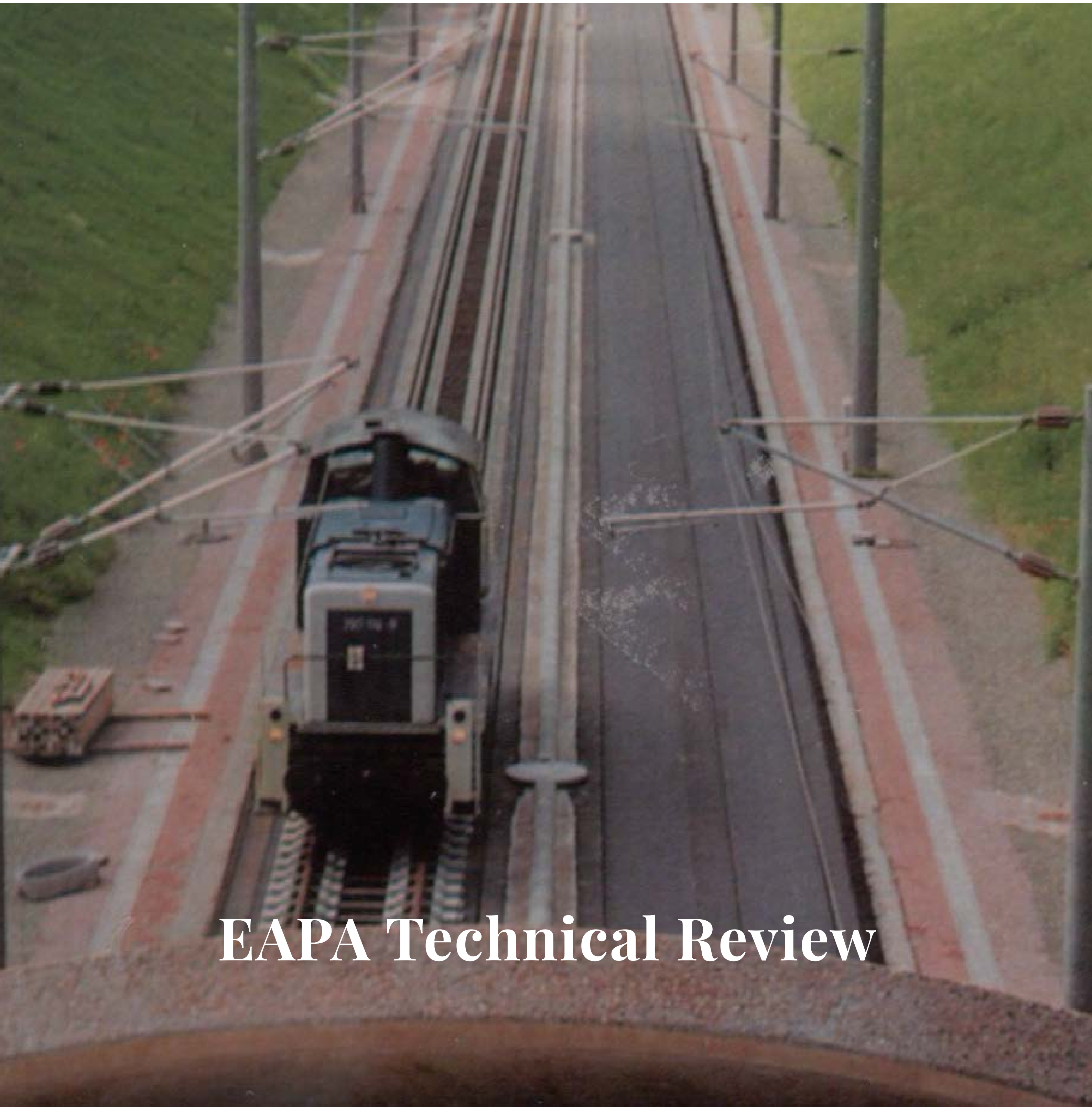
EAPA

Asphalt in Railway Tracks



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Abstract

One of the measures proposed by the EU Commission and included in the "European Green Deal" is the shift of a substantial part of the 75% of inland freight carried today by road onto rail. Increasing traffic loads and volumes and particularly the introduction of high-speed trains in the last decades, have resulted in the need for new technologies in railways engineering, which now, with stronger EU policies, will become more and more necessary. As a reaction to this, the European Asphalt Pavement Association (EAPA) published the present extended state of the art about the main asphalt solutions used around the world. In this document, also the practical experiences carried out in countries, such as Austria, Czech Republic, France, Germany, Italy, Spain, China, Japan, Morocco and USA are described, showing how these technologies are able to significantly improve railways in different aspects, such as better mechanical performance, protection of the substructure, reduction of maintenance needs and costs, as well as greater safety and reliability for users.

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1. Introduction

The "European Green Deal", published by the EU Commission in December 2019, states that to achieve climate neutrality, a 90% reduction in transport emissions is needed by 2050, as these accounts for a quarter of the total EU's greenhouse gas emissions. One of the measures proposed is a strong boost in multimodal transport to increase the efficiency of the transport system. This includes a shift of a substantial part of the 75% of inland freight carried today by road, onto rail and inland waterways. This will require measures to manage better, and to increase the capacity of railways, which the Commission will propose by 2021.

In railway design, as in highway design, increasing traffic loads and volumes and particularly the introduction of high-speed trains in the last decades, have resulted in the need for new approaches, which now, with stronger EU policies, will become more and more necessary. In addition, concern for the environment requires the concept of sustainability to be taken into account in the design process.

Asphalt mixtures have been shown to provide good technical alternatives for several elements of traditional railway construction. In particular, experience with asphalt in the track superstructure (the traditional superstructure consists of the rails, the sleepers, fastenings and the ballast) and in the sub-ballast layer has shown that these types of construction are able to fully meet the requirements of modern railway tracks.

Worldwide experience has shown that use of asphalt can offer a good alternative in modern railway construction. Thanks to the specific properties of asphalt mixtures the materials are able to comply with many of the requirements.

2. Asphalt

Hot and warm mix asphalt are mixtures of mineral aggregate and bitumen. The mineral aggregates can vary from very fine dust (filler) to coarse particles, which could be as large as 40 mm. Bitumen is a product of the crude oil distillation.

The use of bituminous asphalt as a pavement material dates back to the second part of the 1800s when it was placed as an asphalt sheet on a base with concrete. Until the 1930s, the structural design and construction of pavement was based on experience. This is the date in which early efforts to overview the structural design of flexible pavement started [1]. By varying parameters, such as the composition of the mixture, the ratio of the various constituents, the particle size distribution of the aggregate and the type and composition of the binder, the characteristics of the mixture can be adapted to suit the specific requirements of the construction. Depending on the mix composition and the quality of the constituent, bitumen and aggregates, the asphalt mixture may be either stiff with high stability or very flexible. Some mixtures are dense and waterproof, whilst other compositions result in permeable porous asphalt.

The use of special additives or polymer-modified bitumen offers the possibilities of complying with specific high value requirements (heavy duty, lower temperatures) for the mixture or the construction.

The production of asphalt mixes takes place in either mobile or static mixing plants where, in a continuous or batch process, the mineral aggregates are dried and heated and later the hot bituminous binder is added to the required aggregate composition. After production the hot or warm asphalt mix is transported to the job site by trucks. On site, application takes place using pavers that place and pre-compact the material in the required thickness and width, following which final compaction is achieved using rollers (Figure 1). Immediately after the last passage of the compaction roller the asphalt is ready for use.

An asphalt construction may consist of one or more separate layers of possibly different composition. Depending on the design, the various layers perform a specific role in the construction.

Figure 1. Compaction of asphalt layer

3. Application of asphalt in railway construction

Over the last decades, the use of asphalt layers within railway track-beds has been gaining importance in order to cope with higher performance requirements of modern railway transport and construction. This alternative solution has been increasingly used in European countries, such as Austria, France, Germany, Italy or, more recently, Spain, as well as in other countries, such as China, Japan and United States, getting to be considered as an appropriate technology to improve track quality in high speed and heavy traffic lines [2, 3].

It is necessary to mention that the current European Union's strategy includes the construction of maintenance-free slab tracks in appropriate sections (e.g. tunnels) [4], which is an opportunity for designs involving the use of asphalt materials, a more durable alternative than traditional tracks. In addition, there are numerous ongoing investigations to develop new methods and designs for slab track with asphalt or asphalt mortar [5].

A wide range of asphalt materials have been used in different implementations, such as mastic asphalt, hot (HMA) and warm mix asphalt (WMA), with or without polymer modifications, as well as bituminous emulsions for ballast stabilisations.

The four most common applications of asphalt in rail tracks are summarised in Figure 2. As it can be seen, asphalt can be introduced as a component of the railway support system in combination with other ballast and sub-ballast layers or as part of a ballast-less system, where no ballast is used at all. It can be said that, in general terms, European countries have more tendency to use the ballast-less track system than in the USA, where the asphalt sub-ballast system represents the vast majority of applications. The particularities of these systems will be described through the following sections.

Finally, it will be also described in Section 5, a new use of bitumen emulsion as a ballast stabiliser, which according to recent experiences, can extend considerably the service life of ballasted rail tracks.

4. Application of asphalt pavement as a component of railway support system

4.1 Asphalt pavement with ballasted tracks

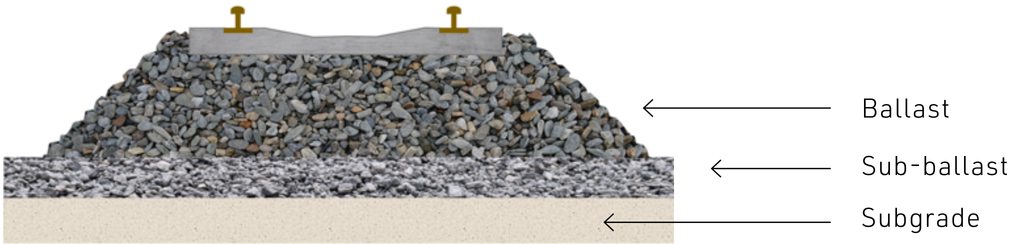
The most common asphaltic configuration used in the world consists on the application of a bituminous layer, similar to Hot Mix Asphalt (HMA) conventionally applied in base and binder road courses, between the sub-ballast and ballast layers or directly substituting the sub-ballast layer [2,6]. In order to obtain an optimal performance, the asphalt sub-ballast is normally laid on a highly compacted embankment layer.

Usually, with such configuration, the bituminous layer extends about 30 cm beyond the cross tie's ends on both sides. The material is commonly made of a dense-graded mixture containing coarse aggregate with maximum size between 25 and 37.5 mm [7].

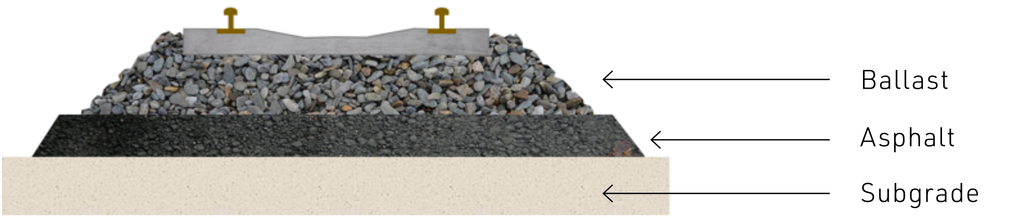
In addition, it was also found that the maximum stress and strain produced at the bottom of the asphalt sub-ballast is strongly affected by the thickness of this, as well as the thickness of the ballast placed on top of it [8]. Studies carried out at the Transportation Technology Centre in Colorado, comparing the performance of sub-ballast HMA layers of 100 and 200 mm obtained a significant increase of the bearing capacity of the sub-structure when the thickness was increased (Figure 3). Consequently, the measured settlement of the 200 mm layer was about 15% lower than that of the 100 mm, which means that maintenance frequency can be reduced. For these reasons, asphalt sub-ballast has been especially used in countries, such as USA, for at-grade rail crossings, as it helps to reduce settlements in the track and road over time.

When a layer of dense asphalt concrete is used as a sub-ballast layer, optimal drainage of the super-structure is obtained, while preventing that water infiltrates the sub-structure. The water-proof asphalt sub-ballast layer can also prevent possible contamination from the sub-structure by vertical hydraulic transport of mud and fines. According to [9,10] the use of HMA layers also helps to reduce track deflection and prevent water from entering the subgrade. This reduces variations in the moisture content in the subgrade and, consequently, also displacements amplitude, permanent deformations and track geometry deterioration [11]. In order to ensure such waterproofing charac-

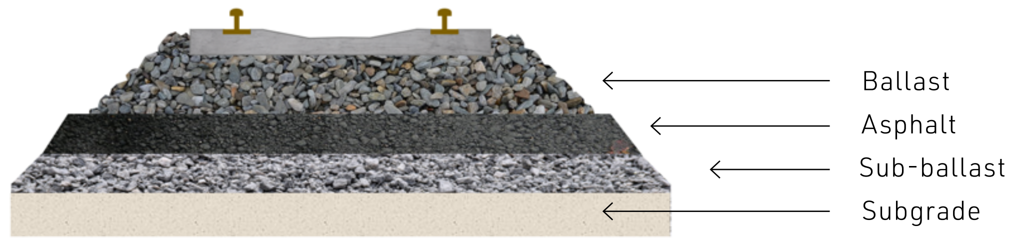
a) Traditional design without asphalt:



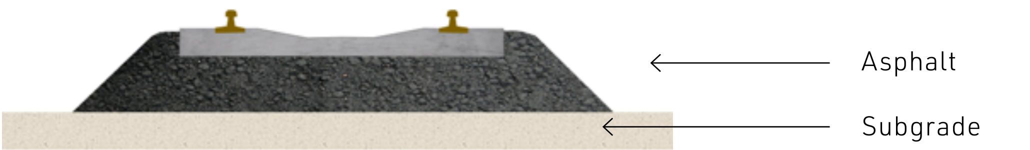
b) Asphalt-ballast combination: Asphalt sub-ballast:



c) Asphalt-ballast combination: Asphalt intermediate layer:



d) Ballast-less configuration: Asphalt slab track:



e) Ballast-less configuration: Asphalt intermediate layer:

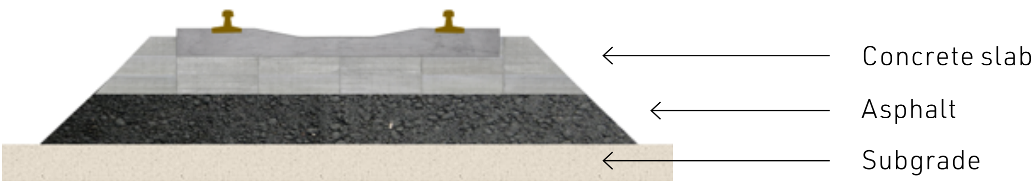


Figure 2. Most common use of asphalt in railway tracks

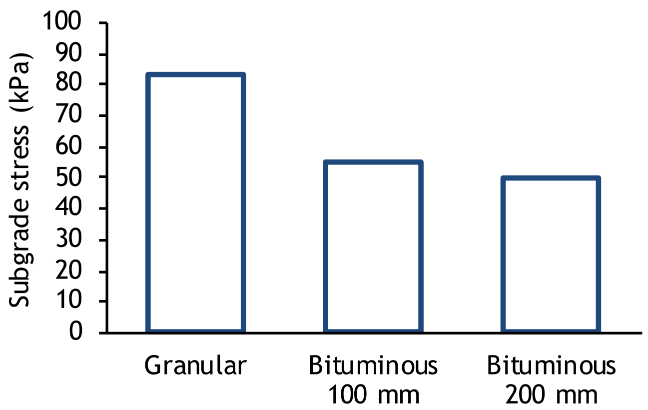


Figure 3. Capacity of bituminous sub-ballast to reduce stress on subgrade adapted from [31]

teristics, air voids content must be usually kept lower than 3-4% [8, 12].

In this sense, Khairallah et al. [13, 14] monitored 4 sections along one of the newest implementations, the 105 km of the new high-speed line Bretagne Pays de Loire (HSLBPL) built with bituminous sub-ballast (Figure 4). For this, more than 100 sensors, such as accelerometers, extensometers, humidity probes, temperature sensors and anchored displacement sensors were used. The study showed a minimal water infiltration under the bituminous layer compared to sections where only granular material was used (Figure 5). In addition, they also observed that in the bituminous section, the temperature gradient measured for 15 months between the top and base of the asphalt sub-ballast (12cm) was negligible, thanks to the protection of the covering ballast.

While studying the same line, Ramirez-Cardona [15, 16] also found other advantages, such as the reduction of vertical acceleration measured on the sleepers, which helped to improve the global structure's stability. Hence, the overall behaviour of the observed sections was comparable or even better than that of the best behaving conventional track sections.

In addition, Villautreix [17] stated in 2017 that this experience in France, represented a small revolution, as it had never gone beyond the experimental stage up to then. As a consequence of the satisfactory results, the technique was approved by French National Railway Company (SNCF) and is being used in other projects, such as the LGV Sud Europe Atlantique high-speed railway and the Nimes-Montpellier bypass.

Asphalt layers can also create a working platform during construction, which allows conventional machinery (with wheels) to drive and access the job site on multiple points. Hence, subsequent work operations, such as installation of electric lines, ballast and rails are faster and more easily undertaken than in conventional ballast railway tracks, where the execution is linear, requiring the construction of the whole structure before accessing along to place rails and other equipment. Consequently, asphalt layers help to secure the planning of the project.

Depending on the project size, the required equipment can vary significantly [18]. For large projects, mainly new construction with a prepared subgrade, the process is similar to that carried out in road construction, with the asphalt being laid down by a conventional paver and compacted by large vibratory rollers. However, in this case, less handwork and smoothness concerns are necessary, which allows to finish the process in a shorter time.

For the case of smaller projects, such as maintenance and rehabilitation, the old track panel is removed, asphalt is normally back-dumped on grade and spread by a excavator, small dozier, bobcat, or similar, and compacted by conventional vibratory roller. The cost of this is practically the same than placing conventional granular sub-ballast. As it replaces the granular sub-ballast, the extra cost of the asphalt material delivered to the job site is not significant, added to the costs of track removal and replacement. Also, as the track has to be removed and the underlaying ballast/ sub-ballast replaced by new ballast, the laying of an asphalt layer does not add a significantly long time.

4.2 Asphalt pavement with ballast-less tracks

For many years there have been developments aimed at improving the stability of the traditional rail-track structure of rail, sleepers and ballast. The introduction of high-speed trains and the desire for less maintenance led to the development of the ballast-less track (also known as asphalt overlayment in USA). In this form of construction, the ballast is replaced by a rigid monolithic element that directly supports the sleepers. The aim is to find a track structure having a good elasticity, regardless of the foundation stiffness.

One of the solutions is a system in which the track frame of rail and sleepers is placed directly on an asphalt layer. The most important requirement of the top

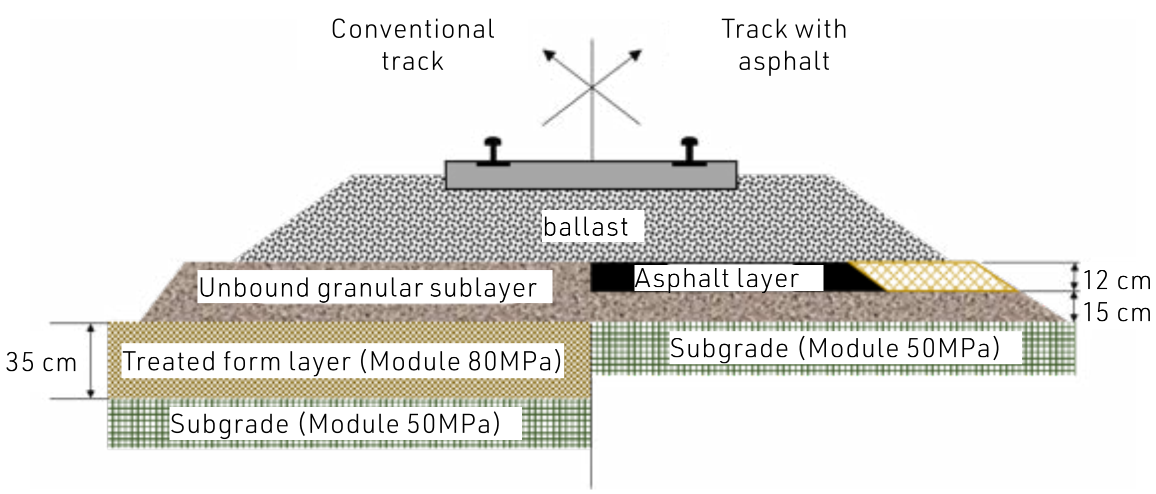
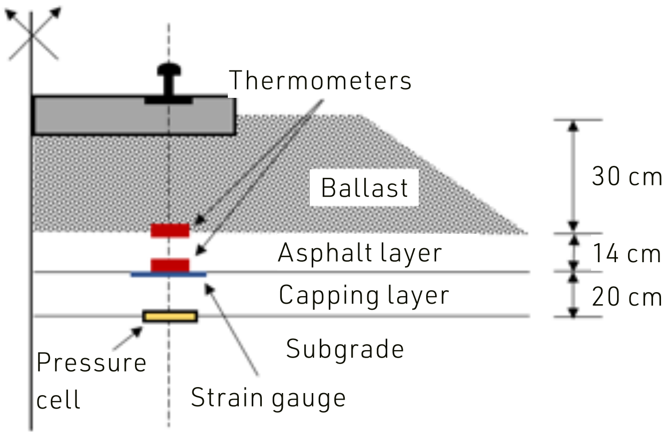


Figure 4. Cross-section of high-speed line Bretagne Pays de Loire (HSLBPL)



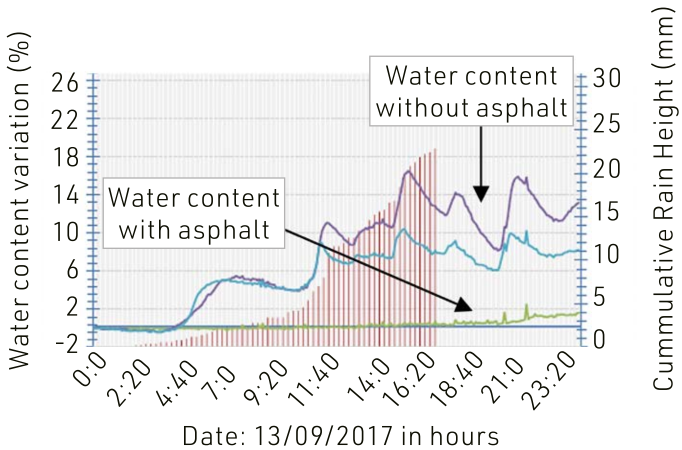


Figure 5. Sensors introduced to measure the water infiltration under asphalt sub-ballast (GB) and granular sublayer (GNT) in the new high-speed line Bretagne Pays de Loire (left) and results obtained over a rainy period (right) [14]

asphalt layer is to have a perfectly smooth and even surface in order to comply with the stringent tolerances that are required for the rail level (± 2 mm). Modern asphalt laying machines can fulfil this requirement, as they make use of the most sophisticated levelling equipment.

The horizontal anchoring of the rail track in order to prevent transverse movement can be achieved by various anchoring systems.

The advantages of these systems are the elasticity of the asphalt layer, especially when polymer modified asphalt is used, and the ease of construction and maintenance. Another important factor in favour of this system is the ability to carry out minor corrections without demolishing and reconstructing the base.

Because this system eliminates the use of ballast it has the great advantage of lowering the track base, allowing the construction of tunnels with smaller diameter or on bridges reducing the weight.

In USA, for maintenance purposes, this configuration is mostly limited to the railway trails with heavy freight traffic [18]. However, this method is more popular in European countries, specifically in constructing high speed railways and urban transit. The first successful application of the ballast-less tracks dates back to the beginning of the 1990's, in Germany, after which, several sections of high-speed railway with asphalt base slab track would follow. Different variations have been developed, such as ATD (Asphalt base course with a rail web), SATO (Concrete sleeper on Y-steel sleeper with double base), FFYS (Y-steel sleepers

Table 1. Specification of asphalt base ballast-less system [19]

Method	*Asphalt Thickness (mm)*	*Superstructure Overall Thickness (mm)*
ATD	300	1021
SATO	300	909
FFYS	300	909
Getrac	300	1021
Walter	300	929

with basic body casting made of supportive girder profiles), Getrac (German Track Corporation Asphalt) or Walterbau (German Track Corporation Asphalt), all of them having shown to be very successful to date.

The system of asphalt track bed directly laid on sleeper (ATD) [20] consists on a combination of a cement-stabilised subgrade and an asphalt layer placed on top and the sleepers seated directly on the asphalt layer (Figure 6). The SATO and FFYS systems are characterised for the use of Y-shape sleepers also fixed directly on the asphalt layer.

The system known as Getrac is probably the most remarkable experience of asphalt in ballast-less rail tracks. There are two versions depending on the sleepers' width: the Getrac A1 and the Getrac A3. In the first method, anchor blocks act as interlockers, transferring the lateral and longitudinal stresses between pre-stressed sleepers with regular base width and the surface of the asphalt layer. The second method is similar but wider concrete sleepers are placed on an upper layer of asphalt, laid on top of one or two lower layers.

Regarding design criteria, and as it can be seen in Table 1, the thickness of asphalt layer in solutions commonly used in Europe is 300 mm. Nevertheless, in other countries, such as Japan, the asphalt layer with a thickness of 150 mm is laid on a 150-mm-thick layer of well-graded crushed stone. It must be noticed that in some sections, a ballast layer was added at the end of the travers to add lateral resistance in track shoulders. Nevertheless, such material was added after the construction of the railway slab track instead of being placed under the railway.

Figure 6. ATD system

The solid railway trackbed laid in Germany to date has been shown to be very successful. This success is fully justified by the reliable paving and by the material-specific characteristics of the construction asphalt material. Hence among the advantages observed in these experiences, it can be highlighted that:

- Asphalt can be paved without joints due to its visco-elastic characteristics; stresses arising from the effects of load and temperature are reduced.
- Asphalt can also be used with extreme super-elevation because no separation arises from the high internal friction in the paved state.
- Asphalt can be paved at a precise tolerance (± 2 mm) due to its material characteristics.
- Load can be put on the asphalt immediately after it cools down; shorter construction times are achieved by using it.
- Corrections in the position that may be needed (e.g. due to settlement of the embankment) can be quickly and easily made either by milling off or by putting on another layer.

For these reasons, the solid railway trackbed made of asphalt resulted a promising alternative to a ballast-type track and other construction methods for the solid railway trackbed.

Table 2: Properties of typical track with asphalt layer (from [25])

Layer	Thickness (cm)	Minimum Young's Modulus (MPa)	Poisson's Ratio	Unit Weight (ton/m^3)
Ballast	20-30	50	0.35	1,800
Asphalt	15-30	4,200*	0.45	2,400
Sub-ballast	10	25	0.35	1,800
Subgrade	500	85	0.4	2,200

*At 67°F (aprox. 20°C)

4.3 Design recommendations for the use of asphalt in railway tracks

The design of the most modern railway trucks is normally carried out by methods, such as the French Alizé or finite elements methods with 3D modelling.

The first is generally used in France for road structures but can be also applied in railway tracks. This probabilistic method based on the characteristics of the materials measured both in the lab and on-site provides, as a result, the number of fatigue axle loads that the track can resist. For this, it is necessary to introduce in the tool several parameters, such as the bearing capacity of the subgrade, the characteristics of the convoys (variable according to the lines), the cumulative total traffic, the mechanical characteristics of the different materials and the service life.

Finite elements methods with 3D modelling allow the calculation of the stress level at the base of the asphalt layer by taking into account the real geometry of the track (including rails and sleepers). These methods can be also used to verify the results obtained by design software (e.g. Alizé).

In many countries, other design methods for asphalt road pavements, such as the Superpave (in USA) or the Marshall mix design method are still mostly used for both asphalt sub-ballast layers and ballast-less tracks.

Different authors have proposed different recommendations [21-24] based on Marshall Stability and Flow and volumetric properties, such as air voids content and density. Nevertheless, in Europe, fatigue is usually the key parameter mainly leading the design.

In addition, Rose et al. [25] studied in USA the construction of different rail tracks with different configurations of ballast, asphalt layer, sub-ballast (if existing) and subgrade. The main characteristics of these can be seen in Table 2.

Regarding the design of asphalt sub-ballast, it is also important to highlight that, due to the beam action of the track on top of several ties and the load reduction effect of the confined high-modulus ballast placed underneath, the stress that asphalt sub-ballast must bear is lower than in road pavements [10, 26]. Thus, distresses such as rutting, bleeding and flushing are less aggressive than in roads [12, 18]. As an example, Rose et al. [18] measured the peak dynamic vertical pressures imposed by a 130 metric ton locomotive (average wheel load 160 kN) on top of the asphalt material, obtaining values between 90 and 120 kPa, significantly lower than the 700-1400 kPa tire pressure imposed by loaded trucks directly on an asphalt road pavement. Despite this advantage, it is also necessary to consider that asphalt trackbeds for railway tracks also need to be designed to be long-lasting (up to 60 years lifetime), flexible and dense in order to avoid maintenance work.

Furthermore, even if limited deformation of the subsoil does take place, this will not affect the asphalt layer because it is capable of withstanding the deformation without losing its integrity because of the visco-elastic properties of asphalt.

Moreover, it has been published that the use of asphalt sub-ballast layers can help to reduce the total construction height of the rail superstructure (compared to traditional designs without asphalt), which is of importance in the case of tunnels and bridges. In addition, the use of asphalt also helps to reduce vibration and noise [27, 28].

According to reports published in the USA [8, 29], bituminous sub-ballast's main concern is related to its relatively high initial costs in comparison with granular sub-ballast. Depending on the configuration, local conditions, access and project size, the initial specific cost of the layer can raise by 2.5 to 5 times when conventional sub-ballast is substituted by HMA. Nevertheless, such cost increases can be recovered within 7 years, due to the reduced maintenance needs. According to Rose and Anderson [29], in cases where the track-bed presents severe maintenance problems, this cost recovering can be even produced within the first service years. Moreover, as the ballast deteriorates slower, its service life could be extended by 50-100% [8]. Finally, a different economic study [30] showed that the bituminous sub-ballast starts to be more effective and profitable when the transportation distances for appropriate aggregates for granular sub-ballast are above 60-80 km, since the asphalt material can be manufactured with aggregates available closer to the construction site (the requirements do not need to be so restrictive).

The cost-efficiency of asphalt sub-ballast can be also improved by implementing technologies, which extend its service life. In this regard, different authors [32-34] reported that the use of modified bitumen can damp vibrations, increase stiffness, reduce plastic deformations, stress and strains at the bottom of the layer, and extend its fatigue life. These aspects have been significantly improved over the last years, when it was noticed that results are strongly linked to design parameters, such as polymer dosage (e.g. SBS or rubber) and how this is added to the mix, type of mix and asphalt thickness.

Also, Pirozzolo et al. [35] worked on the design of a Warm Mix Asphalt, which made possible to produce the asphalt sub-ballast at a temperature 30°C lower and obtaining a performance similar to conventional asphalt sub-ballast. This solution is especially interesting in tunnels, where the use of hot materials and fumes production might be a greater concern.

Finally, can be added that mastic asphalt can be a suitable solution to provide a waterproof coating in rail tracks, especially in high-speed rail tracks placed in cold areas and exposed to freeze and thaw phenomena [36].

5. Bitumen stabilised ballast

Particles composing the granular ballasts can get degraded due to stresses at contact points produced by traffic and maintenance operations. This phenomenon known as fouling, can reduce the mechanical integrity, leading to undesired changes in the track geometry [37]. Tamping is a common treatment used to preserve the structural integrity of fouled ballasts. However, such operations produce themselves further degradation, leading to a vicious circle where the more maintenance is applied, the more maintenance is needed [38].

In order to reduce material consumption and ballast maintenance costs, which round 30% of the total maintenance costs [39], different solutions have been developed, such as the use of elastic elements (e.g. under sleeper pads, under ballast mats or crumb rubber mixed with ballast aggregates [40-42]) and the use of geosynthetics and polyurethane-based techniques. Such solutions were successfully applied with different limitations, such as high initial costs and low productivity [43, 44].

As an alternative, a new more affordable technique is gaining recent interest: the ballast stabilisation by bitumen emulsion (Figure 7). The technique, which consists on spraying bitumen emulsion from above during a routine maintenance operation, can significantly increase the ballast durability without compromising its drainability [37]. According to [45], when the sleeper is raised during the maintenance process, a system analogous to that used by the stoneblower would spray the bitumen emulsion over the surface of the ballast. Great research has been carried out over the last years to optimise the variables of bitumen stabilised ballast (BSB), such as dosage of bitumen emulsion, bitumen emulsion properties, solid content and bitumen properties, ballast layer compaction, ballast fouling level, water damage and temperature among other.

Research carried out at laboratory level [7] based on the Precision Unbound Material Analyzer (PUMA) test [46, 47] (similar to the K-Mould and the Springbox tests) and full-scale ballast box tests, showed that BSB can improve short-term and long-term in-field ballast deformation behaviour, especially when harder bitumens are used. This proves that the solution is effective increasing intervals between tamping operations. Also, the viscoelastic behaviour of the bitumen

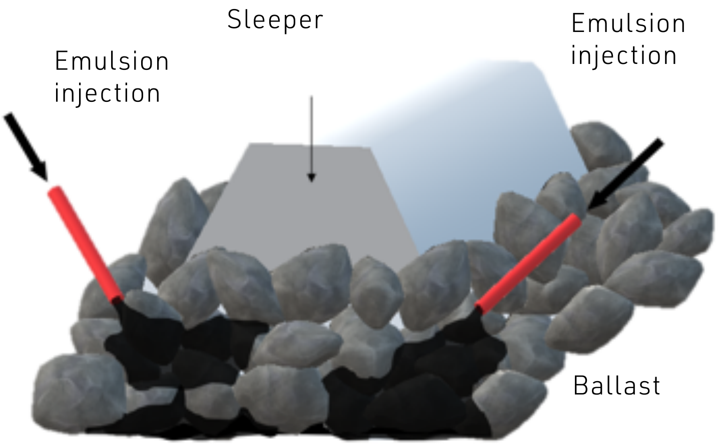


Figure 7. Illustration of ballast stabilisation process with bitumen emulsion

(especially polymer modified) increases the ballast resilient modulus and energy dissipation, which suggests it might be a good solution to reduce vibrations and noise (not proven yet at full-scale). In addition, Life Cycle Costs Analysis show that the use of BSB can produce savings up to 25% compared to traditional ballasted track-beds.

Regarding the material sustainability, Life Cycle Assessment show that when only minor maintenance is considered, this solution is less sustainable than conventional non-stabilised ballast, as the impact added by the emulsion is not balanced by reductions in tamping frequency. However, when the whole life cycle of the rail track is considered, i.e. including major maintenance operations, BSB results in lower environmental impacts, thus greater sustainability.

From the point of view of design, researchers [45] have found an optimum dosage for clean ballast of 1.44% by weight of the ballast underlying the sleeper/ballast contact area [48], which can be translated into 1.5 litres per sleeper end. It has to be taking into account that if the porosity of the ballast is high and the viscosity of the emulsion is low, a great amount of emulsion might be lost during the treatment. On the contrary, if the viscosity is too high for the ballast porosity, emulsion can remain accumulated close to the surface compromising the drainage of this region, while the bottom remains non-stabilised. For this reason, the viscosity of the bitumen emulsion is a key parameter that depends on the ballast material and gradation.

The investigations also showed that the stabilisation process is more effective reducing settlement, when they are carried out at early stages of service life (Figure 8). Once the ballast is fouled and not clean, the air voids are reduced and the penetration of the emulsion is not homogeneous. Consequently, the beneficial effect reduces drastically.

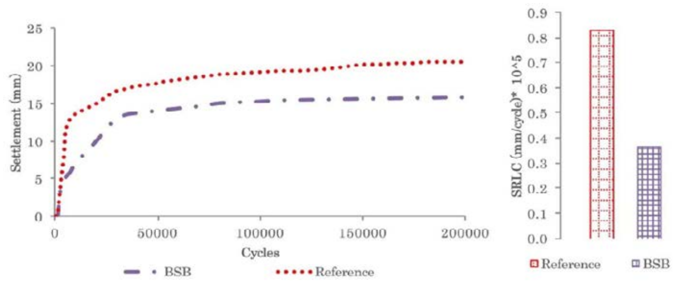


Figure 8. Influence of BSB applied after new construction: settlement (right) and settlement rate per loading cycle, SRLC (right) [7]

6. Practical experiences

6.1 Austria

Austria has experience using asphalt layers in trackbeds since the 1960s. A clear separation between sub- and superstructure is produced by using an 8-12 cm asphalt layer under the ballast bed. Different advantages were reported, being the main ones, (1) allowing road vehicles running on the asphalt sub-layer during the construction phase independently from weather and sub-soil situations, (2) preventing the penetration of rain water into the granular substructure, (3) obtaining optimum elasticity, (4) providing consistent support to equalize stresses on the substructure, and (5) prevent pumping of fines upward. According to Veit (2009), this technique produces annual deterioration rates 50% lower, compared to granular trackbeds, and reduce 67% levelling-lining-tamping frequency.

6.2 Czech Republic

In Czech Republic, an 80m-long test section on the track Pilsen - Česke Budějovice was realized during the reconstruction in 2017 using asphalt mix in the railway bed. The asphalt solution was tested with the aim of reducing the excessive settlement of the rail. Initially, the standard cross section was proposed with 250 mm of unbound gravel layer (crushed stones) but after consultations with the Department of Railway Structures and the Department of Road Structures at the Czech Technical University (CTU) in Prague, part of the unbound layer was replaced by asphalt mix containing 70% of Reclaimed Asphalt (RA). The construction of the asphalt concrete layer was made according to EN 13108-1 using 50/70 bitumen and a rejuvenator. The temperature of the asphalt mixture at loading on the mixing plant was 140°C. Core samples were taken and tested together with the produced mixture in the laboratory.

This section is being closely monitored by the Department of Railway Structures (still in process) and will provide practical knowledge for future implementations.

Based on the experience gained on this test section and considering international experience, the Appendix to Czech technical standard CSN 73 6120 for asphalt mixtures for railroad beds was prepared. Further practical specifications and requirements for paving and controlling asphalt layers on railway tracks are included in revised national specifications S4, which will be published in 2020 by the Ministry of Transport.

6.3 Italy

The first experience with asphalt mixes in high-speed railway construction in Italy date from the early 1970s. Hundreds of kilometres have been built in the last 30 years. The results have been very satisfactory and have shown that the application of an asphalt sub-ballast layer contributed to the stability of the rail geometry. In particular, at critical points such as switch points, expansion joints, level crossings and in areas between concrete structures (bridges) and embankments, where dynamic forces are substantial, the asphalt sub-ballast layer introduced a remarkable improvement of the superstructure stability.

More than 1200 km of high-speed lines in Italy are now equipped with an asphalt sub-ballast layer.

Experience with polymer modified bitumen in asphalt mixes for sub-ballast layers has shown that the application of this type of mix is also very promising with regard of the reduction of noise and vibration. This is another positive contribution of asphalt to both the comfort of rail passengers and to the environment.

The Italian Asphalt Association (SITEB) and the Italian Railways (FS) have carried out extensive research in this field.

The line between Rome and Florence, known as the Direttissima, is the original and most frequently trafficked high-speed line. The typical Italian High-Speed Railway cross sectional profile is shown in Figure 9. It is a multi-layered system consisting of an embankment, super-compacted sub-layer, asphalt sub-ballast, ballast, sleepers and rail.
The embankment has a minimum specified bearing capacity of 40 MPa.

The "super-compacted" layer is then placed on the embankment with a thickness of 300 mm with a minimum subgrade modulus of 80 MPa. The super-compacted layer consists of a sand/gravel mixture and is placed with a cross slope of 3.5%.

The asphalt sub-ballast layer, placed on the super-compacted layer, consists of an asphalt mixture with a maximum aggregate size of 25 mm and has a thickness of 120 mm. It is applied over the entire track cross section, with a total width of around 14 m [30]. The asphalt sub-ballast is placed by using a standard asphalt paving machine.

When the asphalt mix solution is compared with cement mix solutions for the sub-ballast, the following advantages are evident in favour of asphalt:

- reduced use of aggregates due to the lesser thickness of the asphalt sub-ballast layer (average 120 mm thickness compared to at least 200 mm);
- cracks are less likely to emerge;
- there is no need to protect the finished surface by means of bitumen membranes or emulsion spray;
- no curing time.

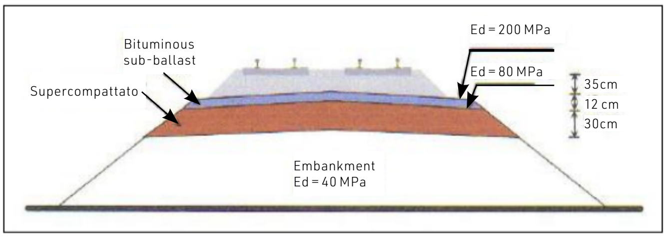


Figure 9. Italian High-Seed Railway Cross-Sectional Profile [27]

Experience shows that the presence of an asphalt sub-ballast layer in the railway structure also results in a reduction in the vibrations transmitted by the passing trains to the surrounding environment; the asphalt sub-ballast then acts as a damping medium.

6.4 Germany

6.4.1 General Issues

In Germany the German rail authority, Deutsche Bundesbahn AG (DB AG) came to the conclusion that the rail web (rails and sleepers) with ballast bedding type of construction had reached a level that is hardly capable of improvement as a classical construction method for railway track.

Furthermore, in the case of routes designed for very rapid passenger traffic, it has been found that wear and tear take place much more quickly than expected through stone displacement, breakage and abrasion because of the dynamic traffic loads on the railway ballast. As a result, track bed deterioration occurred more frequently and required maintenance work at more frequent intervals. This maintenance work was costly and disrupts normal railway operations. So, alternatives were necessary.

The load-bearing ballast can be replaced by asphalt. This construction method was used for the first time in Germany around 35 years ago, with an asphalt base course. Since then several systems of the asphalt construction method have become approved by the DB AG. They are the following, in detail Figures 10-13):

- ATD - Asphalt base course with a rail web
- SATO - Concrete sleeper or Y-steel sleeper with double base
- Walter - System Walterbau
- Getrac - German Track Corporation Asphalt.

In addition to the fastening technique, paving at the precise height is extremely important. Although, in the beginning, milling off was still necessary in part to achieve the required height precision, evenness of paving has since been improved to ± 2 mm, with reference to 4 m, through multi-layer paving and laser-supported paving technology.

With the above-mentioned systems, several sections have been constructed in Germany to date. In [49] the details of above mentioned systems are described.

6.4.2 Requirements for the asphalt layers

In general, the requirements for the asphalt are determined by the load type and traffic. In the case of the solid railway trackbed, loading frequency is at a lower level than with asphalt roads. In contrast, the axle loads and consequently the wheel loads are far higher. On roads, the actual distributed load results in a wheel load of 5.75 tons for a truck with an 11.5-ton axle, which works out to around 0.8 MPa for a surface area of around 710 cm^2. For railways, however, there is a considerable load distribution over the rail and the sleeper. The wheel load of 11.25 tons results in stress on the bottom of the sleeper of around 0.25 MPa, and thus only around one-third of the load experienced on roads.

The asphalt needs to be designed to be permanent, flexible and dense in order to avoid maintenance work and subsequent improvements, which are practically impossible. The lifetime of the solid railway trackbed has been estimated to be around 60 years. Experience in Germany has shown that asphalt types with a high binder content and a low void content have proven to be reliable.

6.4.3 Paving

The paving can be done with the normal types of pavers available today. However, there has to be careful planning of the asphalt work and the paving in order to achieve the required precision (heights, axes) (Figures 14-15). The surveying programs used for road construction cannot be used for the solid railway trackbed; electronic data-processing programs specially developed for this have proven to be reliable.

The guide-wire and supports used to control pavers operating on road construction sites cannot be directly adopted for railway construction. Instead, modifications to the support equipment are necessary to permit fine adjustment. In addition, the supports need to be set up at shorter intervals (< 5 m) in order to avoid sagging of the wire. The structure of the solid railway trackbed will depend on the particular fastening system. As a rule, the asphalt will be laid in at least 4 or 5 layers in order to achieve the required evenness. At least 4 layers are necessary with an overall thickness of 30 cm for the ATD system. The height behind the finisher requires to be checked after every layer is paved.

Compaction of the asphalt after paving could result in a change in the finished level and evenness. The use of pavers with a screed providing a high level of pre-compaction is therefore mandatory. The compaction itself needs to be done with a small smooth-wheeled roller.

6.4.4 Asphalt in tramways

The systems described before for "Solid Railway Trackbed" can also be used for building tramways. Below is an example of the ATD-system used in Berlin (Germany).

Figure 10.Getrac system

Figure 11.Getrac system

Figure 12.ATD system

Figure 13. Two examples of SATO system: with Y-sleepers on asphalt (top) and concrete sleepers (bottom)

The sleepers are placed directly on the bed of asphalt. The total track bed consists of two-layers of asphalt as a base (in total about 160 mm) and covered by a top layer of asphalt concrete (0/11). The sleepers with the rails are laid directly onto this top layer and therefore the specifications with regard to evenness are extremely high (+/- 2mm in both longitudinal and transverse directions).

Further requirements are a uniform composition of the mixture, continuous transport in order to avoid a standstill in the paving, a constant paving speed and a steady paving temperature.

6.5 France

Besides the new high-speed line Bretagne Pays de Loire (HSLBPL) described above, there are other experiences in France where asphalt was used in railway tracks. In 2005 the French National Railway Company (SNCF) has built a 3 km long test section in the high-speed TGV-East line (connecting Paris to Strasbourg)

Figure 14. A paver with a special profile screed paving the top layer for the ATD-system to hold the sleepers in place later on [Source Voegele]

Figure 15. Placing the sleepers on the completed asphalt supporting layer [51]

with an asphalt sub-ballast layer. The goal of this test section was to determine whether an asphalt sub-ballast could be considered as an acceptable alternative for future high-speed rail infrastructure projects [52].

Figure 16 shows the comparison of the traditional cross section with an aggregate (sub) ballast layer used in the TGV-East line with the asphalt sub-ballast layer in the 3 km test section.

The traditional system consisted of 300 mm thick ballast layer on a 200 mm thick sub-ballast layer. This ballast and sub-ballast layer rested on a 500 mm granular layer of limestone.

In the alternative with the asphalt sub-ballast layer, the 500 mm limestone layer was replaced by 140 mm

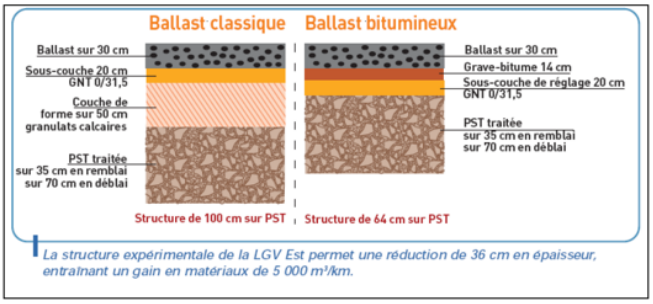


Figure 16. Traditional and bituminous sub-ballast sections [52]

asphalt sub-ballast and a 200 mm thick sub-base layer (GNT 0/31,5). In this way the total thickness was reduced by 360 mm, which reduces the amount of material used by approximately 5,000 m^3 per km track [52].

On top of the 200 mm sub-base layer, a surface dressing was applied (0,8 kg bitumen/m^2) with fine aggregate over the total width of 14,50 m. The goal of the surface dressing is to protect the sub-base layer against the construction equipment and to improve surface drainage.

After installation of the asphalt test section SNCF did various test for 4 years to evaluate the impact on maintenance and to observe the behaviour during temperature changes. Various sensors were built in to measure the temperature, pressure, acceleration, strains and deformations of the base layer of asphalt and finally the TGV-East line was opened in June 2007.

Besides the benefits in the construction constraints, Robinet [53] listed numerous additional advantages, such as: 1) reduced structure thickness by 36 cm, 2) lower amount of fill material by 5,000 m^3/km, 3) 50% reduction of pressure under asphalt layer, 4) deflections reduced to one-third of maximum limit, 5) sleeper acceleration is not affected, 6) reductions in maintenance and 7) good mechanical performance of asphalt layer.

Since this first trial and the conclusions, which have been drawn, SNCF decided to use this solution for all the new tracks for High Speed Train, such as the lines LGV East (from Paris to Strasbourg), LGV Sud-Europe Atlantique, LGV Bretagne – Pays de la Loire and LGV Contournement Nîmes-Montpellier (CNM, designed for passengers and freight), where thickness reductions of more than 20 cm were obtained (see Figure 17).

The mechanical requirements for asphalt concrete for being used in High speed train tracks are:

- Stiffness modulus at 15°C and 10 Hz ≥ 11,000 MPa (EN 12697-26 Annex A method)
- Fatigue ≥ 110 με (EN 12697-24 - Annex A method)
- i/C ratio ≥ 0.70 (EN 12697-12 – Method B Duriez), or ITSR ≥ 87% (EN 12697-12 method A)

Since that, new studies have been performed and a trial has been carried out to use 20 and 30% of RA in the formulation of this specific asphalt concrete.
In France asphalt concrete is also used for tramways. One of the most famous cases are the new lines in Paris, where a sub-base of high-modulus asphalt with a thickness of 100-120 mm was used.

6.6 Spain

6.6.1 Sub-ballast layers

The Spanish Railways decided to test the use of a bituminous sub-ballast layer instead of a granular sub-ballast layer in trial sections in four sites [54-56] (Figures 18-19):

- Valdestillas – Río Duero (Line Madrid – Valladolid, 2007)
- Sils – Riudellots (Line Barcelona – Figueras, 2013)
- Villodrigo – Villazopeque (Line Valladolid – Burgos, 2015)
- Aspe – El Carrús (Line Alicante – Murcia, en construcción)

The longest test track (10 km) was built between Villodrigo and Villazopeque.

The 1 km trial section between Sils and Riudellots of the Barcelona-French Border is a high-speed line and has been fully equipped with numerous monitoring gauges. It will be monitored during 4 years in full operation under mixed traffic conditions (high-speed train sets at 300 km/h together with railway freight trains at maximum speeds of 120 km/h). The results will later be used to support the validation of the use of this technical structure as one of the possible solutions for the more than 2,000 km of new high-speed lines still to be built in the next coming years in Spain.

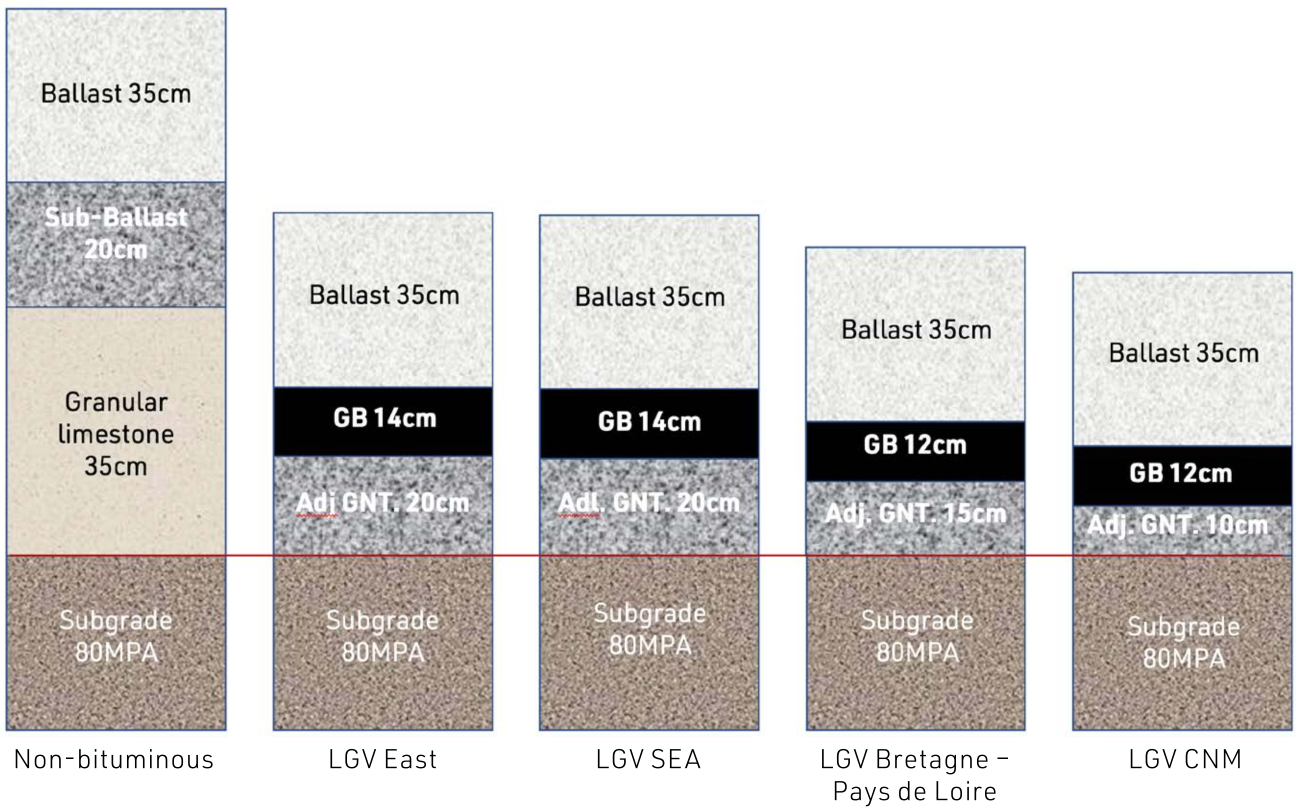


Figure 17. Comparison between a traditional section and those used in the most modern LGV lines, which include asphalt sub-ballast layers
*GB = asphalt sub-ballast; GNT = untreated granular sublayer

Figure 18. Bituminous sub-ballast sections built on the high-speed line Madrid-Valladolid, section between Segovia and Valdestillas (left) and on the high-speed line Barcelona-French Border, section Sils-Riudellots (right) [54]

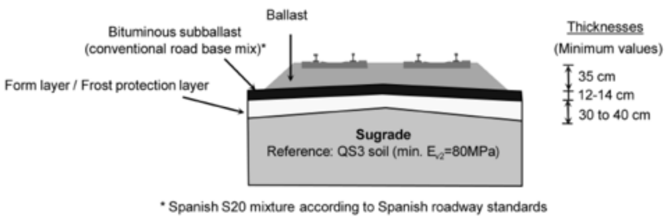


Figure 19. Track design with bituminous sub-ballast for Spanish high-speed lines standards [54]

According to these experiences, ADIF (Spanish Rail Infrastructure Agency) has defined a set of technical prescriptions:

- Bituminous binders: B50/70 or B70/100.
- Aggregates:
  - Sand equivalent > 50 (or >40 if blue methylene tests is <10)
  - Angular particles >90%
  - Flakiness index <25
  - Los Angeles test > 25
  - Added filler > 50%
  - Recommended grading in Table 3
  - Binder content; > 4,75% (over mass of asphalt mix)
  - Filler/binder relationship: 0,9-1,2
  - Void content EN 12697-8 (annex B EN 13108-20): 3-5%
  - Water sensitivity (EN 12697-12 ITS test method 15°C): >85%
  - Dynamic stiffness modulus (EN 12697-26 - Annex C): 3700-7100 (20°C)
  - Fatigue resistance (EN 12697-24 - Annex D): ε_6 > 120 με

A further step, in order to collect former experiences, has been provided by Asefma. In its Monograph nº 13

Table 3. Recommended grading

	AC 22 S	AC 32 S
sieves UNE-EN 933-2 (mm)	% passing	% passing
45	-	100
32	100	90 a 100
22	90 a 100	-
16	70 a 88	68 a 82
8	50 a 66	48 a 63
2	24 a 38	w24 a 38
0,5	11 a 21	11 a 21
0,25	8 a 16	8 a 16
0,063	4,5 a 8	4,5 a 8

(use of bituminous mixes in railway track-beds) an annex has been edited where specifications for materials and asphalt mixes for bituminous sub-ballast are detailed. Besides, a clear explanation of the criteria required is included.

6.6.2 Ballastless asphalt applications

The only test track of this type of application has been constructed between Las Palmas de Castellón and Oropesa del Mar (Castellón) in 2003. It supports both: standard and high speed traffic.
The main goals of these project were: safety, quality and availability of the railtrack besides a reduced maintenance cost.
Six systems were tested in this test track: Edilón, Rheda Dywidag, Rheda 2000, Stedef, GETRAC and ATD. The last two were carried out using bituminous mixes.

By external instrumentation (151 sensors) data from cross-channel relative motions, deflections, dynamic rail noise and vibrations are recorded. Regular monitoring is also performed on the track geometry and torques of the fasteners.
The ultimate purpose of the instrumentation is to set a valid, rational and consistent approach for the approval models with ballastless configurations.
A further step in on the way, by mean of the R&D project Bituvia where several companies developed mathematical models for the application of ballastless systems based on asphalt mixes [57]. In addition, a new design of bituminous slab track as an alternative to more extended European patents (GETRAC and ATD) was developed.

6.7 Japan

In Japan asphalt track beds have been widely used in railway ballast tracks for many years on both high-speed lines and regular lines [56].

The first goal of using asphalt track beds was to provide a firm support for the ballast and to improve the evenness. It will also reduce the load on the subgrade to prevent subgrade deformation. In Japan the roadbed design methods are described in the Design Standard for Railway Structures (Earth Structures). In the revised design standard of January 2007 performance-based design was introduced.

Before 2007 the thickness of each layer of the roadbed was specified. Now the performance-based design standard considers the fatigue life of the track based on the number of train passes.
The performance-based design procedure has the following three different standard track designs according to performance [58]:

- Performance Rank I: Concrete roadbed or asphalt roadbed for ballast-less track
- Performance Rank II: Asphalt roadbed for ballasted track
- Performance Rank III: Crushed stone roadbed for ballasted track

The Performance Rank I track is a ballast-less slab track that has either a concrete or an asphalt support with concrete ties directly fixed to the slab. It is considered to be the highest quality track. It is designed/checked for track settlement, breakage of concrete reinforcement base, fatigue damage, cracking, contraction, and thermal stresses.
Typical dimensions for the Performance Rank I asphalt ballast-less track are [58]:

- Width of slab: 2220 mm
- Thickness of concrete slab: 190 mm
- Thickness of asphalt-concrete base: 150 mm
- Thickness of well graded crushed stone layer: 150 mm

The Performance Rank II design is a ballasted track with a 50 mm thick asphalt layer.

This design has been used for over 30 years in Japan due to the ability of asphalt to distribute loads and facilitate drainage. For performance-based design, the settlements of the track and fatigue damage to the asphalt are the primary design criteria.

Performance Rank II is displayed in Figures 20 and 21.

- Thickness of ballast beneath the sleeper: 250-300 mm
- Thickness of asphalt-concrete layer: 50 mm
- Thickness of well graded crushed stone layer: 150-600 mm

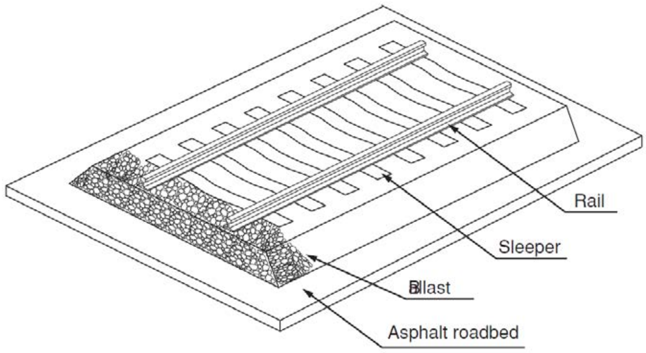


Figure 20: Ballasted track [58]

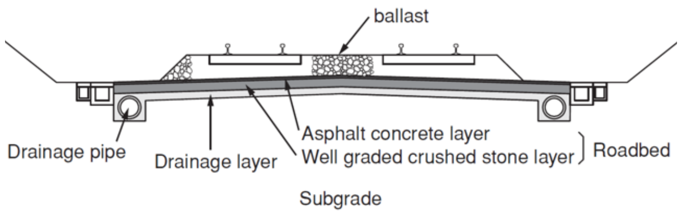


Figure 21. Cross section of ballasted track and asphalt roadbed [58]

6.8 United States

In the United States the use of asphalt track beds has steadily grown since the early 1980's [56], when it was built the Santa Fe Railway (now part of BNSF) and the CSX Transportation, L&N Railroad/Seaboard System, in the Kentucky area, both with asphalt sub-ballast (so-called Asphalt Underlayment in USA). It was conceived as a solution to rehabilitate specific sections, which historically required significant maintenance, such as crossings, switches, bridge approaches or tunnels [18]. Nevertheless, the improved performance obtained in these experiences, numerous railroad and rail agencies created specifications for materials and structure configuration and started to routinely specify the use of asphalt in special trackworks or chronic track instability sites. The two main configurations used are the asphalt sub-ballast and the partial replacement of granular sub-ballast layer (so-called Asphalt Combination) (Figure 2).

In the USA the asphalt sub-ballast layer design and construction standards for railways typically follow recommendations set forth by the Asphalt Institute (Asphalt Institute, 1998; Asphalt Institute 2007). The typical asphalt layer is approximately 3.7 m wide and is approximately 125 to 150 mm thick. For poor track bed support conditions and high impact areas, a 200-mm thickness is commonly used. Thickness of the overlying ballast normally ranges from 200 to 300 mm [56].

The typical asphalt mixture specification is the prevailing dense-graded highway base mix in the area having a maximum aggregate size of 25 to 37.5 mm. This slight modification to the typical highway mix imparts ideal properties to the track structure. Normally the asphalt binder content is increased by 0.5% above that considered optimum for highway applications resulting in a low to medium modulus (plastic) mix, having design air voids of 1 to 3%. This mix is easier to compact to less than 5% in-place air voids and therefore facilitates adequate strength and an impermeable material. Rutting of this mix is not a concern in the track bed since the pressures are applied through the ballast over a wide area.

The largest implementations of asphalt sub-ballast in USA consist on portions of the Burlington Northern Santa Fe (BNSF) Railway Company's high-speed, double-tracking, heavy tonnage and high-traffic transcontinental main line east of Amarillo, Texas (Figure 22). Although the initial sub-projects specified a design in asphalt combination, as a result of succeeding implementations, the granular base was later removed, placing the asphalt sub-ballast directly on top of the granular subgrade. Over 300 km of asphalt trackbed design have been placed during new track construction in the area [59].

Figure 22. Placing asphalt sub-ballast (left) and the new track prior to adding the ballast and pulling the track up on the BNSF Railway 'transcon' capacity improvement project

Among thousands of other successful implementations carried out over the last years, it can be highlighted that the middle-of-street project of 1000 m long renewal on Main Street in West Brownsville, PA, a NS crossing on a heavy-tonnage coal line, which was renewed in four sections to rectify a previous chronic maintenance expense. According to Rose [60] the crossing is performing extremely well, showing no indication of distress or deterioration, and requiring no maintenance. This same author also pointed out the great success in applications, such as railway-highway at-grade crossings (e.g. SBD Railroad mainline through downtown Cynthiana, KY and a CSX crossing at Ashton, WV, which has not received any maintenance during the intervening 17 years and remains in perfect condition).

Regarding urban applications, The Caltrain, in San Francisco, and Metrolink, in Los Angeles, metro systems were among the first, which included an asphalt layer under crossovers and crossings. The thickness of these was 20 cm and 15 cm respectively. In addition, most of the newly added crossovers and turnouts in both lines are built over asphalt (Rose 2017).

6.9 China

Over the last years, China has carried out important investments to increase the speed and capacity of the rail network. Hence, a series of major projects were carried out in the main cities. A common adopted solution to avoid high maintenance costs in high-speed lines, was the use of a continuous concrete base layer and bearing boards supporting the rails. In order to adjust levels while buffering the high-speed heavy loading, in between both previous elements, it is placed a layer of bitumen emulsion mixed with fine aggregate and additives, which help to control the on-site emulsion performance.

Both cationic and anionic emulsions have been used, for example, in the lines Harbin-Dalian and Beijing-Shanghai respectively. Nevertheless, normally only slow setting polymer modified bitumen emulsions are used to allow longer application times without curing.

The used aggregates come from different sources, from river gravel to crushed rock, and with a common maximum size of 1.18 mm. Requirements for these include an apparent density higher than 2.55 g/cm3, water absorption lower than 3.0% and dust content lower than 1.0%.

Different factors affect the workability of this layer, such as the high bitumen content, working temperature, mixing conditions and mix temperature. According to the Shell Bitumen Handbook [61], the requirements of Table 4 must be met to ensure a successful performance.

6.10 Morocco

The new high-speed line (under construction) has a solution, which includes asphalt sub-ballast along the entire length of the line (180 km). Its characteristics are very similar to those applied on LGV in France (14 cm of asphalt layer, 15 cm of adjustment layer in GNT).

Table 4. Requirements for asphalt bonding layer according to Shell Bitumen Handbook [61]

Property	Unit	When using cationic emulsion	When using anionic emulsion
Layer temperature	°C	5-40	5-35
Spread and passing	-	-	ASTM D5: ≥280 mm, T 280 ≤16 s ASTM D30: ≥280 mm, T 280 ≤22 s
Flow	s	18-26	80-120
Workability	min	≥30	
Air content	%	8-12	<10%
Apparent density	kg/m	≥1300	≥1800
Compressive strength			
1 day	MPa	≥0.1	≥2
7 days	MPa	≥0.7	≥10
28 days	MPa	≥1.8	≥15
Flexural strength			
1 day	MPa	-	≥1
7 days	MPa	-	≥2
28 days	MPa	-	≥3
Elastic modulus (28 days)	MPa	100-300	7000-10000
Separation	%	≤1%	<3%
Change of volume	%	1.0-3.0	0-2
Bleeding	%	0	-
Freeze/thaw loss (28 days)	-	Relative dynamic modulus ≥60%, mass loss <5% after 300 freeze/thaw cycles	No failure on surface. Mass loss <2000 g/m^2. Dynamic modulus ratio greater than 60%
Weathering tests (28 days)	-	No peeling, cracking	No cracking after 10000 cycles

7. Conclusions

As explained throughout the paper, asphalt in rail tracks can contribute to:

- secure the planning of the project by creating a working platform during construction, suitable for conventional machinery and with multiple access points to job site, on which subsequent work operations, such as installation of electric lines, ballast and rail laying, are faster and more easily undertaken;
- assist in gradually distributing the loads transmitted by passing trains (lower vertical stress transmitted to the supporting embankment), eliminating any "rupture" of the embankment and producing higher and more homogeneous vertical stiffness values (this can also lead to reduce thickness compared to a conventional granular design);
- protect the embankment body from the seepage of rain-water and from seasonal thermal extremes (so protecting the upper part of the embankment from freeze/thaw action);
- eliminate contamination of the ballast from fine material migrating up from the foundation;
- reduce the vertical acceleration of the superstructure components, extending their service life and increasing travel comfort.
- slow down the degradation rate of the track geometry and reduce maintenance operations and costs.
- increase performance and structural reliability due to increased modulus and uniformity
- reduce life-cycle cost on the infrastructure from reduced subgrade fatigue
- increase homogenization of the track bearing capacity on the longitudinal profile and better ballast confinement
- reduce ballast fouling due to improved drainage

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