

The Use of Bituminous Subballast on Future High-Speed Lines in Spain: Structural Design and Economical Impact

P. F. Teixeira ^{*,**}, P. A. Ferreira ^{**}, A. López Pita ^{*}, C. Casas ^{*}, and A. Bachiller ^{*}

Abstract

The development of structural solutions for high-speed or very high-speed tracks that minimize total life cycle costs of the system is a key issue to improve the operational profitability of new investments. In opposition to conventional ballasted tracks, slab track solutions can be a cost-effective solution, but only in the cases where the benefits due to the increase in track availability and the reduction of track maintenance offsets its much higher construction costs. In the cases where such investment is not feasible, it is worth to evaluate possible structural improvements to ballasted track that allow reducing its maintenance needs without increasing too much its construction costs. This paper evaluates the design requirements and the impact of improving conventional high-speed ballasted tracks by using a bituminous subballast layer. It is divided into two main parts: first the design requirements of the structural solutions with bituminous subballast and its possible benefits on high-speed track deterioration, and secondly the evaluation of the economic impact, in terms of construction costs, of using this structural solution material in future Spanish high-speed lines.

Keywords : Slab Track, Ballasted Track, Bituminous Subballast

1. Introduction

Conventional ballasted high-speed (HS) track structures with all granular trackbed have been in use for the last two decades in Europe, presenting good results although requiring certain maintenance needs. To limit track maintenance costs to a minimum and increase track availability, ballastless track structures have been applied for a long time in high-speed lines in Japan and more recently also in Europe (Germany and Netherlands). However slab track systems require much higher investments making it still difficult to be cost-beneficial in most European new high-speed lines, particularly where the line has a low density of bridges and tunnels, as it is usually the case in Spain. In those situations while the advantages of slab track solutions do not compensate its higher construction costs, it is important to look for some midway solutions: the goal is to improve HS ballasted track design, in order to reach a reduction on its maintenance needs, with slight (if any)

increases on the investment.

Consequently, in order to reduce ballasted track maintenance costs, so called "intermediate solutions" emerge from acting within two main areas (as illustrated in Fig. 1):

- i. Improving track superstructure design by increasing track vertical resiliency using for example softer rail pads, under-sleeper pads or ballast mats;
- ii. Enhancing track substructure long-term bearing capacity, by incorporating stiffer and more durable materials between the subgrade and the ballast layer.

This paper focuses mainly on the second issue, discussing the limitations of conventional granular sub-ballast and evaluating the possible interest of incorporating a bituminous sub-ballast layer on new high-speed lines.

2. The Use of Bituminous Sub-Ballast In High-Speed Tracks as a Possibility to Fulfil High Bearing Capacity Standards

Railway research has confirmed the importance of having a stiff subgrade [5], in what concerns the optimisation of track design for low maintenance needs. Structural catalogues were developed with increased thicknesses of the sub-ballast layers in comparison to conventional tracks, in

*Centre for Innovation in Transport (CENIT)-Technical University of Catalonia (UPC), Spain

**Technical Superior Institute (IST) - Technical University of Lisbon (IST), Portugal

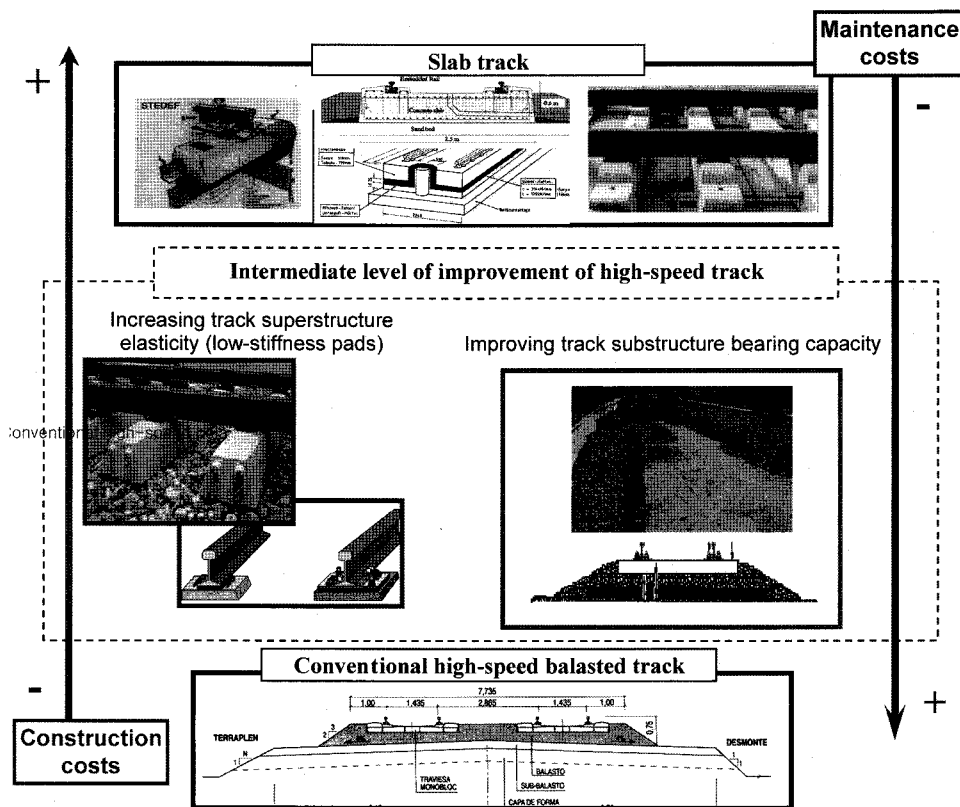


Fig. 1 Schematic representation of structural design options to minimize track maintenance costs

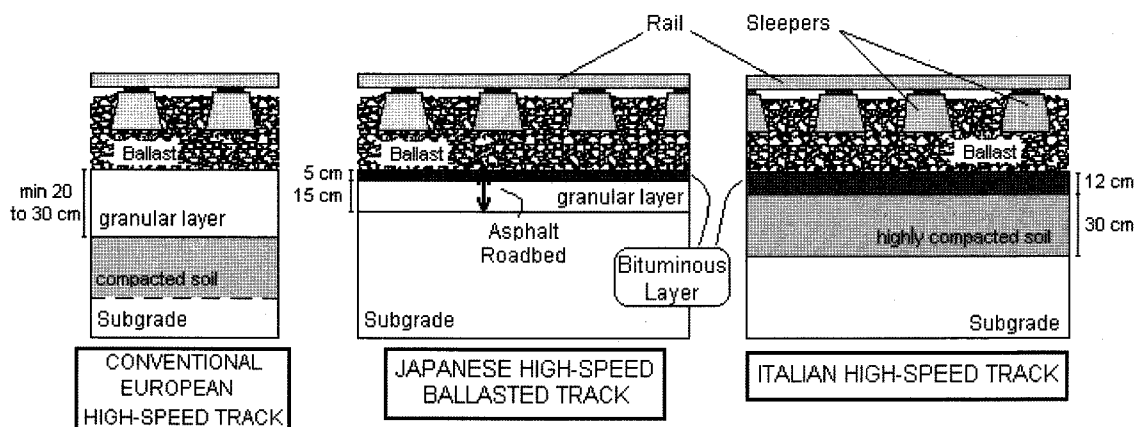


Fig. 2 Typical cross-sections of ballasted high-speed tracks [11]

line with the consequent increase on the bearing capacity requirements for high-speed lines. Thus, minimum bearing capacities within a range of 80 to 120 MPa under the ballast layer are usually required.

As discussed previously, almost all European high-speed ballasted tracks built so far use granular-only materials (sand and gravel). However, this solution might require in certain circumstances the need for very high thicknesses to reach the minimum bearing capacity standards for an high-

speed line. In certain railway administrations, a cement-treated gravels or even an asphalt trackbed is used as an alternative to these granular solutions. That was the case in the first Italian high-speed line and also in Japan. The experience obtained in Italy evidenced a good long-term structural behaviour of the track on the sections with bituminous sub-ballast, leading to the generalization of its use to all the new high-speed ballasted tracks. Fig. 2 shows the structural configuration of Japanese and Italian high-speed

ballasted track structures, in comparison with usual track-bed configuration in Europe.

As it can be seen, on the track sections used in all Italian high-speed tracks, a 12 cm bituminous sub-ballast layer lies on a highly compacted soil that must guarantee a bearing capacity of 80 MPa. In the Japanese solution, the asphalt trackbed is composed by a 5 cm bituminous layer on top of a granular base layer (crushed stone) with a minimum thickness of 15 cm (for good quality subgrade) and can vary to up to 60 cm.

To evaluate the possible interest of using a bituminous subballast, a study was performed to find out the requirements for a bituminous subballast track structure in order to meet current standards applied on the current Spanish very high-speed lines.

3. High-Speed Track Design With Bituminous Sub-Ballast

From a theoretical point of view, the effect of sub-ballast type can be related to the following track design parameters (possible to assess theoretically):

- Vertical stresses and acceleration level on the ballast, as an indicator of possible track settlement (and thus, track maintenance needs and costs)
- Tensile strains on the sub-ballast as an indicator of its service life
- Vertical stresses on the subgrade, as an indicator of subgrade long-term behaviour (track maintenance costs) and overall track service life.

To evaluate the impact of using a bituminous subballast on the static side, a parametric analysis was carried out on a previous study [11], using a well-known and validated numerical model of the track, KENTRACK [10], based on multilayer elastic theory. In this study, the minimum requirements for the bituminous sub-ballast were evaluated and compared with a traditional solution of granular

sub-ballast with thickness of 30 cm, which is the minimum value used in the new high-speed line under construction in Spain and, hence, taken as reference for comparison. The analysis pointed out that slightly increasing sub-ballast thickness is more effective than using high modulus bituminous mixes. The minimum thickness required was found to be between 12 cm to 14 cm to fulfil equivalent stress-strain behaviour (in relation to granular sub-ballast). These considerations were further validated through elasto-plastic finite element modelling. The analysis was performed using common assumption used in railway track finite element modelling for design purposes:

- Concerning the material properties: for soil and granular layers, Drucker-Prager elasto-plastic constitutive laws were used, while both elastic and visco-elastic model were used for the bituminous subballast. An elastic railpad stiffness of 100 Kn/mm was considered.
- Concerning model geometry: the track model geometry considers 12 ties, a width of 4,8 m and 3 m of subgrade depth, considering usual symmetries on vertical plans as usual boundary conditions.
- Concerning track load: as for the previous analysis with Kentrack model [11], an equivalent dynamic axle load was obtained by considering Shenton's criteria, considering current high-speed vehicles used in Spanish high-speed lines.
- Concerning finite elements type: 20-nodes hexahedral elements
- Concerning contact elements: contact interface were considered for the interaction between sleeper and ballast, to substitute rigid nodes between these two surfaces of contact: double nodes were considered and displacements on the surface plan are allowed while on the perpendicular direction displacement are restricted.

Fig. 3 shows the finite element mesh used and the vertical stress results for the current Spanish standards solution (30 cm granular) in comparison with the solution used in

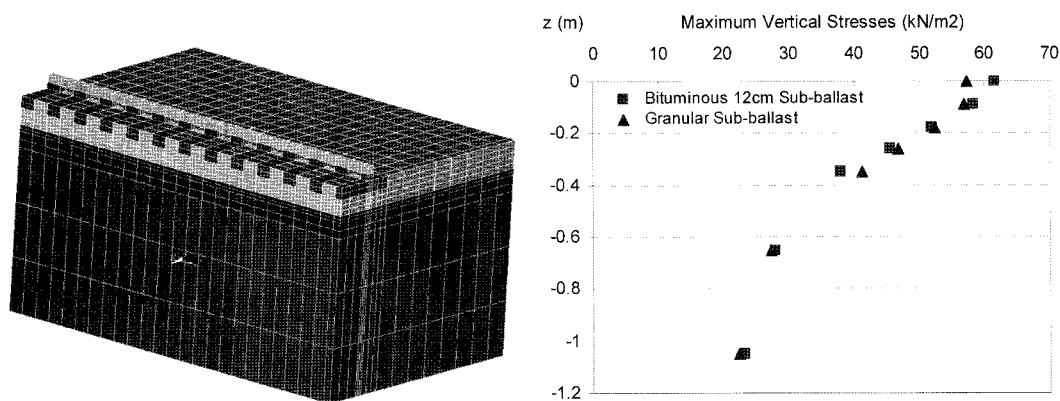
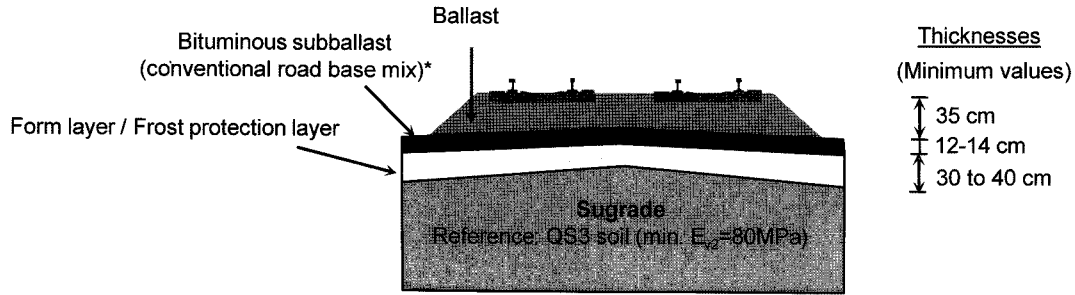


Fig. 3 Example of the finite element mesh used (left) and results for track deformation (right) [1]



* Spanish S20 mixture according to Spanish roadway standards

Fig. 4 Track design with bituminous sub-ballast suitable for Spanish very high-speed lines standards

Italy (12 cm bituminous sub-ballast).

The result obtained for track on good quality subgrade confirmed the previous assumptions and proven that the track configuration exposed in Fig. 4 would guarantee a good theoretical behaviour and an expected service life at least equivalent (from a stress-strain level point of view) to the current track configuration criteria used on Spanish very high-speed lines.

As regards specifically the life service of the bituminous subballast: using common (highway) fatigue criteria based on horizontal tensile strain on the bottom of the layer (from the Asphalt Institute and current Spanish roadway standards) it is found that for a soil of required bearing capacity this fatigue will occur after the fatigue of the subgrade.

4. Advantages of Using a Bituminous Sub-Ballast

When comparing with all-granular solutions, bituminous sub-ballast can offer important comparative advantages from the point of view of long term deterioration of

the subgrade. Fig. 5 enhances the conclusions of a study where it is shown that under a bituminous underlayment, the subgrades' moisture content is kept closer to optimum moisture content. Being almost completely water-resistant, the bituminous subballast enables to maintain unchanged the moisture content during all year and over its life cycle, a factor known to have an important incidence on the subgrade deformation process.

Apart from the improvements reached for the subgrade life cycle, other advantages of using a bituminous mix sub-ballast layer are concerned with the differential settlement of the track. In fact, the use of stiffer materials as subballast can also reduce vertical stiffness variations on the track. A first study [3] carried out by the authors (in collaboration with the University of Rome) analysed the geometric quality deterioration records on sections with and without bituminous sub-ballast on the Rome-Florence high-speed line, as an attempt to evaluate the possible benefits of this solution. Although still requiring further developments, this study indicates a slight positive effect of using bituminous subballast in the maintenance needs at transition sections (bridge-embankment), one of the main

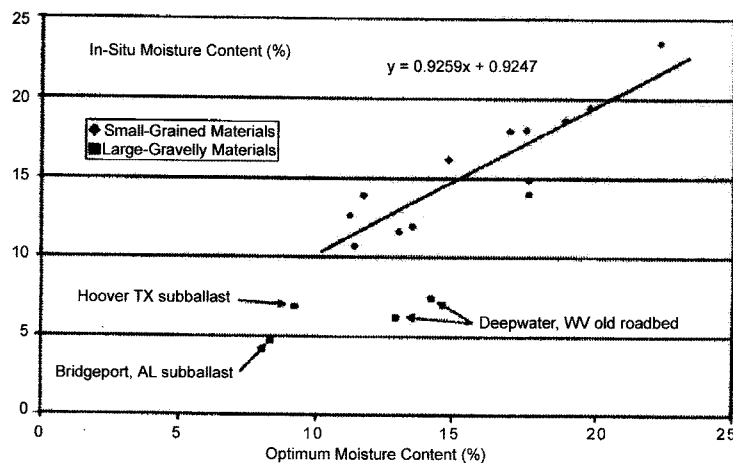


Fig. 5 Relationship between in situ subgrade moisture contents and its optimum moisture contents under a bituminous subballast, after a 16 years monitoring plan, [9]

problems of deterioration in high-speed lines [6, 8]. Ongoing research from the author is aiming to reach some quantitative conclusions about this positive effect provided by bituminous sub-ballast in homogenizing track support settlements.

Another of the major factors of track settlements where the bituminous subballast can play an important part is related to the dynamic behaviour of track at high-speed and very-high speeds, a key factor of track deterioration [7]. To assess this question, displacements and vibration accelerations within the track and sub-track generated by a two-wheel vehicle set travelling at high speeds (300 and 350 km/h) were calculated using a dynamic finite element model. Comparisons made for different types of sub-ballast in what concerns track dynamic behaviour were performed. The following Fig. 6 shows a first approach on this comparison, concerning vertical accelerations.

As it can be seen in Fig. 6, the use of a bituminous sub-ballast can reduce vibration acceleration levels inside the track for speeds of 300 and 350 km/h, comparing to those of a track with an all-granular track bed. Thus, even if in-situ measurements would be required to confirm these first results, it seems reasonable to believe that the use of bituminous material in the sub-ballast layer enhances the dynamic performance at high speeds.

Moreover, according to [2], the benefits already attained using an asphalt sub-ballast layer, may even be increased by adding rubber granulates into the bituminous mix, as it seems to further improve its tendency to dissipate energy and damp vibrations. Similarly, [12] showed that an asphalt mixture with 20% rubber content has an average damping ratio of about 9.5%, whereas without rubber is approximately around 6%, but still greater than normal subgrade soil layers (<3%). These research studies pointed out the great propensity to dissipate energy of this kind of composite material (as the loss factor increases with the increase of rubber content) and, thus, provided evidence of

the good dynamic performance of rubber-modified asphalt when applied to sub-ballast layers of railway high-speed tracks. Furthermore, both groups of authors believe that the bright use of this waste material, enhancing the track sub-ballast anti-vibrating properties, all-together with new design and construction methods, may result in an innovative bituminous mixture to be used in railway tracks in future. However, as referred, it is still required further site experimental measurements in order to obtain more validated conclusions on this matter.

5. About the Economical Impact of Using Bituminous Sub-Ballast in Future High-Speed Lines in Spain

In order to evaluate the feasibility of using bituminous sub-ballast in future high-speed lines to be built in Spain, the impact in terms of investment costs of adopting this solution has to be estimated (in comparison with current structural solution with granular sub-ballast). An analysis was performed focussing on the structure composition of costs for both solutions, assessing the most critical cost factors and its variation along the Spanish territory. For that, an extensive amount of data was recompiled and taken from different sources: infrastructure managers (both road and railway), project consultants, construction companies and material suppliers. The digest of the data obtained, enabled the definition of threshold values for each of the structural solutions [3].

The conclusions show that the transport distance is a key factor in the cost of the granular sub-ballast: in fact, the cost of this layer is highly dependent on the local availability of quarries with material suitable to fulfil Spanish high-speed track standards (LA coefficient < 24). As it can be noticed, from Fig. 7, the price of granular layer can double for distances to quarry varying from 20 to 80 km (a survey carried out among construction sites showed that

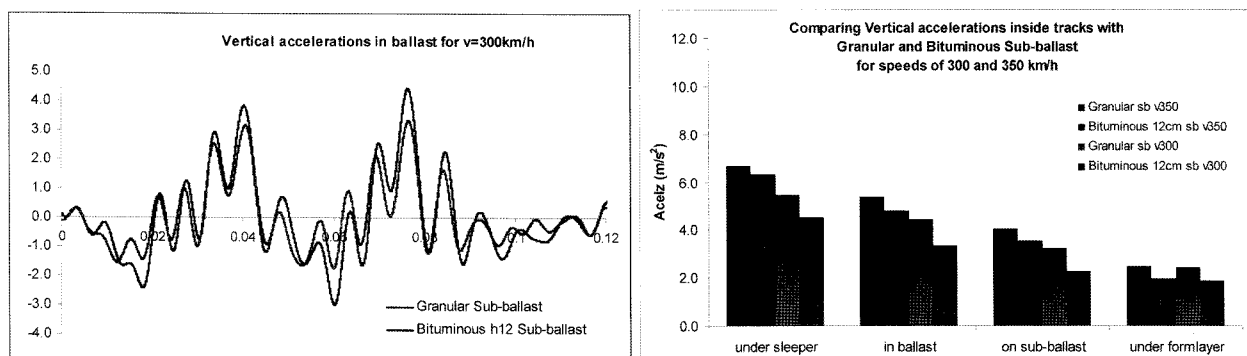


Fig. 6 Vertical accelerations: time-signals in ballast for $v = 300$ km/h (left) and maximum values at different levels in the track for speeds of 300 and 350 km/h (right), comparing two identical HS Tracks with different sub-ballasts [4]

for some sections of the Madrid-Barcelona high-speed line these transport distances were even greater than 80 km). On the other hand, the price of a conventional bituminous mix was found much more stable. The bitumen cost was found to be the factor that most affects the bituminous subballast cost. Comparing both cost functions obtained (for 2005 Spanish construction price levels), it was found that due to the high sensitivity of granular material cost with distances from quarry, the granular sub-ballast starts even to be more expensive than bituminous solution for transport distances above 60 to 80 km. Prices used on this evaluation referred to bitumen prices of November 2005, thus lower than they are today (bitumen cost is related to variations on petroleum prices). As shown in Fig. 7, assuming a variation in 30%, it would suppose a variation on the bituminous subballast cost of about 10%.

In synthesis, from an investment cost viewpoint, these results enable to have a first approach on the economical impact of using bituminous sub-ballast in Spain. When focusing in an application on different future high-speed line corridors to be built in Spain and taking into account the value of the mentioned cost-drivers, it was shown that

in certain occasions the differences in costs of using a bituminous subballast instead of granular-only layers are nearly around 5% [3].

Moreover, another issue that should be considered when evaluating the economical impact of using a bituminous sub-ballast layer is the reduction of around 200 m³/km/track in the volume of ballast required for this solution. This decrease in ballast material needs is due to the water-proof characteristics of bituminous sub-ballast layer, which enables the track lateral slope to be reduced from 5% (required in Spain for granular sub-ballast) to nearly 3% (as adopted in Italy for bituminous sub-ballast), as evidenced in Fig. 8. This saving in ballast material can be equivalent to around 5% of the price of the bituminous sub-ballast layer, considering the average costs of the ballast material suitable for high-speed lines.

These figures show the interest of considering a bituminous subballast structural solution as one of the possible solution for track designers to select, for future high-speed lines in Spain. In line with these findings, a trial section following this solution was built in the Barcelona-Perpignan high-speed line currently under construction, with the

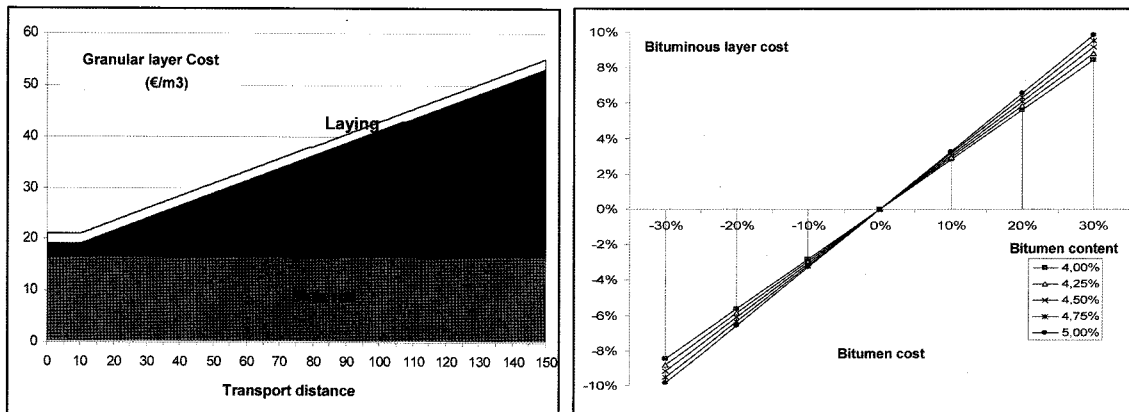


Fig. 7 Variability of a granular sub-ballast cost with distance from quarry (left) and sensitivity of bituminous sub-ballast cost to variations in the bitumen price (right)

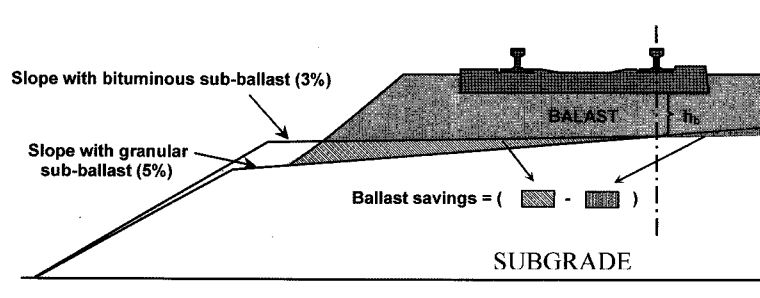


Fig. 8 Schematic representation of the savings in ballast material due to the use of a lower lateral slope for the bituminous sub-ballast solution

purpose of assessing the practical behaviour of this structural solution.

6. Conclusions

The use of bituminous subballast as a possible alternative to all-granular layers for future high-speed ballasted tracks was discussed. A theoretical design recommends the use of a minimum thickness of 12 cm to 14 cm of a conventional bituminous mix is required (as an alternative to the usual granular layers used) in order to meet the Spanish standards for high-speed tracks.

The bituminous subballast solution might bring relevant advantages in terms of: subgrade protection and life cycle; track differential settlement and track dynamic performance. Furthermore, an economical study allowed to define the cost impact of both bituminous and granular subballast, for the Spanish conditions. It is shown that the cost of the bituminous subballast might in certain sections be close to the cost of the granular solution, thus confirming the interest of having a bituminous subballast structural solution as one of the possible solutions to choose, depending on local characteristics. To evaluate this interest, the Spanish Railways have built a trial section (with a length of approximately 3 km) in the Barcelona-French Border high-speed line currently under construction.

The ongoing research on the evaluation of maintenance needs of tracks with bituminous sub-ballast will make it possible in the close future to perform solid life-cycle costs analysis on the viability of this solution, depending on local conditions, such as availability of granular material.

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