Viability of using a bituminous sub-ballast layer on high-speed ballasted tracks

P. F. Teixeira
PhD, Dipl-Ing., Researcher at the Center for Innovation in Transport (CENIT) of the Technical University of Catalonia (UPC), Barcelona, Spain.

A. López-Pita
Professor of Railways, Technical University of Catalonia (UPC).
Director of the Center for Innovation in Transport (CENIT), Barcelona, Spain.

ABSTRACT: The design of higher quality infrastructures reducing its life cycle costs is a major priority to increase the profitability of high-speed railway lines. The experience gained so far has evidenced the influence of track configuration on its maintenance costs. Recent railway research has shown that to fulfil a reduction of those costs one should act optimizing both the resiliency of the fastening system and the subgrade-sub-ballast system. With reference to this last aspect, the aim of this paper is to expose the first results obtained on a research project carried out by the authors concerning the viability of using a bituminous mix sub-ballast layer on the new Spanish high-speed lines. The interest of this solution to increase long-term performance of the track is discussed based on the available experience. Furthermore, the results of a parametric study evidences in what terms this solution can be technically feasible to reduce maintenance costs and increase service life of ballasted high-speed tracks.

KEY WORDS: Track, high-speed, sub-ballast, bituminous layer.

1 INTRODUCCIÓN

About forty years after the inauguration of the world first high-speed line between Tokyo and Osaka, and more than twenty years after the building of the first European high-speed line (Paris-Lyon), high-speed rail has proved to be one of the most competitive means of transport on intercity medium distances. Among other aspects, the improvements made on the railway track design have played an important part on the development of the performance of this transport mean. Indeed, in a time where conventional railway track design seemed to have reach a certain level of optimization, the building of the first high-speed lines in Europe led to an important improvement on the track configuration. The perfection of rail-fastening-sleeper system as well as the progress in the ballast-subgrade requirements made it possible to suit higher speeds services without increasing too much maintenance costs.

In that context, most European railway administrations have developed structural recommendations for the design of its high-speed infrastructures. In most cases, to fulfill the required bearing capacity of the track, the use of granular layers (as sub-ballast) is specified. The results obtained with the use of granular materials have been globally positive so far. However it is worth to recognize that the use of granular sub-ballast presents some limitations, like the need in some occasions to built elevated thicknesses to reach the required bearing capacity.

Conversely, in Italy, the national railway administration (FS –Ferrovie dello Statto) developed structural configurations using other materials on the building of its first high-speed line Roma-Firenze, like a cement-based granular layer and, specially, a bituminous sub-ballast layer. The good results obtained on this line with this last material led the Italian Administration to adopt this solution for all the new lines actually under construction in that country.

This paper analyses the interest that may present the use of the mentioned bituminous sub-ballast layer on the new Spanish high-speed lines, as an alternative to granular sub-ballast used so far.

2 CONVENTIONAL HIGH-SPEED TRACKS

The development of the European high-speed rail network started on the 60's and 70's when the Italian, French and German Railway Administrations decided to build their first links. Nowadays, European high-speed rail network reaches almost 4.000 km with the distribution and the structural characteristics showed on table 1 (those characteristics refer to plain track configuration, i.e. excluding tunnels, bridges or other particular situations along the route).

Table 1: Main characteristics of the high-speed lines built in Europe until 2005. Source: based on data form UIC.

COUNTRY (KM OF HSL)	HIGH-SPEED LINES	RAIL TYPE – SLEEPER TYPE (EFFECTIVE SURFACE AREA) - RAILPAD STIFNES (k_{pa})	SETTING BED (BALLAST-SUBGRADE SYSTEM)
FRANCE (1541 km)	TGV Sud-Est, Atlantique, Nord, Rhône-Alpes, Jonction, Méditer.	Rail UIC 60 Bi-block/monoblock sleeper (2436-3944 cm^2) k_{pa} = 90-100 Kn/mm	Ballast: 30-35cm + **granular sub-ballast** (min. thickness: 20-55cm)
GERMANY (754 km)	Mannheim-Stutt. Hannover-Würzb. Hannover-Berlin	Rail UIC 60 Monoblock sleeper (3340-3780 cm^2) k_{pa} = 30-500 KN/mm	Ballast: 35-40cm + **granular sub-ballast** (min. thickness: 30-70cm)
	Köln-Frankfurt	Slab track	----
SPAIN (916 km)	Madrid-Sevilla Madrid-Lérida	Rail UIC 60 Monoblock sleeper (3010 cm^2) k_{pa} = 100-500 KN/mm	Ballast: 30-35cm + **granular sub-ballast** (min. thickness: 25-30cm)
ITALY (466 km)	Roma-Firenze Roma-Napoli	Rail UIC 60 Monoblock sleeper (3900 cm^2) k_{pa} = 100 KN/mm	Ballast: 35cm + **Bituminous sub-ballast** (min. thickness: 12 cm)
BELGIUM (150 km)	Brussels-France	Rail UIC 60 Monoblock sleeper (3688 cm^2) k_{pa} = 50-100 KN/mm	Ballast: 35cm + **granular sub-ballast** (min. thickness: 20-55cm)
UK (74 km)	CTRL - 1	Rail UIC 60 Bi-block sleeper (2436 cm^2) k_{pa} = 60-100 KN/mm	Ballast: 35cm + **granular sub-ballast** (min. thickness: 20-55cm)
FRANCE-UK (52 km)	Channel Tunnel	Slab track	----

As it can be observed from the former table, conventional ballasted track is used in almost all the current high-speed lines (exception from the last German links). On these ballasted tracks, it is worth to point out that there is a certain homogenization on some important parameters of the track design such as the rail type or the use of monoblock sleepers. The sleeper spacing parameter is not shown, but it is known that it is around 60cm in all lines. The only track "superstructure" parameter that presents relevant differences from one line to the other is the railpad stiffness, that can vary from 30 kN/mm to up to 500 kN/mm. A methodology to optimize this important parameter for high-speed lines was developed by the authors (Teixeira, 2003; López Pita et al., 2004).

In relation to the infrastructure conception, large majority of solutions adopts a granular sub-ballast layer with thicknesses that varies according to the formation bearing capacity, but with a minimum of around 20cm to 30cm. Fig.1 shows a typical configuration of the subgrade system with the minimum bearing capacity required for the sub-ballast layers in Germany.

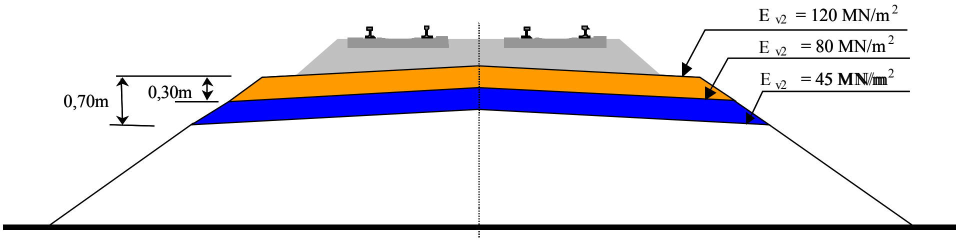

Fig.1: Characteristics of the track subgrade of the Hannover-Würzburg high-speed line.

3 LIMITATIONS OF THE GRANULAR SUB-BALLAST LAYER

The use of granular materials as sub-ballast is a solution that has been improved with the experience along the last decades and it has shown, in general, good practical results.

However, it should be said that the thickness values on table 1 and fig.1 correspond to minimum values, since it might be necessary in certain occasions to increase that thickness when the subgrade has a low stiffness, in order to fulfil the needed bearing capacity for the ballast bed, as it can be deduced from fig.2. In particular situations during the construction of the track, the technical unfeasibility of keeping increasing the thicknesses of the granular layers lead to the use of stiffer materials, such as cement-treated granular layers.

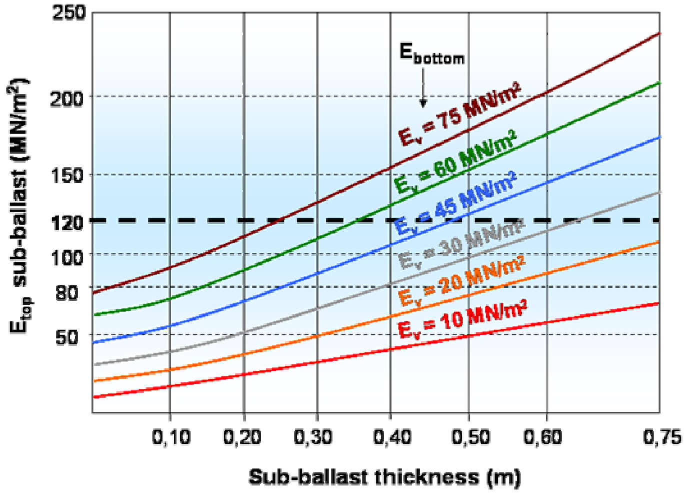

Fig.2: DB (Deutsche Bahn) design chart to evaluate the necessary thickness of the granular sub-ballast layer, depending on the bearing capacity of the bottom layer.

Furthermore, the limitations of granular materials as sub-ballast are not only its reduce stiffness when the subgrade is weak. Among others, some well known limitations of the tracks with granular sub-ballast layers are:

1. Difficulty to fulfil an homogenous bearing capacity along the track
2. Possible problems related to the permeability of the sub-ballast, possible subgrade and ballast contamination, moisture content variation of the subgrade

Concerning the first aspect, it is known that the ballasted track bearing capacity presents important variations along a route, as it can be seen on the example of fig.3. Those pronounced variations on the track vertical stiffness appear as well on tracks along an infrastructure of good quality such as it is generally the case in most high-speed lines.

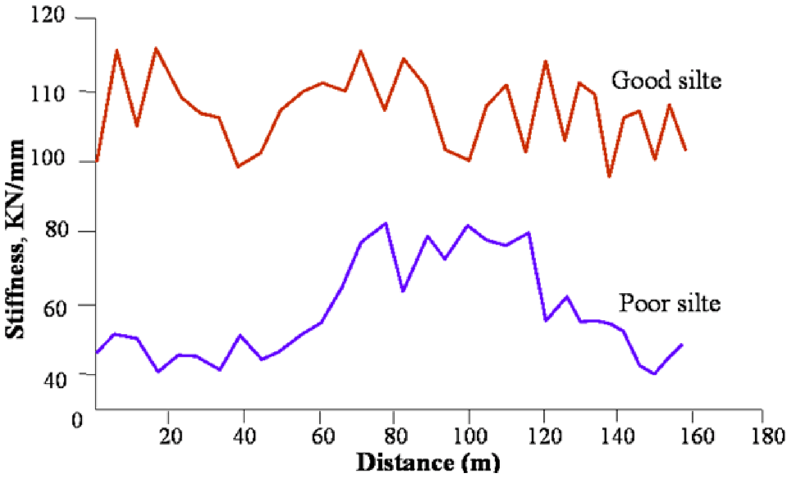

Fig.3: Measurments of track vertical stiffness on good and poor quality subgrade. Source: Hunt (2000)

The effects of the track vertical stiffness variations on the track geometry deterioration are well known, like for example in the case of the transitions embankments-rigid structures (such as a bridge). The experience has shown considerably higher track deterioration on those critical points than in plain track. As a matter of fact, an extensive statistical analysis of the track maintenance needs of the Madrid-Sevilla line, during its first ten years of commercial operation, has shown that the track deterioration process on the transitions bridge-embankment are about 7 times higher than in plain track (Ubalde, 2004).

In another hand, there are numerous theoretical studies that proved the negative effects on track maintenance needs of usual stiffness variations along a route, even on plain tracks. In consequence, to avoid an excessive deterioration of high-speed tracks geometry, the authors of this paper have proposed the establishment of a criteria that limits the maximum allowable stiffness variation measured between consecutive sleepers (López Pita and Teixeira, 2001; Teixeira, 2003). In certain circumstances the use of a sub-ballast of low stiffness such as the granular-only materials may difficult the accomplishment of this criteria.

In relation to the second limitation mentioned, the difficulty to protect correctly the subgrade along its life cycle, it is worth to refer the frequent problems that occur on certain soils when the moisture content of the subgrade varies along the year. Granular sub-ballasts tend to loose its properties of waterproofing along the time, generating problems of subgrade deterioration.

Furthermore, the structural design of the high-speed tracks must consider some important aspects of the commercial offer of this transport mean on the close future, such as:

- The increase and diversification of the use of the high-speed European network, with mix traffic and new services such as regional high-speed and high-speed night trains that will, in one hand, increase the maintenance needs, but in another hand, reduce the available time for maintenance purpose.
- The increase in maximum speeds to up to 350 km/h, as it is the case on the future line Madrid-Barcelona-French Border, actually under construction.

Both aspects justify the interest and the need in investigating possible improvements on the track structural design in order to limit its maintenance costs. In relation to the sub-ballast role, the abovementioned limitations of the granular layer usually employed give good reason for the study of the viability of using other materials, such as the bituminous mix used in Italian high-speed lines.

4 THE POSSIBLE INTEREST OF THE BITUMINOUS SUB-BALLAST LAYER: THE ITALIAN EXPERIENCE

As it was shown in table 1, the only European administration that doesn't use a granular-only sub-ballast on its high-speed ballasted lines is the Italian one.

Indeed, for the construction the "diretíssima" Rome-Florence (the first high-speed project in Europe), the Italian Railway Company "Ferrovie dello Stato" (FS) state very high levels of track bearing capacity, with a minimum modulus of up to 180 MPa under the ballast. To accomplish this criteria, FS design department proposed the use of a gravel treated with cement ("misto-cementato") as sub-ballast. The material used is generally crushed limestone with a reduced percentage of cement (3% to 4%) and a water content of around 6%. Its thickness varies depending on the characteristics of the foundation, but most common values are around 20cm.

However, during the construction of the first sections of the line, an alternative solution with a bituminous mix was proposed by the track contractors and the FS research department. The high performance that could be reached on the building of the track with this new solution, together with the important savings in terms of crushed stone comparing to the former solution (and the high distance of transport of that material in those sections) justified the development of the bituminous sub-ballast solution.

After the good results obtained on the 3 trial sections built (11,2 km between Settebagni and Stimigliano, 5 km between Figline-Firenze and 3 km between Barsano-Città de la Pieve), the Italian administration decided to incorporate this solution as a possible alternative on all the sections of the Rome-Florence line. The characteristics of the cross-section with the bituminous sub-ballast are shown in fig.4.

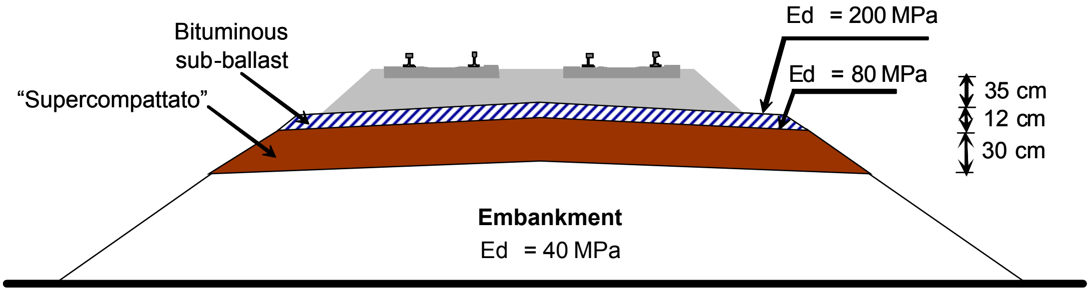

Fig.4: Characteristics of the track subgrade of the Rome-Florence high-speed line.

As it can be seen, the bituminous sub-ballast has a minimum thickness of 12cm. Underneath there is a highly compacted trackbed (called “supercompattato”) that must guarantee a minimum E_{v2} modulus of 80 MPa.

The very good long-term behaviour of this track configuration led the Italian Railways and more specifically the engineering department ITALFERR to stipulate its use on all the new high-speed lines in that country.

From an approximate qualitative approach shown in table 2, it is clear that the use of a bituminous mix as sub-ballast on high-speed ballasted tracks might bring some relevant benefits (comparing to the usual granular layers) in important factors of the track design problematic. Indeed, it can promote a positive effect on track reliability, track life-cycle and track maintenance needs, although with an estimate higher construction cost.

Table 2: Qualitative effect of using a granular or a bituminous sub-ballast layer, in relation to the most relevant track design factors.

FACTOR	**QUALITATIVE EFECT**		**OBSERVATIONS**
	GRANULAR SUB-BALLAST	**BITUMINOUS SUB-BALLAST**	
Safety and Structural reliability	Positive	Very positive	Bituminous sub-ballast increase track reliability.
Life-cycle of the infrastructure	Positive	Very positive	With a higher modulus, bituminous sub-ballast reduces subgrade fatigue (even with much lower thickness).
Track geometry deterioration and maintenance needs	Positive	Very positive	Bituminous sub-ballast gives: - Better homogeneization of the track bearing capacity on the longitudinal profile. - Better ballast vertical confinement.
Possible ballast contamination	Positive	Very positive	Bituminous sub-ballast gives an excellent protection of the ballast.
Draining of raining water	Positive	Very positive	Bituminous sub-ballast is almost completely waterproof.
Construction	Positive	Very positive	The use of bituminous sub-ballast give rise to higher performance in terms of time and behaviour during construction period (unaffected by the atmospheric conditions)
Layer substitution	Positive	Negative	It is more difficult to substitute the bituminous sub-ballast (specially when maintenance intervals are short)
Vibrations and noise transmitted to the environment	Not relevant	Very positive	Measurements performed by Italian Railways have shown an important effect of the bituminous layer in reducing vibration levels (specially if the mix incorporates rubber grains)
Use of natural resources	Negative	Negative	Higher thicknesses for granular layer (and thus high use of material). The bituminous mix uses less degree of material, but it incorporates a derivative of petroleum.
Cost	Not relevant	Negative	Granular sub-ballast has a delimited price (but depends in great deal on the on the availability of the material on the construction site –transport distance). Bituminous sub-ballast is generally more expansive.

5 THEORETICAL ANALYSIS OF THE BITUMINOUS SUB-BALLAST BEHAVIOUR IN COMPARASION WITH GRANULAR SUB-BALLAST

Some theoretical analysis of track behaviour with a bituminous sub-ballast have been carried out in the past mostly in Italy (Crispino et al. 1997 or Buonanno, 2000 among others) and in the U.S. (Rose et al.,2003). However the results are in one hand (Italy) mostly dedicate to fulfil an improvement of the bituminous mix or, in another hand (U.S.), applied to lines with very heavy freight traffic.

To get deepen into the possible interest of using a bituminous sub-ballast in new high-speed lines, it is important to compare the performance of this new solution to the existing ones, from two perspectives:

1. Defining the design requirements for the new solution (modulus, thickness) in order to fulfil at least the same or superior performance than the exiting granular solution. This performance is defined by track design parameters (such as "sub rade fatigue")
2. Those track design parameters should be able to be correlated to economical aspects in order to evaluate the best solution on a life-cycle cost analysis (LCC)

From a theoretical point of view, the incidence of sub-ballast type can be related to the following (easily assessable) track design parameters:

- Vertical stresses 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 those aspects a parametric study is carried out, using a well-known and validated numerical model of the track (KENTRACK). This track model is based on the resolution of the equations from the elastic multi-layer theory and incorporates also a finite element procedure for the rail-railpad-sleeper system (fig.5). A detailed description of the track model can be found in Rose et al.(2003).

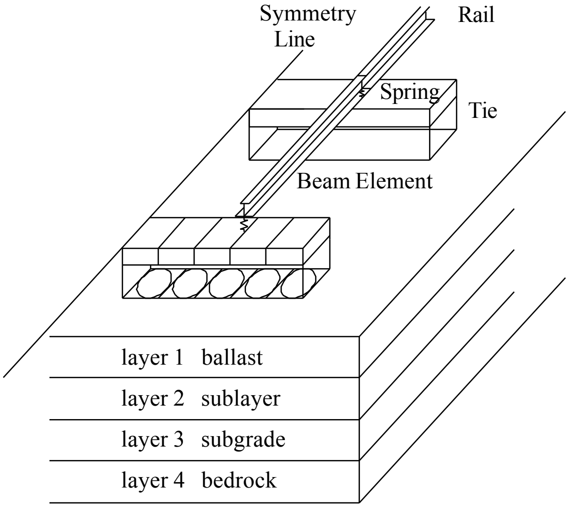

Fig.5: Sketch of the railtrack model (KENTRACK) used. Source: J.Rose et al. (2003)

Furthermore, an algorithm was developed to evaluate track load inputs, that must represent the design quasi-static loads at high-speeds (CENIT, 2004), based on a development of the well-known findings established by French National Railway Comapany, SNCF (Prud'homme, 1970; Alias, 1984). In that methodology, the dynamic overloads transmitted to the track are obtained taking into account the standard deviation of the dynamic overloads or the unsprung and sprung masses. An additional improvement was made to take into account as well the semi-sprung masses. The parameters involved in that formulation are the masses of the vehicle, the damping of the vehicle springs, the maximum speed, the spectral density of track defects and the track vertical stiffness and damping, among others.

The vehicles considered on the study are the high-speed trains that are operating or will be operating on Spanish high-speed lines: AVE 101 (Alstom TGV), AVE 102 (Talgo-Bombardier 350) and AVE103 (ICE 3). The maximum running speed considered is 300 km/h for the first vehicle and 350 km/h for the other two. On this paper the results presented are for the AVE 101 vehicle, thus with a design running speed of 300 km/h. To evaluate the effect on track fatigue of different axle loads, a representative double-axle is obtained by using the well known Shenton's law that gives a higher value than the arithmetic average but lower than the maximum axle.

Concerning track geometric quality, three levels of track quality were considered to calculate the spectral density of the defects, corresponding to a high, medium and low level of quality. The results presented in this paper are for low level of quality, thus, the most unfavourable situation (even if it the less susceptible to happen on high-speed tracks, it is the recommendable from a design perspective).

Since one of the factors (track stiffness) depends on the track characteristics (variable on this study) the calculation of the load input is an interactive procedure: for an initial load Q_0 it calculates the track vertical stiffness (K_0), then evaluates the dynamic load Q_i, and calculates again track stiffness (K_i) until it converges.

The first phase of the study was based in an elastic linear assumption, with the properties of the materials showed in table 3.

Table 3: Properties of the track components considered on the study.

MATERIAL	GRANULAR SUB-BALLAST STRUCTURE	BITUMINOUS SUB-BALLAST STRUCTURE
Rail UIC60	E = 210 GPa; I = 3055 cm^4; Weight = 60,34 kg/m	
Monoblock sleeper	E = 64 GPa; Weight = 315kg; (2,60m x 0,30m x 0,22m) Sleeper spacing = 0,60m	
Railpad stiffness	k_{pa} = 25 to 500 KN/mm ***(Referente: 100 kN/mm)***	
Ballast	E=130 MPa; ν=0,2; Thickness = 0,35 m	
Sub-ballast modulus	100 to 200 MPa ν=0,3 ***(Reference: 200 MPa)***	2.000 to 11.000 MPa; ν=0,45 f (temperature, voids, bitumen volume, frequency)* ***(Reference: 9.000 MPa)***
Sub-ballast thickness	20 to 50 cm ***(Reference: 30cm)***	8 to 14 cm ***(Reference: 12 cm)***
Subgrade (Poor, medium and good quality)	E (variable) = 12,5 to 80 MPa ; ν=0,3 to 0,4 ***(Reference: 80 MPa, n=0,3)***	

(*) see Huang et al. (1984)

Fig.6 shows the part played by the magnitude of different track parameters, in this case related to the vertical stresses transmitted to the subgrade. As it can be observed, track geometric quality and the railpad stiffness are the parameters in which a change may suppose a higher degree of variation on subgrade stress level, and thus, on subgrade fatigue and service life (apart of course from the bearing capacity of the subgrade itself). Regarding the bituminous sub-ballast layer, it is worth to point out that increasing slightly the thickness will be a more important factor for the subgrade fatigue than increasing the sub-ballast dynamic modulus itself (using a high-modulus bituminous mix for example will have a reduce effect).

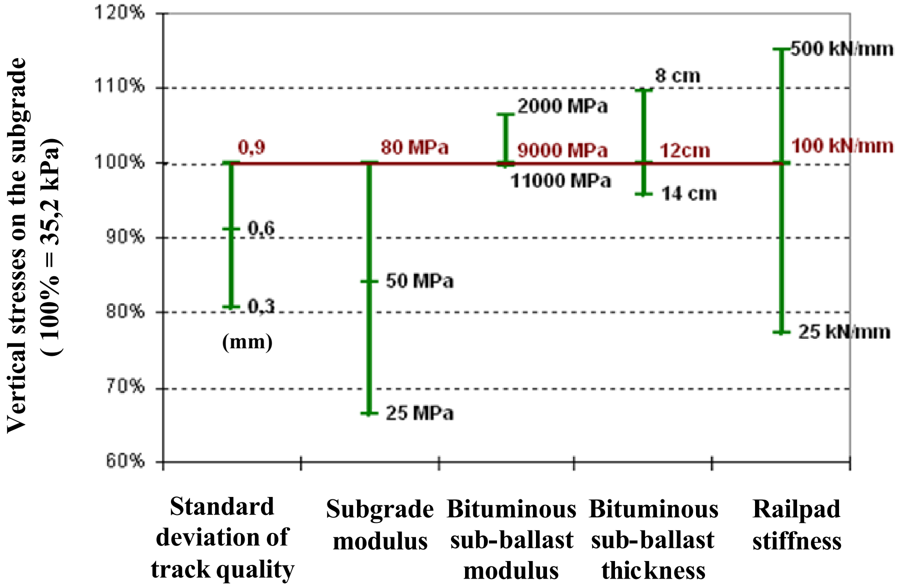

Fig.6: Role of different track parameters on subgrade stresses (bituminous sub-ballast).

The first step of the study is to evaluate the minimum requirements for the bituminous sub-ballast comparing to the actual solution. Actually, the new high-speed line under construction Madrid-Barcelona requires a minimum of 30cm of granular sub-ballast, and therefore this the value that is taken as reference. The analysis has shown that, to fulfil equivalent stress-strain behaviour, a conventional bituminous mix should reach a minimum thickness of 12 to 14cm. As it can be observed on fig.7, in this situation the stress level in the ballast layer and on top of the subgrade will be equivalent. That means that starting from these values, maintenance costs are expected to be at least equivalent using the bituminous mix solution (assuming a stress-based track deterioration criteria).

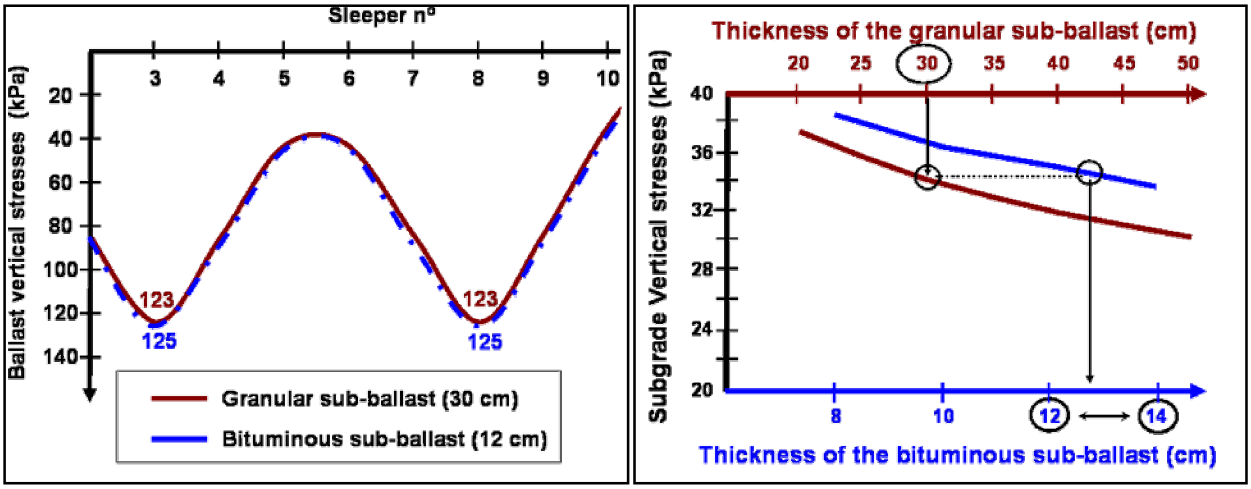

Fig.6: Schematic representation of the results of ballast (left) and subgrade (right) maximum vertical stresses for granular and bituminous sub-ballast.

Lastly, concerning the service life of the bituminous subgrade itself, it is found that this fatigue will always occur far after the fatigue of the subgrade, and thus it will not be a constraint on the estimation of track service life (using common fatigue criteria based on horizontal tensile strain on the bottom of the layer, from Asphalt Institute and Spanish roadway standards –"Norma 6.1.IC", 2003).

In synthesis, from a stress-strain point of view, the use of bituminous sub-ballast with 12cm to 14cm of thickness will fulfil the usual high-speed tracks requirements.

CONCLUSIONS

The possible interest of using a bituminous sub-ballast layer on new high-speed tracks was discussed. A theoretical analysis settle the bases from which the use of this material can be worth, which is a minimum thickness of 12cm to 14cm for a conventional bituminous mix. Nevertheless, as it was evidenced in table 2, the use of a bituminous sub-ballast would present further benefits that are not possible to evaluate theoretically, such as the better homogeneization of the track stiffness, an higher protection against environmental conditions, water proofing and keeps subgrade moisture along the time. Therefore track maintenance costs are expected to be lower with this solution. At present, CENIT's research project is comparing the maintenance needs of tracks with different sub-ballast in order to identify and quantify the practical effects of a bituminous sub-ballast in high-speed life-cycle costs.

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REFERENCES

Alias, J. 1984. La voie ferrée -Techniques de construcción et d'entretien. Deuxième edition. Editions Eyroles et SNCF.

Buonanno, A., 2000. *Il sub-ballast in conglomerate bituminoso*. La Tecnica Professionale n. 9, September 2000, pp. 43-48.

CENIT, 2004. *Estudio sobre la viabilidad de incorporar capas de sub-balasto en material bituminoso en las líneas de Alta Velocidad en España*. Confidencial Report.

López Pita, A. and Teixeira, P.F., 2001. *Resistant track homogeneity: a way to reduce maintenance costs*. Proceedings of the 4th International Conference "Railway Engineering 2001", London, April-May 2001, pg. 1-10, ISBN 0-947644-45-8.

López Pita, A, P. Fonseca Teixeira and F.Robusté, 2004. *High speed track deterioration: the role of the vertical stiffness of the track*. Proceedings of the Institution of Mechanical Engineers - Part F - Journal of Rail and Rapid Transit. Vol. 218, Issue 1, March 2004.

Prud'homme, A., 1970 . *La voie*. Revue Générale des Chemins de Fer, nº 1, pp.56-72.

Rose, J.G., Bei Su and Long W., 2003. *Kentrack: A Structural Analysis Program for Heavy Axle Load Railway Trackbed Designs*. Proceedings of the 5th International Conference Railway Engineering, London, 2003.

Teixeira, P., 2003. *Contribución a la reducción de los costes de mantenimiento de las vías de alta velocidad mediante la optimización de su rigidez vertical*. PhD Thesis. Technical University of Catalonia (UPC-ETSECCPB), Barcelona, Spain.

Ubalde, L., 2004. *La auscultación y los trabajos de vía en la línea del AVE Madrid-Sevilla: Análisis de la experiencia y deducción de nuevos criterios de mantenimiento*. PhD Thesis. Technical University of Catalonia (UPC-ETSECCPB), Barcelona, Spain.