction of a sub-ballast layer in the track design. About the construction process and the position in the railway section, the sub-ballast is topologically identified as the top layer of the railway embankment or railway cutting. Their well cared densification and finishing characteristics are functional to form a regular and uniform ballast laying surface, having sufficient bearing capacity, offering stability to seasonal temperature variations and ensuring the most effective removal of rainwater (Bono et al., 1997). The sub-ballast for ordinary railway lines traditionally involves the use of dry aggregates adopting a mono-layer configuration, i.e., a mix of coarse to medium crushed aggregates and fine sand (mainly in England, Germany and Switzerland), or a dual-layer configuration, in which the crushed aggregates are placed at the bottom and a mix with a relevant content of fine sand (typically between 30% and 80% w/w) at the top (a very common solution in France) (Guerrieri, 2017). This sub-ballast design not only allows to ensure the hydraulic performances (effective drainage and proper moisture control), but also provides a better distribution of the stresses within the ballast, so much so that in simplified structural modelling, ballast and sub-ballast are often considered as a single layer having a Winkler elastic behaviour and a variable total thickness up to 90 cm (Kerr, 2000). The use of hydraulic binders to stabilize granular sub-ballast mixes has gradually been introduced, abandoning the use of entirely granular layers and often achieving some thickness reductions, to limit geometric defects and reduce maintenance costs (Bono et al., 1997). However, cemented sub-ballast mixes, which typically have a thickness of about 20 cm, are frequently affected by cracking phenomena and susceptibility to freeze-thaw cycles, which do not allow them to guarantee the expected service life of railways, especially for main and high-speed lines.

Derived from the road pavement technology and the related paving methods (EAPA, 2021; Teixeira et al., 2006), bituminous sub-ballast, also called asphalt sub-ballast, entered the European railway field with the first applications in Italy in 1970. Specifically, three pilot sections (total of about 20 km) with a double-track configuration and a design speed above

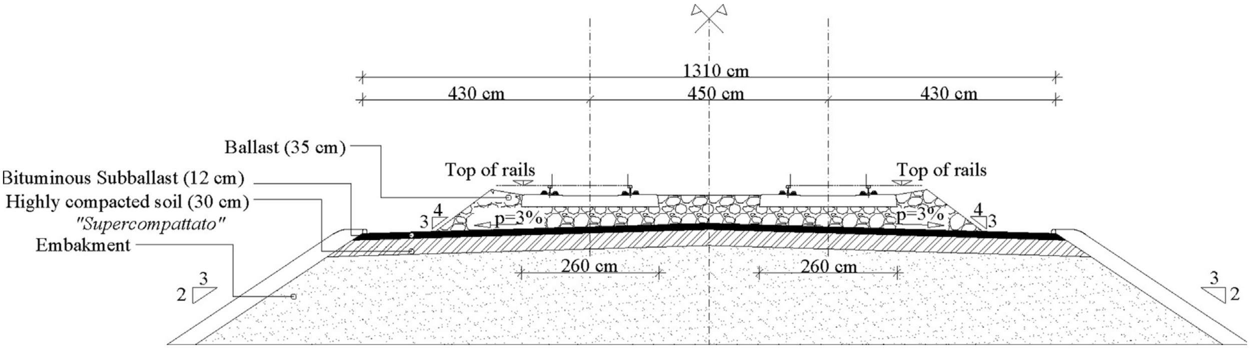

Fig. 1. Italian double-track standard section with introduction of asphalt sub-ballast layer (RFI, 2020b).

250 km/h were realized in the Italian "*Direttissima Roma – Firenze*" (Teixeira and López-Pita, 2005). Starting from the early 2000s, with the extensive construction of high speed (HS) / high capacity (HC) railway lines, the asphalt railway sub-ballast solution was adopted in new realizations (Buonanno and Mele, 2000) and became, just in Italy, the standard typological approach for the construction of about 1200 km of HS/HC lines and the planning of additional 400 km (Ramirez Cardona et al., 2020) (Fig. 1). Currently, the asphalt sub-ballast is the only type provided in the Italian specifications both for the new constructions and for ordinary and extraordinary maintenance of the existing lines (RFI, 2020a). The asphalt sub-ballast technology is also known as asphalt underlayment (AUL), particularly in the USA (Xiao et al., 2021). The use of bituminous binders in sub-ballast is not unique in the railway infrastructure panorama but has other applications in the superstructure to improve certain functional durability characteristics. These solutions include asphalt stabilised ballast (ASB), which is used to prevent water from entering the subgrade and damaging the railway, and asphalt impermeable layer (AIL), which stops silt pumping and moisture from affecting the railway infrastructure.

Focusing on bituminous sub-ballast, years of railway operation make now it possible to describe in this article a more comprehensive knowledge framework of this railway construction strategy. A summary of the solutions available at European level, the compositional and technical characteristics required by the specifications, as well as a review of the main advantages offered by the asphalt sub-ballast, is reported with the perspective of the advisability of adequately characterising this layer in the future, according to specific mechanical-functional performances, in a production process that is as sustainable as possible from an economic and environmental point of view.

2. Use and spread of asphalt sub-ballast in the European context

2.1. State of the practice and main functions

The "*Ferrovie dello Stato Italiane – FS*" (Italian State Railways), as already mentioned, was one of the first and most prolific users of asphalt sub-ballast. This layer, which is 12 cm thick, is placed on a significantly compacted soil surface no less than 30 cm thick having a high bearing capacity, known as "*supercompattato*" (Fig. 1).

The applications of asphalt sub-ballast in the European context are very limited, particularly in terms of the extent and significance of operational experience. Anyway, all these applications date back after the early 2000s (Fig. 2). In Austria, the pioneering application in Jauntal in 1963 (Veit, 2000), which also showed reduced maintenance requirements in the experimental section compared to classical solutions, has not been followed up. Small, well-instrumented and monitored sections can be found on the French and Spanish rail networks, according to the specifications of the *"Société Nationale des Chemins de fer Français – SNCF*" (National Company of the French Railways) (Blanc et al., 2022a) and the *"Administrador de Infraestructuras Ferroviarias – ADIF*" (Spanish Railway Infrastructure Administrator) (Rose et al., 2010a; Teixeira et al., 2010), respectively. The asphalt sub-ballast is also included in the overview made by the *"Office National des Chemins de Fer du Maroc – ONCF*" (Moroccan National Railways Office), for the first high-speed line Tangier – Kenitra in Morocco (about 200 km), which is in service since 2018. Specifically, the sub-ballast was composed of a specific asphalt mixture (*Grave Bitume 4*) in accordance with the French technical specifications (Ramirez Cardona et al., 2016). The French high-speed line has traditionally been built with 30 cm of ballast on 20 cm of granular sub-base, with an additional 50 cm of limestone aggregates. The SNCF also decided to include the asphalt sub-ballast in the catalogue of railway track pavements in the French technical specification "*IG 90260 – Conception et dimensionnement des plateformes ferroviaires nouvelles pour voie ballasteé*" (SNCF, 2018). This decision came after the first construction phase of the Eastern European high speed line Paris – Strasbourg (EE HSL) begun in 2004, in which excellent performances and reduced maintenance costs were observed and reported. At present, the French technical solution is used on about 500 km of railway lines (including the above-mentioned Moroccan HS line). After the success of the first HS line on the African continent, the ONCF is planning to extend this line from the northwest coast to Marrakech in the south (about 350 km of new tracks), probably using the same construction standards (UIC, 2023). In Spain,

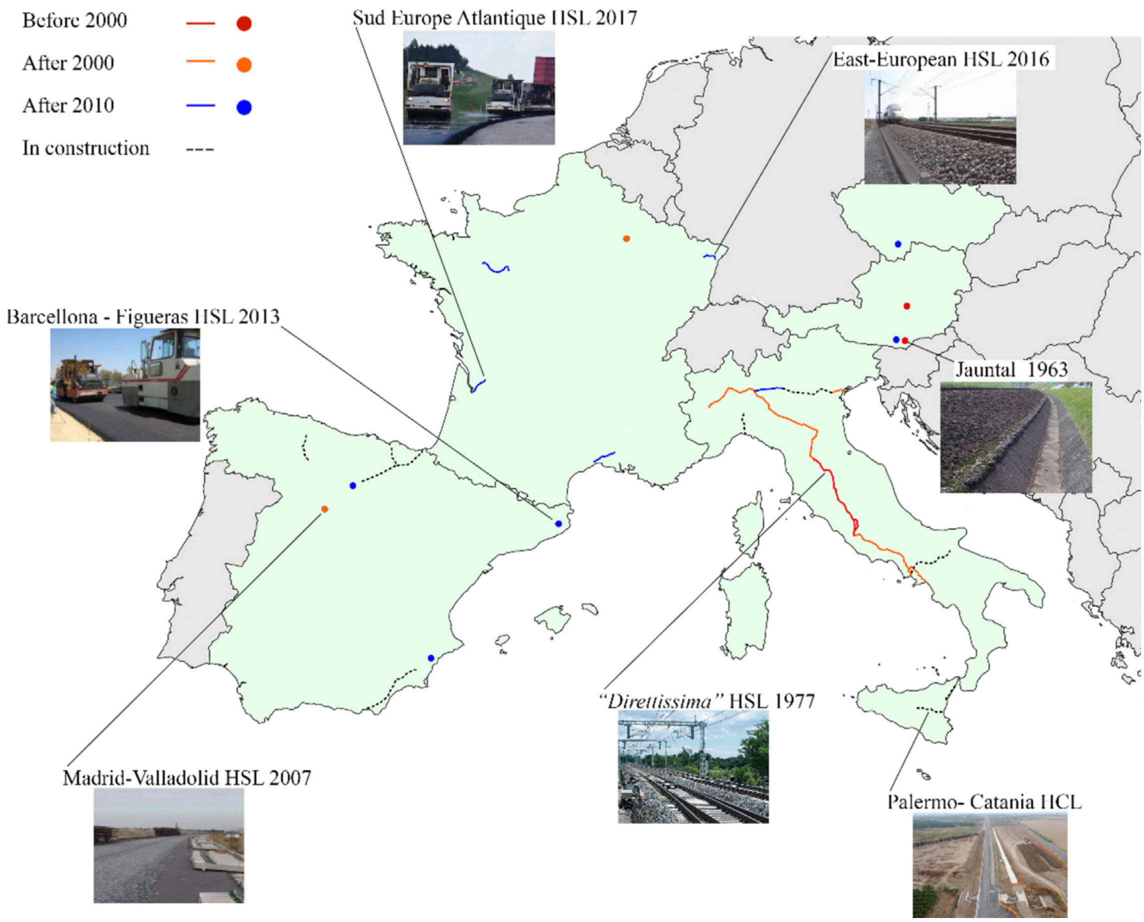

Fig. 2. Main applications of bituminous sub-ballast in the European context.

the first applications date back to 2007 on the Madrid – Valladolid line between Valdestillas and Río Duero. Other test sections have been realized, the largest of which is 10 km between Villodrigo and Villazopeque on the Valladolid – Burgos line (2015), leading to this technology as a possible solution for the more than 2,000 km of new HS lines to be built in Spain in the coming years (EAPA, 2021). Other very short applications, essentially experimental in nature, in the European context are documented in the Czech Republic and Austria (Holzfeind and Hummitzsch, 2009; Kucera et al., 2021; Veit, 2000).

The use of asphalt sub-ballast in Europe (Table 1) systematically falls within the broader functional typological framework of the general use of asphalt-based materials for the railway works (Fig. 3), also as a result of the important American (AREMA, 2017; Asphalt Institute, 2007; Fang et al., 2020; Rose, 2006) and Japanese (Momoya and Sekine, 2007; Railway Technical Research Institute, 2007; Rose et al., 2010a) experiences related to the improvement of the track quality of the HS/HC lines (Teixeira, 2009). The *"Union des transports publics de Suisse"* (Union of Swiss Public Transport) limits the use of asphalt for railway sub-ballast essentially to an impervious covering to inhibit vegetation growth (Union des transports publics de Suisse, 2015), using thinner layers than in other countries (Table 1). In Germany, asphalt mixes are introduced mainly in the logic of roadbed preparation and base layer creation for ballastless railway solutions, which are generally the locally preferred ones (Freudenstein, 2005; RailOne, 2012). These include Getrac, ATD, SATO and Walter systems, which differ in composition, function and application specifications to meet different structural, stability and drainage requirements. Further and more extensive applications of asphalt binders in railways can be documented in the United Kingdom (Bressi et al., 2018a; Fang et al., 2020) and are now very widespread in China (China railway ministry, 2008; Le et al., 2021; Umar et al., 2021), where their use is limited to ballast stabilization or as emulsion adhesion layer between the concrete roadbed and the track slab.

2.2. Composition of asphalt mixtures for railway sub-ballast layers

Asphalt mixtures, obtained by hot mixing asphalt binder with stone aggregates and fillers, have a traditional and well-established use in flexible road pavements. The design standards in the European railway field are largely based on the road experience, with considerable overlap in the formulation and mechanical evaluation of mixtures. No specific evaluation

Table 1
Main railway asphalt applications, compared to country of use.

Country	Case application (referred to Fig. 3)	Local name	Thickness (cm)	Bottom layer (cm)	Top layer (cm)	Function
Austria	Sub-ballast(a)	Asphaltdeckschicht	8–12	Subgrade	Ballast 30	Support, elasticity and protection from water and temperature effects
England	Ballast(d)	Bitumen stabilized ballast	25–30	Subgrade 10–15	/	Stabilisation and reduction of ballast degradation
France	Sub-ballast(b)	Grave bitume (GB3-GB4)	12–14	Subgrade 10–20 ($E_V \geq 80$ MPa)[1]	Ballast 30–32	Loads distribution and protection from water and temperature effects
Germany	Slab (ballastless)(c)	Asphaltdeckschicht (Getrac, ATD, SATO, Walter)	15–20	Base (HBL) 30 ($E_V \geq 120$ MPa)[2]	/	Assure the geometric conditions of the track, take up induced stresses and long-life cycles with minimum maintenance
			30–35	Base 60 ($E_V \geq 120$ MPa)[2]	/	Assure the geometric conditions of the track, take up induced stresses and long-life cycles with minimum maintenance
Italy	Sub-ballast(b)	Subballast in conglomerato bituminoso	12	Subgrade 30 ($E_V \geq$ 80 MPa)[3]	Ballast 35	Loads distribution and protection from water and temperature effects
Spain	Sub-ballast(b)	Subbalasto bituminoso	12–14	Subgrade 30–40 ($E_V \geq 80$ MPa)[3]	Ballast 35	Loads distribution and protection from water and temperature effects
Switzerland	Sub-ballast(b)	AC Rail + Granulato d'asfalto	7–10	Subgrade 25–40 ($E_V \geq 60$ MPa)[4]	Ballast 30–35	Barrier layer

E_v, strain modulus according to:
[1] Dynamic plate (*Dynaplaque* 1o 2) – NF P 94 117–2:2004.
[2] Plate load test – DIN 18134.
[3] Plate load test – CNR B.U. N.146/1992 – NLT-357.
[4] Plate load test – SN 670 317b.

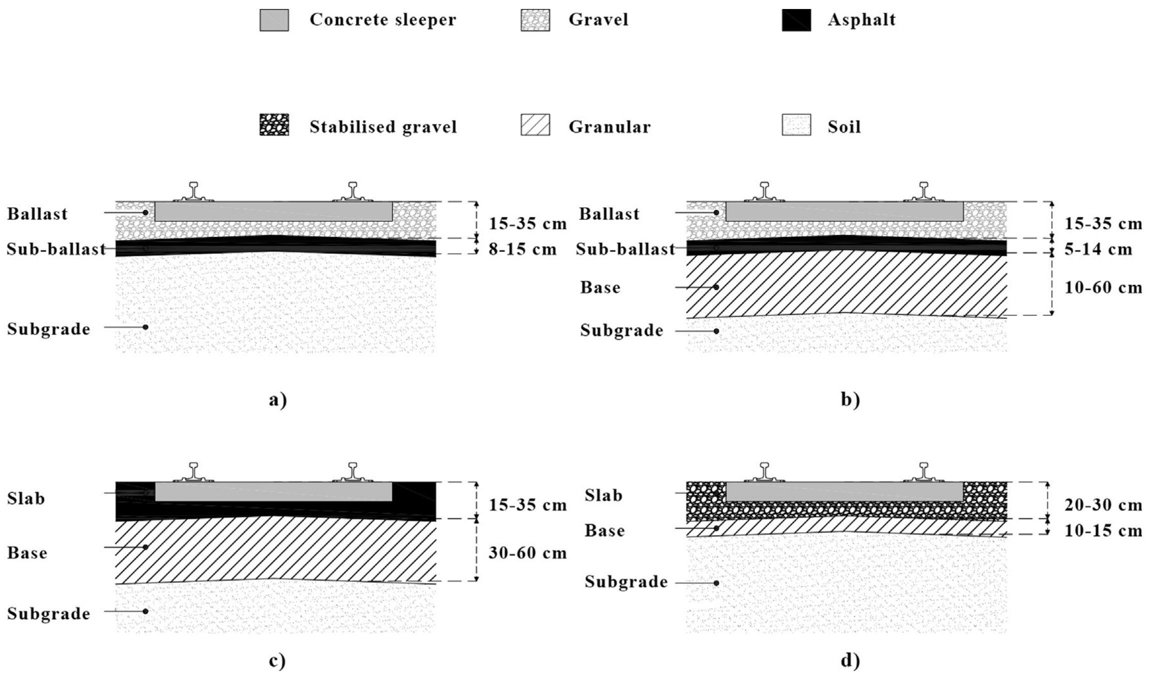

Fig. 3. Main uses of asphalt in railways.

parameters, that consider the substantial differences between road and rail operations in terms of loads type and distribution (type of ballast contact, intensity and frequency) and durability prospects, are recognized. The European standards and technical specifications are therefore derived from the established road experience. The mix design of the asphalt railway sub-ballast layer does not methodologically or quantitatively differ from that widely required for the binder and/or base lay-

Table 2
Aggregates grading for asphalt mixtures.

		Size (mm)														
		45	32	31.5	22	20	16	14	10	8	6.3	4	2	0.5	0.25	0.063
		Passing in mass (%)														
Italy		–	–	100	–	80–100	–	–	54–76	–	–	36–56	23–40	10–22	8–16	6–10
Spain	AC 22S	–	100	–	90–100	–	70–88	–	–	50–66	–	–	24–38	11–21	8–16	4.5–8
	AC 32S	100	90–100	–	–	–	68–82	–	–	48–63	–	–	24–38	11–21	8–16	4.5–8
France	GB4	–	–	–	–	100	–	92.4	58.8	–	43.8	–	32.2	–	12.6	6–8.5

ers of flexible road pavements but imposes a layer having thicknesses between 12 and 14 cm laid on granular subgrades characterised by a strain modulus (E_v), derived from plate load tests exceeding 80 MPa (ADIF, 2023; RFI, 2020a). Asphalt mixes shall be designed with a target combined aggregate particle size distribution (including filler) and binder content (Table 2). Although the Spanish standards propose two possible grading curves, the AC 22 S is preferred to reduce segregation during the paving process. Clean, hard, tough, durable and sound aggregates are required for bituminous sub-ballast. The considered standards define the performance parameters to be achieved, without specifying the type of aggregates to be used. However, based on the consolidated experience in the road sector, where recycled aggregates (Stimilli et al., 2017) or those derived from industrial waste and by-products such as steel slag (Autelitano and Giuliani, 2021; Sherwood, 2001) are often used in the circular economy perspective, the railway sector is gradually considering the use of these artificial materials. There are currently documented cases of steel slag being used for unbound or cement-bound sub-ballast (Alves et al., 2024; Autelitano and Giuliani, 2015; Chamling et al., 2022), suggesting a possible future application also in the asphalt ones. The asphalt binder is usually semi-hard, belonging to the 50/70 or 70/100 penetration grade. The optimum amount of asphalt binder must be between 4.1% and 4.8% of the weight of the aggregates (RFI, 2020a; SNCF, 2018), or more than 4.75% of the weight of the total mix (ADIF, 2023). In addition, a specific filler-to-binder ratio ranging from 1.5 to 2.0 and from 0.9 to 1.2 is recommended by the Italian and Spanish standards, respectively. Among the volumetric properties of the compacted mix, an air voids between 2% and 6% in specimens prepared using the impact compactor method (EN 12697–30) is required. In the case of mixes with a nominal maximum aggregate size greater than 22 mm, Spanish regulations require the use of a vibratory compactor (EN 12697–32), specifying an air voids content between 3% and 5%.

2.3. Mechanical properties of asphalt mixes for railway sub-ballast layer

Mechanical characterization of the mixes is carried out on specimens compacted according to the Marshall method. A Marshall stiffness, i.e., stability (minimum value of 10 kN) to flow (2 to 4 mm) ratio, greater than 2.5 kN/mm is essential. The Italian standards also require a minimum value of 0.8 MPa adopting the indirect tensile strength test (EN 12697-23) and an assessment of water sensitivity, prescribing a Marshall stability loss of less than 25%. The French and Spanish standards include the determination of the effect of saturation and accelerated conditioning in water (method A of EN 12697-12), demanding an indirect tensile strength ratio (ITSR) greater than 85%. A detailed overview of the physical and mechanical tests required by the technical specifications for the acceptance of asphalt mixtures for sub-ballast is given in Table 3.

2.4. Field experience

The implementation of the Bretagne-Pays de Loire HS line included a systematic comparison on an experimental basis between a conventional (unbound granular material on 77 km) and a bituminous sub-ballast (*Grave Bitume 4* on 105 km) along the line in service from 2017 (Fig. 4). More than one hundred sensors have been installed during the construction of the track and the dynamic responses of more than 60,000 train passages, at different speeds and under different environmental conditions, have been recorded (Blanc et al., 2022b). The study clearly showed that the use of an asphalt layer reduced the stresses induced in the subgrade and reduced the accelerations in the ballast, increasing the ballast stability and diminishing the deterioration induced by the mechanical wear. Furthermore, the horizontal deformations measured at the base of the bituminous layer resulted to be lower compared to those commonly recorded in the road infrastructures. These findings allow to revise the predictions of fatigue distresses in asphalt mixtures, which are more delayed than those expected from models designed for road traffic.

Studies carried out on the same railway line (Khairallah et al., 2020a) have shown that a bituminous sub-ballast is an effective way of protecting the subgrade layers from water infiltration, ensuring excellent watertightness. The presence of ballast, due to the nature and thickness of the gravel bed, exposes the bituminous sub-ballast to more limited temperature variations compared to the road scenario, which in turn makes the prediction of the mechanical behaviour of the mixes more stable over the seasons and the related climatic conditions. After 25 years in service of the bituminous sub-ballast installations in Italy, the track geometry has remained largely unchanged, especially at critical points such as transitions between structures, switches and joints. Furthermore, the excellent condition of the asphalt layer limited the maintenance needs, since the increase in the modulus of the subgrade has led to a reduction in the tensile stresses and, consequently, in the shear

Table 3
Mechanical characterisation of the bituminous mixture.

Type of test	Parameter	Standard	Italy	Spain	France
Marshall	Stability	EN 12697–34	≥ 10 kN	≥ 10 kN	/
	Flow		2–4 mm	2–4 mm	/
	Quotient		≥ 2.5 kN/mm	/	/
Indirect tensile strength	*ITS*	EN 12697–23	> 0.8 MPa	/	/
Water sensitivity	Loss of Marshall quotient	EN 12697–34	< 25%	/	/
	ITSR	EN 12697–12 Method A	/	≥ 85%	≥ 87%
	i/C ratio	EN 12697–12 Method B	/	/	0.70
Stiffness	Complex modulus	EN 12697–26 Annex A	[*1]	/	≥ 11,000 MPa
	$\|E^*\|$	EN 12697–26 Annex C		3,700–7,100 MPa	/
Cyclic compression	Permanent deformation	EN 12697–25	[*2]	/	/
Resistance to fatigue	ε_6	EN 12697–24 Annex A	/	> 120 µm/m	/
		EN 12697–24 Annex D	/	/	> 120 µm/m

[*1] $|E^*|$ @20° C and @30° C and f = 10 Hz. No minimum values have been specified.

[*2] Permanent deformation at f = 10 Hz, 2 bar sinusoidal vertical pressure amplitude, @30° C and 1.5 bar lateral pressure. No minimum values have been specified.

stresses in the ballast, reducing the degradation and wear of the stone elements (Buonanno and Mele, 2000). Exactly regarding these aspects, a Spanish study (Teixeira and López-Pita, 2005) presents, using a qualitative approach, a series of advantages derived from the introduction of a bituminous sub-ballast layer in the track in terms of reliability, service life and maintenance requirements, even assuming a higher initial construction cost with respect to the traditional unbound granular material.

3. Expected benefits from the use of asphalt railway sub-ballast

The distinction between functional and structural benefits of the railway sub-ballast is a purely descriptive licence for simplification and representation of the practical and constructional concepts related to the design and management of the railway superstructure and substructure. It is important to remember that degradation or loss of sub-ballast functions typically leads to constitutive weaknesses and increased stresses in the subgrade, which can have significant structural implications for the subgrade itself and the track. Conversely, even localised structural damage or deterioration can compromise the expected functionality of the sub-ballast, raising concerns about the expected benefits in terms of both cost and service regularity.

3.1. Functional benefits

The selection of a bituminous sub-ballast layer presents potential benefits, including improvements to the phenomena that trigger and contribute to the rail fouling (Bruzek et al., 2016; Touqan et al., 2020). Regarding the ballast saturation and fouling, several authors have conducted extensive research, identifying the underlying causes (Nguyen et al., 2019). The dust and, consequently, mud slurry can originate from external sources (fines and waste) and from the breakage and/or abrasion of the ballast crushed stone elements. Additionally, the degradation and infiltration of filter and subgrade layers may be a contributing factor of fouling, though this is dependent on the geographical and morphological characteristics of the regions traversed by the railway (flood plains or cutting sections) and on the amount of fine generated and/or migrated through the granular ballast. Nevertheless, the detection of fouling is typically indirect, occurring in conjunction with the initial track anomalies identified by diagnostic trains or as part of routine visual inspections of vegetation growth in the ballast. The most recent ground-penetrating radar (GPR) systems are particularly relevant for monitoring the ballast and diagnosing phenomena, with the ability to quantify the depth and extent of fouling anomalies that reduce the first reflection of the signal (Bianchini Ciampoli et al., 2019). Thus, the sub-ballast represents an inner source of fine causing the ballast fouling and contributes to the mechanism of internal erosion and fluidisation of the mud slurry produced by the same material until it comes into contact with water. The sub-ballast has a role that should be further emphasised as a regulator of the fouling phenomenon. The construction of a substantially impermeable bituminous sub-ballast would make solutions involving capping layers with geogrids, which contribute to the reduction of mud migration, less necessary (Nguyen et al., 2019). Furthermore, it would permit the layer to attain a superior mechanical and, consequently, geometric stability by preventing the formation of water stagnations, which are frequently obscured by the tamping of the ballast. The bituminous sub-ballast has also an effective hydraulic protection function, allowing, as envisaged in the Italian railway network (RFI, 2020a), a

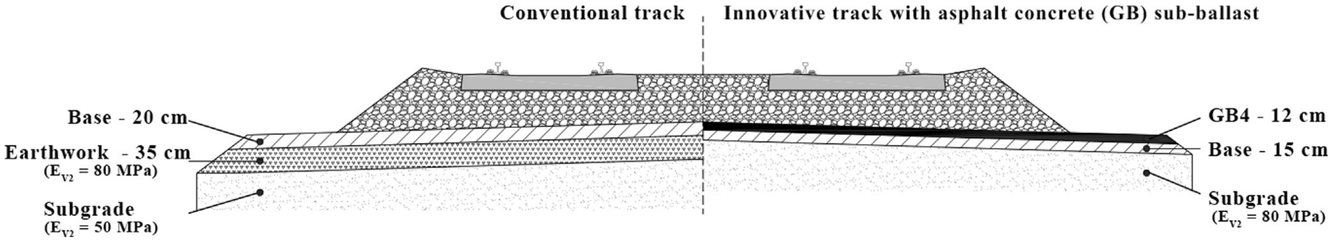

Fig. 4. Different structures of the Bretagne-Pays de Loire HSL.

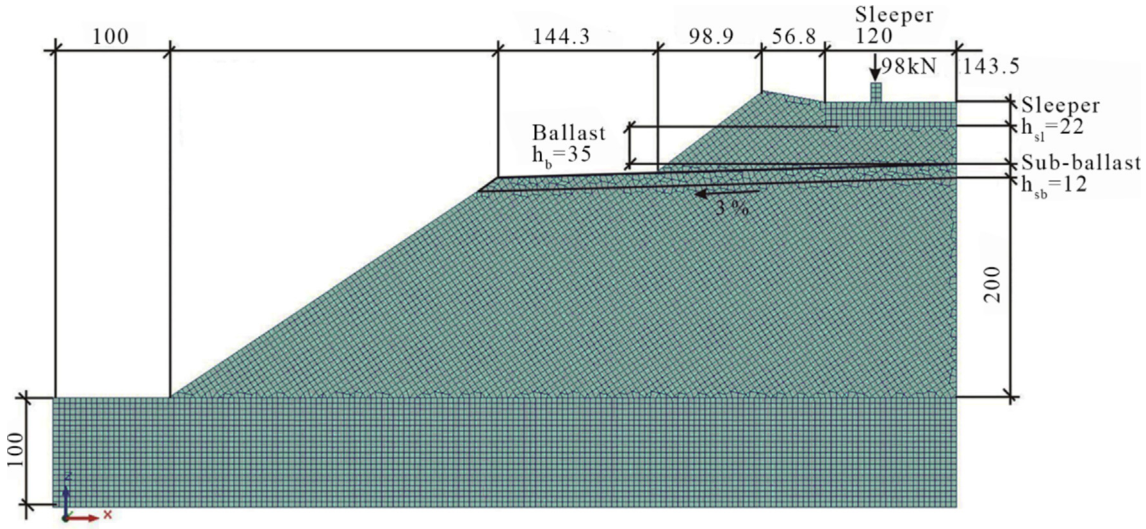

Fig. 5. Finite Element Model. All measurements are given in cm.

Table 4
Geometric properties and maximum vertical stresses.

Case	Rail		Sleepers		Ballast		Sub-ballast		Subgrade		σ_z (MPa)	
	h (cm)	*E* (MPa)	*h* (cm)	*E* (MPa)	*h* (cm)	*E* (MPa)	*h* (cm)	*E* (MPa)	*h* (cm)	*E* (MPa)	Top of sub-ballast	Top of subgrade
1A	17.2	210,000	22	40,000	35	100	12	9,000	30	80	0.43	0.19
2A	17.2	210,000	22	40,000	35	100	/		30	80	/	0.32
2B	17.2	210,000	22	40,000	35	100			30	200	/	0.34

reduction in the transverse slope of the ballast laying surface from the standard 3.5% intended for granular or cemented mixes (or 5% for granular-only layers in Spain) to 3.0%. This construction option, which is justified by the greater ease of rainwater runoff and by the sealing of the intergranular voids, provides a greater protection of the subgrade from frost and seasonal hygrometric variations (Teixeira et al., 2010). One of the most significant functional improvements is the greater stability and regularity that a bituminous sub-ballast can provide on a railway construction site. More efficient accommodation of ballast laying or tamping machines is ensured, making use of the extensive know-how and paving equipment derived from road construction. A traditional sub-ballast is susceptible to greater exposure to local climatic variations and potential deterioration in surface finishing due to the passage of construction machines. In contrast, an asphalt layer is relatively easy to lay, drawing on the consolidated experience of road construction and the possibility of using techniques that enhance the workability even at lower temperatures, due to the distance from production sites or the prevailing climatic conditions (Giuliani and Merusi, 2009).

3.2. Structural benefit

Several studies in the literature (Castro et al., 2022; Fang et al., 2013; Hashemian et al., 2023; Mpye and Gräbe, 2021) present structural analyses aimed at estimating the extent of stresses transmitted to the subgrade by the passage of a train in a specific and non-aggregated form, with a focus on the type and stiffness of the individual track parameters. Researchers (Rose et al., 2010b) have identified that geometric quality of the track and the stiffness of the railway platform are the most sensitive parameters, i.e., those whose defect leads to the greatest degree of variation in the stress level on the subgrade while maintaining the same bearing capacity. During the preliminary studies for the construction of the new Madrid – Barcelona HS line, comparisons were drawn, and structural equivalences were sought between traditional sub-ballast and asphalt sub-ballast. It was observed that equivalent subgrade stress levels could potentially be achieved with 30 cm of granular mix and approximately 12–14 cm of asphalt mixture. The results of parametric analyses conducted with the KENTRACK software (Rose et al., 2003) indicate that the introduction of a bituminous layer results in an improvement in the fatigue life of the subgrade, with the benefit being more dependent on the thickness of the layer than on the dynamic modulus value of the used asphalt mix. The use of numerical modelling is an effective tool for analysing the stress state in the sub-ballast. A two-dimensional (2D) finite element analysis was carried out on a railway section with a 35 cm thick ballast layer on a 12 cm thick asphalt sub-ballast layer (Fig. 5), which is in turn placed on a granular subgrade having a modulus of elasticity of

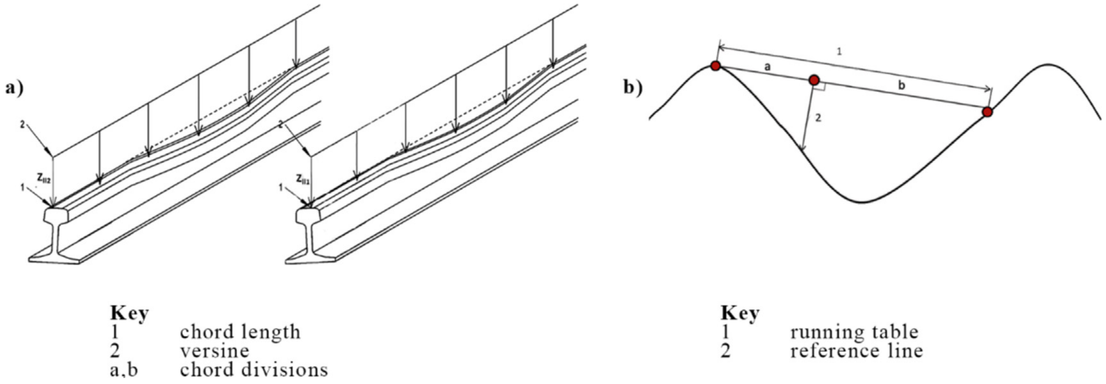

Fig. 6. Measuring longitudinal level: a) longitudinal defect (EN 13848-1); b) versine system (EN 13848-3).

80 MPa. The properties of the modelled section are given in Table 4. Using a load of 98 kN, corresponding to a 20-tonne axle wheel (category C according to EN 15528), the vertical stresses acting on the subgrade were analysed. Two scenarios were compared: presence of asphalt sub-ballast layer (case 1A) and ballast placed directly on the subgrade. For the latter case, the modulus of elasticity of the sub-base was varied according to two hypotheses, i.e., 80 MPa (case 2A) and 200 MPa (case 2B). The sub-ballast is in a complex three-dimensional stress state characterised by the presence of compressive, tensile and shear stresses. This behaviour is determined by the transverse slope (3%), which creates different stress conditions in the material, resulting in a variation of stress states between the different sections. The asphalt layer allows a more homogeneous distribution of loads on the subgrade, optimising the transfer of stresses to the lower layers and reducing the stress concentration. This effect significantly improves the mechanical performance of the structure, contributing to greater stability and durability of the system (Table 4). These results are in line and comparable with those obtained by analytical methods based on the Burmister theory, considering the operating conditions planned for the "*Direttissima*" (Celard et al., 1976). Since bitumen is a viscoelastic material, whose properties are strongly thermo-dependent, the analytical models should implement these features to better simulate the real behavior of the mixture at various temperatures. For example, the Huet-Sayegh model, which includes an elastic branch in parallel with two parabolic dampers in series with another elastic branch. Specifically, this model has been integrated into the specific design software ViscoRail and has already been used to analyse deformations and stresses under repeated loading, respecting changes in stiffness due to seasonal and climatic changes (Khairallah et al., 2020b). The load transfer through the sleepers is treated as a system of load waves propagating through the different layers of the substructure. Each dynamic load generated by the passage of a train is divided into waves propagating through the medium and the response of the structure is calculated in a moving coordinate system associated with the movements of the train itself. A thermo-hydro-mechanical analysis allows the accumulated permanent deformations to be considered, with the stiffness of the layers dynamically adapting to thermal conditions and seasonal variations (Ferreira et al., 2011). All the analytical models highlight the important structural role of the sub-ballast, which helps to reduce and distribute more evenly the stresses (σ_z) transmitted to the road body, thus limiting differential settlements. In this case, the presence of the asphalt sub-ballast induces a 44% reduction in the stresses transmitted to the subgrade. This effect leads to improved operating conditions and greater durability of the entire infrastructure.

3.3. Economic and environmental sustainability

An accurate evaluation on the use of a bituminous layer below the ballast cannot ignore its economic sustainability. The impact of this solution on the railway structure and provide a rationale for its potential use in comparison to conventional solutions (unbound granular material) are essential properties to assess. In examining the financial aspects of the project, it is important to note that the paving equipment and construction techniques are the same adopted for the road installations. When considering the cost of the materials, the initial higher cost related to the bituminous binder is partially offset by the reduction in the overall layer thickness, which in turn leads to a corresponding decrease in the amount of high-quality stone

Table 5
Limits for corrective operation.

Parameter	Conventional	High Speed	
	Reference value	Reference value	Isolated defect*
Longitudinal defect	± 5.0 mm	± 2.5 mm	± 5.0 mm

* Part of the signal exceeding a given limit with at least one sample for a sampling distance of 0.25 *m*.

Table 6
Longitudinal defects –maximum values and limit of standard deviation.

Speed [km/h]	Immediate Action Limit [mm]	Limit value of standard deviation [mm]				
		A	B	C	D	E
v ≤ 80	28	< 1.25	1.75	2.75	3.75	> 3.75
80 < v ≤ 120	26	< 0.75	1.10	1.80	2.50	> 2.50
120 < v ≤ 160	23	< 0.65	0.85	1.40	1.85	> 1.85
160 < v ≤ 230	20	< 0.60	0.75	1.15	1.60	> 1.60
230 < v ≤ 300	16	< 0.40	0.55	0.85	1.15	> 1.15
v > 300	14	N.A.	N.A.	N.A.	N.A.	N.A.

Considering that speeds higher than 300 km/h were not taken into account in the ETQ survey, no value can be provided for this range.

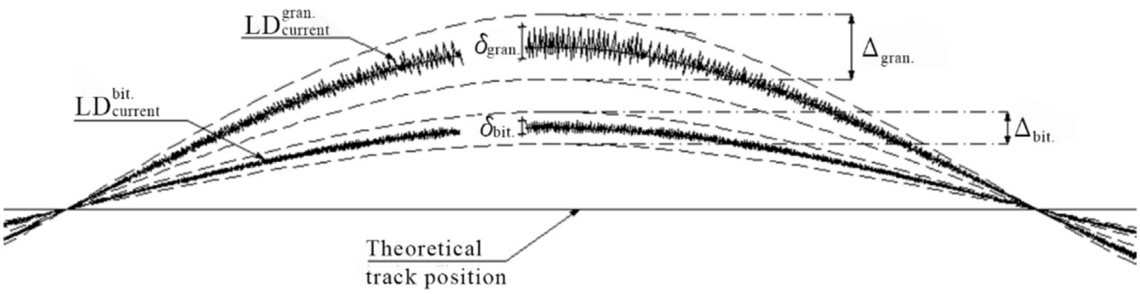

Fig. 7. Register for longitudinal defects: Granular vs. bituminous (Ferreira et al., 2009).

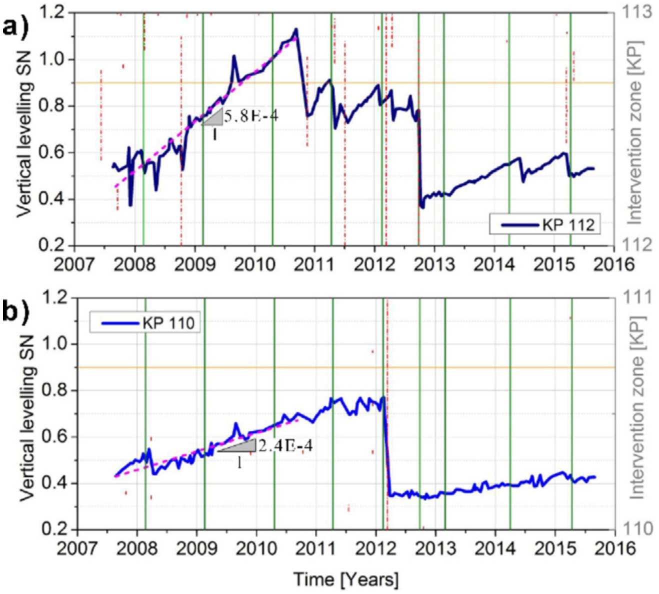

Fig. 8. Vertical levelling, variation over time: a) conventional track structure; b) structure with bituminous (Ramirez Cardona et al., 2016).

aggregates. The lower transverse slope of the bituminous sub-ballast (3%) results in a notable reduction in the volume of processed materials to approximately 200 m^3/km/track. This value corresponds to approximately 5% of the bituminous layer cost (Teixeira et al., 2010).

3.3.1. Ballast tamping interval

The inherent degradation of a railway line requires the implementation of maintenance activities by the infrastructure manager to control the level of degradation and ensure the safety and reliability of the overall line in service. Innovative way-side monitoring technologies and machine vision-based systems, possibly integrated with artificial intelligence algorithms, are particularly useful for identifying possible degradation phenomena, facilitating the transition to a predictive

Fig. 9. Sub-ballast layer: Italian line after 20 years of service life in perfect conditions.

maintenance approach (Bianchi et al., 2024, 2025; Kumar and Harsha, 2024). The measurement of specific geometric parameters (track gauge, longitudinal level, cross level, alignment, twist) enables the identification of representative indicators of the ballasted track quality condition. Among the track quality indexes (TQIs), the standard deviation (SD) is a reliable measure of the defect magnitude (EN 13848–6). Whenever it exceeds a defined threshold, suitable maintenance actions, such as ballast tamping, are implemented with the purpose of restoring the infrastructure to an optimal condition. The longitudinal defect, i.e., the deviation z_{II} in z-direction of running table levels on any rail from the smoothed vertical position, reference line, expressed in defined wavelength ranges (Fig. 6a), is known to be the factor that determines the extent of the need for mechanical tamping of the tracks due to the excessive compaction of the ballast caused by normal operation over time. The unbound nature of the ballast determines an initial compaction after the construction phase and a subsequent compaction due to the progressive degradation of the ballast elements (D'Angelo et al., 2018), whose dust contributes to approximately 70% of the ballast fouling (Huang et al., 2009). The measurement of the longitudinal defect can be carried out with either inertial or versine systems: the track geometry is obtained from the offset measured at an intermediate point from a straight-line chord (Fig. 6b). The offset is measured either by mechanical sensors (trolleys or rollers) or by non-contact sensors (EN 13848-3). The SNCF gives the values shown in Table 5 as limits for longitudinal defects, diversified according to the type of line (conventional or high-speed) (Ferreira et al., 2009). These values are generally determined by diagnostic trains, which measure, among other quantities, the longitudinal defect according to a 10 m measurement base. The immediate action limit (IAL) and standard deviation of the longitudinal defects are listed below in Table 6. The standard deviation is based on the cumulative distribution of the weighted average of all the networks participating in the European track quality (ETQ) survey performed in 2010. The five track quality classes are:

- Class A – best 10% of the distribution of ETQ
- Class B – between 10% and 30% of the distribution of ETQ
- Class C – between 30% and 70% of the distribution of ETQ
- Class D – between 70% and 90% of the distribution of ETQ
- Class E – above 90% between 10% and 30% of the distribution of ETQ

The use of asphalt in the sub-ballast layer can effectively reduce maintenance requirements. A 50% reduction in the amount of displacement and annual amplitude has been estimated for defects in the longitudinal layer (Ferreira et al., 2009). Assuming $LD^{gran.}_{current}$ the value of the longitudinal defect for a granular sub-ballast and $\Delta_{gran.}$ its seasonal amplitude, the corresponding values for a bituminous sub-ballast would be halved ($LD^{bit.}_{current} = 0.5 \cdot LD^{gran.}_{current}$ and $\Delta_{bit.} = 0.5 \cdot \Delta_{gran.}$). Reducing the longitudinal level would therefore reduce the longitudinal deflection values and consequently increase the period during which tamping is not required (Fig. 7). In the experimental section of the HSL EE Paris – Strasbourg, a comparison was made between two adjacent sections, one conventional and one with a bituminous sub-ballast, by measuring the standard deviation of the longitudinal level (Ramirez Cardona et al., 2016). Fig. 8 illustrates the two degradation profiles from

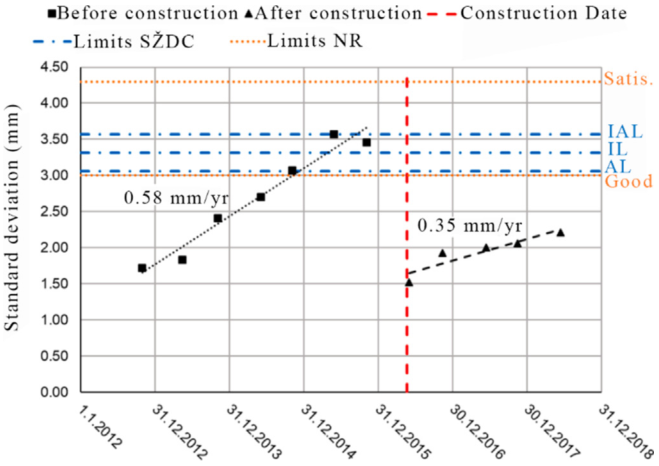

Fig. 10. Evolution of the standard deviation of the track top of the Štáhlav trial section (Kucera et al., 2021).

2007 to 2016. The green continuous vertical lines represent the grinding interventions, while the red dashed lines display the tamping ones. The initial intervention, which was required to remove the surface defects, was conducted with the objective of preventing the formation of short-wavelength defects on the rail surface. Consequently, it was carried out simultaneously in the two adjacent sections. As far as tamping is concerned, 10 maintenance operations have been performed on the conventional track since 2007, while only one tamping operation resulted to be necessary on the section with bituminous sub-ballast over the eight years. This is in accordance with the threshold value of the standard deviation, which was set at 0.9. The slope of the degradation curve represents a highly relevant parameter for the study of defect evolution and for the calibration of predictive maintenance tools. The slope of the curve in the case of the section in bituminous sub-ballast, calculated by linearly adjusting the values of the standard deviation of the first three years, was found to be 37.5% lower than that of the solution with sub-ballast in unbound granular material. In contrast to the traditional track, it can be observed that following the tamping operation, the initial quality is fully recovered, and the degradation rate is close to zero, with the rapid achievement of the optimal arrangement of the overlying ballast. Considering the planned preventive maintenance, which is intended to facilitate more efficient service operations and enhance economic efficiency (Khajehei et al., 2020), the bituminous sub-ballast has the advantage of extending maintenance intervals, as the evidence of degradation is significantly delayed. Studies conducted in Sweden have indicated an increase in time between tamping operations equal to 1.5 to 5 times with respect to traditional unbound sub-ballast (Sàrik, 2018). In addition to the overall cost reduction resulting from a decrease in the number of maintenance operations, there are additional and related economic advantages deriving from a reduced frequency of temporary track closures and increase in the expected service life of the infrastructure. Indeed, the ballast renewal operation is also scheduled, on the basis of the performed tamping operations. It has been demonstrated that higher tamping intervals result in an extension of the ballast's service life. The ballast renewal operation is significantly simplified by the presence of the bituminous sub-ballast, which, if properly designed and constructed, provides an ideal surface for the mechanical shovels to operate on, resulting in reduced damage and increased hourly production rates (Fig. 9). In consideration of the aforementioned factors, the initial investment required for a bituminous layer, in comparison to traditional unbound granular materials, is offset by a notable reduction in maintenance frequency and costs over an extended period. The use of asphalt surfacing has been demonstrated to reduce the rate of deterioration by approximately 33% in comparison to conventional unbound granular materials. This results in a longer interval between maintenance operations, such as levelling and tamping, of 3 to 5 years, which ultimately increases the useful life of the infrastructure by 17% (Holzfeind and Hummitzsch, 2009). These longer intervals and reduced degradation directly contribute to optimising economic efficiency and simplifying ballast renewal operations, further underlining the benefits of using bituminous sub-ballast layers in the design of modern rail infrastructure.

3.3.2. Innovative developments and sub-ballast life cycle

From a technical and economic point of view, the asphalt sub-ballast can also incorporate many of the formulation advancements that have been developed in recent years for the sustainable re-use and environmental upgrading of asphalt road pavements into the railway construction processes. From the circular economy perspective, the most significant experience relates on the one hand to the addition of crumb rubber (CR) from end-of-life tyres and on the other hand to the incorporation of reclaimed asphalt pavement (RAP) from the demolition of old pavements or the recycling of industrial wastes and by-products (e.g. artificial aggregates derived from slags) (Bressi et al., 2018b; Hashemian et al., 2023; Li et al., 2016). The CR in asphalt mixture, as well as road applications, it has also proved to be a good technology for the railway's context, especially for the sub-ballast layer. The feasibility and potential benefits of using a high-performance asphalt mix produced with a high rubberised low penetration bitumen for sub-ballast in railway tracks has been evaluated to improve the properties of the mix in terms of durability and fatigue strength (Castillo-Mingorance et al., 2021). The fatigue life of the CR modified mixes (20% CR modified bitumen) was found to be approximately 7.2 times that of the unmodified mixes. In addition, reducing the air void content from 4% to 2% by increasing the binder was found to extend the fatigue life by up to 18.2 times (Asgharzadeh et al., 2018). Numerical analyses simulating the stresses due to traffic and average seasonal temperatures revealed that CR asphalt sub-ballast is particularly suitable for obtaining a more rigid and elastic layer, leading to reductions of rail track vibration damping (Martinez Soto and Di Mino, 2018). However, a life-cycle assessment study has highlighted how CR mix is not more environmentally sustainable than the conventional mixes (Bressi et al., 2018b).

The use of recycled materials and innovative technologies is key to reducing environmental impact and improving resource efficiency in the current search for sustainable solutions for railway infrastructure. Although there are no specific standards for their use in railway infrastructure, some laboratory studies and experimental applications have been carried out in the last decade. Kucera et al. evaluated a 100% RAP mix for a sub-ballast in a lab scale, obtaining promising results in terms of reducing permanent deflection after 500,000 cycles (Kucera et al., 2021). Subsequently, a trial test section was built along the Pilsen – Česke Budějovice (Czech Republic) railway line, near Štáhlav, in 2016 to test the long-term behaviour of the analysed mixture. However, due to technological limitations of the production plant, the applied mixture contained 80% RAP. The longitudinal and relative standard deviations (SDs) of the track section were measured to monitor the long-term effects. As shown in Fig. 10, the longitudinal defect SD linearly grew of approximately 0.58 mm/year prior to the start of the study, reaching the alarm threshold according to the criteria of the National Railway Infrastructure of the Czech Republic (SŽDC) in 2014. After the track geometry was restored and the new asphalt sub-ballast layer installed, the SD was reduced to 0.35 mm/year. An Italian study performed laboratory analyses according to the national specifications for asphalt mixture design, testing mixtures containing RAP aggregates. The results showed that a 30% RAP content increased the Marshall stability and indirect tensile strength of the mix. In addition, fatigue tests showed an increase in stiffness modulus, which positively correlated with increased durability of the material (Fiore et al., 2023). In parallel, numerical simulations on the use of RAP in railway sub-ballast, analysing different percentages and thicknesses, were carried out. The simulations showed that 100% RAP sub-ballast layers 20 cm thick can improve the stiffness of the railway platform compared to a traditional layer of unbound granular material, reducing sleeper settlement and tensile stresses at the base of the sub-ballast by approximately 40% (Hashemian et al., 2023). A life-cycle assessment (Bressi et al., 2018b) from the resource extraction to the transport to the construction site, passing by the material production, revealed that RAP asphalt mixtures are sustainable solutions, possibly even using rejuvenating additives to improve the mix workability and reduce the use of virgin binder content (Pradhan and Sahoo, 2022).

4. Conclusions

The use of asphalt sub-ballast in the railway construction is a well-established solution that offers significant functional, structural and economic advantages, with an excellent cost-benefit ratio. Derived from the road pavement technology and the related paving methods, bituminous sub-ballast entered the European railway field with the first applications in Italy dating back to the 1970s. Based on the Italian experience and on experimental findings derived from laboratory scale and trial sections experiences, this technology is spreading in several countries, where this construction technique has been included as a design solution in the forthcoming high-speed and high-capacity rail network extensions. Experimental data indeed confirm its effectiveness in improving the track stability, reducing maintenance costs and extending the life of the railway infrastructure. Functionally, asphalt sub-ballast provides greater resistance to deformation, improves water drainage and optimises load distribution across the different layers of the track. These enhanced features results in improved track performances, ensuring high safety standards over a longer period. As a result, maintenance activities, such as ballast tamping, can be carried out at longer intervals compared to unbound solutions, which require more frequent intervention. Also, the use of bituminous sub-ballast reduces the tensile stresses within the ballast, thereby reducing the fatigue induced phenomena. This aspect translates in a lower wear and fragmentation of the ballast material, thus limiting fouling. Structurally, asphalt sub-ballast increases the load-bearing capacity of the track and mitigates the adverse effects of freeze-thaw cycles and dynamic stresses caused by passing trains. This results in longer track life and reduced differential failures, improving operational safety. Economically and environmentally, the use of asphalt sub-ballast is highly sustainable. The long-lasting durability and the limited maintenance requirements imply significant long-term cost and resource savings. Another advantage is the ease of installation, backed up by the extensive experience in road construction. Paving equipment and construction techniques are the same used for the road installations. Furthermore, the use of innovative asphalt mixes with a lower environmental impact, coupled with the extended life of the track substructure, makes this solution an optimal choice for modern railway infrastructure. In addition, the incorporation of reclaimed asphalt or advanced materials is a key technology for the future of railway maintenance, contributing to the sustainability and resilience goals outlined in the European Union's strategic initiatives. However, further studies are needed to refine the mechanical and functional characterisation of these innovative mixtures and to optimise the production processes to ensure an increasingly minimal environmental impact.

CRediT authorship contribution statement

Aldo La Placa: Writing – original draft, Resources, Conceptualization. **Federico Autelitano:** Writing – original draft, Resources, Conceptualization. **Larysa Neduzha:** Writing – review & editing, Resources. **Oleksii Tiutkin:** Writing – review & editing, Resources. **Felice Giuliani:** Writing – original draft, Resources, Funding acquisition, Conceptualization.

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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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