EVALUATION OF DESIGN OF RAILWAY'S SUB-STRUCTURE IN HIGH-SPEED

João Nogueira Alves

Abstract: The design of transport infrastructure within the high-speed rail does not always reflect environmental and economic aspects. The purpose of this study was to define alternative hypotheses to the use of traditional materials, which sometimes may require the unnecessary extraction of soil or the purchase of land of good quality.

In order to carry out this analysis it was necessary to conduct a thorough study of this type of alternative materials, by characterizing materials stabilized with lime and cement (lime-stabilized soil, soil reinforced with cement, soil-cement and cement-stabilized gravel) and bituminous mixtures. Traditional materials were also classified according to their mechanical properties.

Using finite element analysis, representative models of the railway have been created, which simulated the appliance of alternative materials, namely the replacement of the granular sub-ballast layer by bituminous mixtures and of the formation layer on good soil by materials treated with lime and cement.

Due to the degradation process caused by the movement of the train it became necessary to perform an analysis that took into consideration long-term behavior. The models of structural deterioration for each type of material used in the simulations were tabulated and studied and a comparison was made to an equivalent period of life associated with the use of traditional materials on track.

Finally, a range of section samples has been created, allowing the designer an easy reading on the type of section to be applied depending on the materials available *in situ.*

Keywords: high speed railway, material stabilized with lime and cement, bituminous mixtures, granular sub-ballast, formation layer, models of structural deterioration.

1 Introduction

This article aims to summarize a theory that studies the profile characterization of high speed railways, making the use of alternative materials in the layers of sub-structure. This solution makes it ideal when there are no soils *in situ* with the minimum requirements for this type of use. It will be examine the feasibility of using materials stabilized with both lime and cement and bituminous mixtures, in terms of structure and durability, which requires an intense study of these materials because of their little characterization in the international bibliography.

In a first analysis the railway and its elements will be characterized, summarizing some basic functions that are crucial for this study. Then, alternative materials will be analyzed in order to obtain the mechanical characteristics necessary for this analysis. To characterize the durability of these materials, when subjected to the process of deterioration, methods of analysis of the deterioration of the track subgrade were defined as well as some models of structural deterioration in the evaluation of substructure’s layers. This subchapter becomes crucial in this context since the whole subgrade design that will be made depends on the life-time of the track subgrade in the traditional high-speed railway, composed of high soil quality. In the fifth chapter the conditions imposed on the finite element method, in which the model was made, will be set and finally, in the last chapter, the final results obtained using all the assumptions made, will be shown.

2 Elements of a railway

A railway track is composed by several elements that ensure a balanced overall operation so that the train movement is carried out with safety, comfort and low cost.

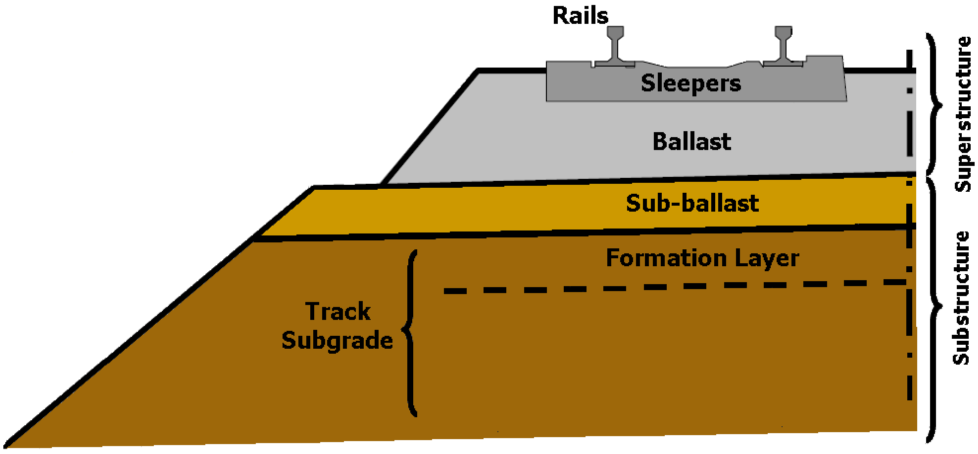

Fig. 1 – Elements of a railway – Super and substructure

The superstructure is composed by the visible elements of railway track: the ballast, the rails, the sleepers and the fastenings (it connects the rails and the sleepers). On the other hand, the substructure is defined by the structures below the ballast, which are the sub-ballast layer, formation layer and finally the track subgrade.

The sub-ballast layer has the primary function of reducing the impact of traffic loads on the track subgrade without requiring the excessive increase in thickness of the ballast. Standard granular materials of good quality are used in its constitution. The track subgrade absorbs the efforts coming from the upper layers and transmits them to the natural terrain; this structure is usually composed of local soils.

Finally there is the formation layer, which is particularly important when the sub-ballast layer and the track subgrade have different materials (depends on the quality of the soil in situ). It normally consists of good soil, allowing a smooth transition of the loads. The formation layer also allows a reduction in efforts at the top of the track subgrade, avoiding the excessive increase in thickness of the sub-ballast or ballast. The reduction of such efforts has a direct implication on the length of the track subgrade, being important to be considered when long-term analyses are made. The International union of railways, UIC [21], ranks the track subgrade in the classes of P1, P2 and P3 corresponding to mediocre, average and good quality respectively. This ranking is done by UIC 719R document, defined in table 1. Only the P3 class is suitable for use in high-speed railways.

Table 1 – Track subgrade classes for high-speed railways – UIC –[21]

Track subgrade soil[1]	Track subgrade class	Formation layer	
		Formation layer soil	Thickness (m)
QS1	P1	QS1	-
	P2	QS2	0,5
	P2	QS3	0,35
	P3	QS3	0,5
QS2	P2	QS2	-
	P3	QS3	0,35
QS3	P3	QS3	-

[1]The same institution, UIC, classifies the track subgrade soils in four classes according to increasing quality: QS0, QS1, QS2 and QS3. The QS0 and QS1 correspond to clay soils, and the QS2 and QS3 to granular soils.

The traditional track subgrade for high speed railways is usually composed of only QS3 soil, belonging to the class P3 (the last row of table 1).

3 Characterization of alternative materials adopted

In this chapter the alternative materials were characterized for a correct design in this study. The following materials were defined: lime-stabilized soils, cement-stabilized soils, cement-stabilized gravel and bituminous mixtures.

3.1 Lime-stabilized soils

Lime is a widely used material in the construction sector designated chemically as calcium oxide or calcium hydroxide. The lime stabilization, a chemical process that begins with the reaction between the lime and clay component of the soil, is not recommended for soils with a low amount of clay (granular soils). During the process, there is an assemblage of clay particles, making the soil less clayey, and at the same time increasing the resistance. Given the short study of this kind of materials a study carried out based on formulations by various authors, both theoretical and experimental. The graph in figure 2 relates the elastic modulus with its lime content in various soils stabilized with lime, and it was made by the application of expressions, which correlates these two values, to a set of tests of soil treated with lime made by several authors who sought to obtain compressive strength. The tensile strength was estimated in a similar way, the rest were obtained from literature. Table 2 shows these values.

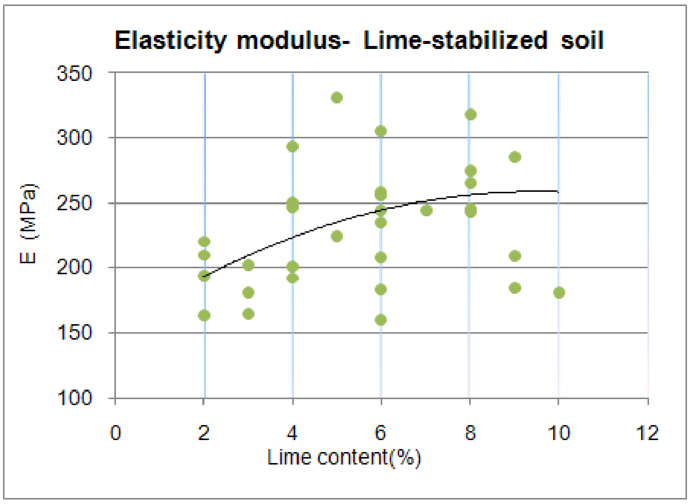

Fig. 2 – Elasticity modulus versus Lime content

Table 2 – Characterization of lime-stabilized soils

Mixture type	Elasticity Modulus (MPa)	Poisson's ratio	Density (kg/m^3)	Tensile strength (MPa)
Lime-stabilized soil	250	0,2	1690	0,24

3.2 Cement-stabilized soils.

The cement, especially Portland, is one of the most used materials in construction worldwide. It consists of one part of calcium, silica, aluminum and a small fraction of gypsum . In the soil cement stabilization process, initially, a process similar to the phenomenon of assemblage of lime takes place, because of the small amount of calcium. Then there is a filling of the empty air voids of the soil by the molecules of the cement, forming a rigid matrix and increasing the resistance of the soil significantly. It is a process recommended for granular soils or little clay, only granular soils were analyzed. Two types of soils stabilized with cement, cement-treated soil (2 to 3% cement content) and soil-cement (5 to11% cement content) were adopted. [4].. In a way similar to the previous case, an analysis was done with a set of tests, carried out by different authors and concerning the soils treated with cement. Thus it was possible to plot the figure 3 as well as to obtain a relationship that allows relating the elastic modulus with the content of the cement. The remaining values were properly referenced in the dissertation and are shown in table 3.

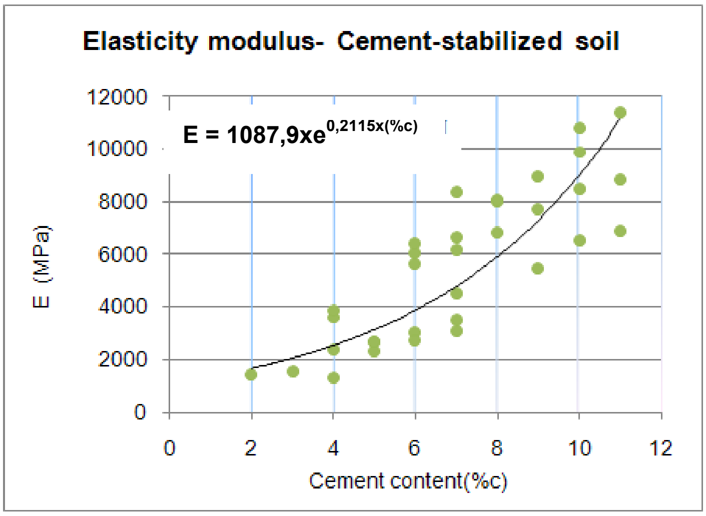

Fig. 3 – Elasticity modulus versus Cement content

Table 3 – Characterization of cement-stabilized soils

Mixture type	Elasticity Modulus (MPa)	Poisson's ratio	Density (kg/m^3)	Tensile strength (MPa)
Soil reinforced with cement	1600	0,25	1760	0,24
Soil-cement	4800			0,95

3.3 Cement stabilized gravel

The simple compression gravel provides an excellent resistance to compression, however, it does not guarantee any tensile strength, not being suitable for layers of railroad substructure. Mixing this material with cement, it develops a process similar to the case of soils stabilized with cement, filling the empty air voids of the gravel matrix and providing a strong resistance. The properties obtained in the study, which are bibliographically referenced along the thesis, are described in table 4.

Table 4 – Characterization of cement-stabilized gravel

Mixture type	Elasticity Modulus (MPa)	Poisson's ratio	Density (kg/m^3	Tensile strength (Mpa)
Cement stabilized gravel	15.000	0,2	2300	1,32

3.4 Bituminous mixtures

The bituminous mixtures are materials of wide use in highway engineering, combining the characteristics of granular materials to the cohesive properties of bitumen. There are various types of bituminous mixtures according to their structural function and performance. Under the railway engineering this type of option, when used in replacement of sub-ballast granular layer, increases the lifetime of the track subgrade and guarantees waterproofing [6]. The characteristics of the bituminous mixtures for the present study were based on an intensive literature research and they are described in table 5.

Table 5 – Characterization of bituminous mixtures

Mixture type	Elasticity Modulus (MPa)	Poisson's ratio	Density (kg/m^3)
Bituminous mixture	6000	0,35	2300

4 Models of structural deterioration

A proper structural design must take into account the behavior of substructure in the long run, being necessary to study the process of deterioration of materials constituting the respective layers. The failure by plastic deformation, fatigue and shear deformation are the main failure mechanisms that occur in layers of transport infrastructure.

4.1 Granular's track subgrade

The type of failure condition in granular soils is the rupture by plastic deformation. It is noted that the application of such relationships requires some care because their behavior does not depend only on the vertical efforts, but also mechanical properties such as modulus of deformation, angle of repose, cohesion, shear stresses, diversion, among other [15]. Huang et al. [8] established a relationship that could accommodate the mechanical characteristics of the track subgrade. The next relationship allows, through the tension at the top of the track subgrade (σ_p) and modulus of elasticity (E), estimate the track subgrade life-time.

$$N = 3.632.10^6.\sigma_p^{-3.734}.E^{3.582} \qquad \textbf{(1)}$$

This formula was adopted to determine the life cycle of the track subgrade in the case study. With the same formula it will be possible to estimate the life-time of the track subgrade of the traditional high-speed railway, which is the value adopted for the design of other track subgrades composed of soils of a poorer quality.

4.2 Clay's track subgrade

To evaluate the mechanisms of structural deterioration of subgrades consisting of clay soil, it was chosen to use a method that encompassed both the rupture by plastic deformation and rupture by shear deformation.

Authors Li et Selig [10][11] defined an approximate method that involves estimating a useful height of a granular layer (equivalent to the layer of ballast, the sub-ballast layer and the formation layer) to put on the deformable subgrade layer (equivalent to track subgrade) in order to prevent the occurrence of two common types of failure. The approximation is represented by the figure 4.

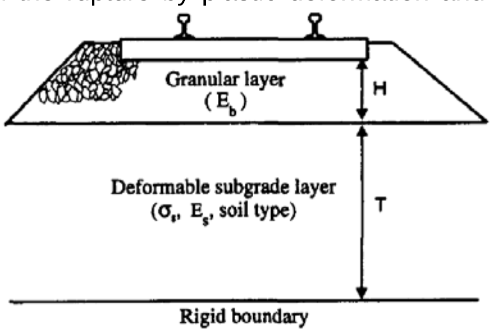

Fig. 4 – Design of clay track subgrade. Li and Selig [10]

4.3 Methods for assessment of structural deterioration in the layers of substructure

Given the different types of materials applied to the sub-ballast layer and the formation layer, the evaluation of these structures on the process of structural deterioration required a specific study for each case. In table 6 there are tabulated relations studied for all materials being analyzed, according to its author.

Table 6 – Models of structural deterioration of the layers of substructure

Layer's Materials	Author	Relationship
Granular	Dormon e Metcalf (1965) [18]	$N = 6{,}07 \times 10^{-10} \left(\frac{1}{\varepsilon_v}\right)^{4{,}76}$
	Shell's method (85% fidelity) [9]	$N = 1{,}94 \times 10^{-7} \left(\frac{1}{\varepsilon_v}\right)^{4}$
	Shell's method (90% fidelity) [9]	$N = 1{,}05 \times 10^{-7} \left(\frac{1}{\varepsilon_v}\right)^{4}$
	Belgian (Izquierto et al., 1990) [16]	$N = 3{,}05 \times 10^{-9} \left(\frac{1}{\varepsilon_v}\right)^{4{,}35}$
	French (Izquierto et al., 1990) [16]	$N = 1{,}02 \times 10^{-7} \left(\frac{1}{\varepsilon_v}\right)^{4{,}16}$
	English (Izquierto et al., 1990) [16]	$N = 4{,}14 \times 10^{-10} \left(\frac{1}{\varepsilon_v}\right)^{4{,}16}$
	Brown y Pel (Izquierto et al., 1990) [16]	$N = 4{,}14 \times 10^{-13} \left(\frac{1}{\varepsilon_v}\right)^{3{,}57}$
Bituminous mixtures	Shell – CEDEX (1986) [16]	$N = 1{,}02 \times 10^{-6} \left(\frac{1}{\varepsilon_t}\right)^{5}$
	Shell – ESPAS (1990) [16]	$N = 1{,}89 \times 10^{-13} \left(\frac{1}{\varepsilon_t}\right)^{5}$
	CEDEX – COST324[16]	$N = 9{,}06 \times 10^{-9} \left(\frac{1}{\varepsilon_t}\right)^{3{,}67}$
	Illinois Department of Transportation[5]	$N = 5{,}00 \times 10^{-6} \left(\frac{1}{\varepsilon_t}\right)^{3}$
	ACESA [1]	$N = 9{,}57 \times 10^{-14} \left(\frac{1}{\varepsilon_t}\right)^{5}$
	BOE [3]	$N = 1{,}18 \times 10^{-8} \left(\frac{1}{\varepsilon_t}\right)^{3{,}67}$
	Asphalt Institute (1982) [15]	$N = 1.1386.\, \varepsilon_t^{-3.291} E^{-0.853}$
	Mulungye [14]	$N = 10^{16.664 - 3.291.\log\left(\frac{\varepsilon_t}{10^{-6}}\right) - 0.854.\log(E)}$
	Shell Pavement Design Manual (1978) [17]	$N = 0.0685.\, \varepsilon_t^{-5.671} E^{-2.363}$
Soil –lime stabilized	Swanson e Thompson (1967) [12]	$N = 10^{(0{,}923 - SR)/0{,}058}$
Soil stabilized with cement	Ceratti (1991)[2]	$N = 10^{(SR - 125.63/-14.92)}$
	Tompshom [20]	$N = 10^{(0.9722 - SR)/0.0825}$
	Mollenar [13]	$N = 10^{9.110 - 0.0578\, SR}$
	BOE [3]	$N = 10^{(1-SR)/-0.08}$
	Crespo et al. (1986) e Izquierdo et al. (1990) [16]	$N = 10^{(1-SR)/-0.065}$
Cement stabilized gravel	Balbo (1997) [2]	$N = 10^{17{,}137 - 19{,}608 SR}$
	BOE [3]	$N = 10^{(1-SR)/-0.065}$

$N - Life\ cycle\ number$ $\varepsilon_v - Vertical\ deformation$ $SR = \sigma_t/\bar{f}_{ctk} - Stress\ ratio$

$E - Elastic\ modulus$ $\varepsilon_t - Traccional\ deformation$ $\sigma_t - Strain\ tension$ $\bar{f}_{ctk} - Max.strain\ tension$

5 Finite element design of a railway

The design by finite element method consists in defining a mesh approximate to the real case and the allocation of the mechanical properties of each material in accordance with their constitutive laws. The elements of the railway were approximated to simple forms in order to maintain the continuity of the model, it has been simulated for a speed of between 250 to 300 km/h, which according to Fomento [7] accounts to the applications of a vertical static force of 170 kN at the top of the track. Given the boundary conditions of the model set out in table 7, only one quarter of the model was taken, equivalent to applying only half load, 85 kN. Serendipity finite elements of 20 nodes were used in the design, ensuring a good approximation to reality.

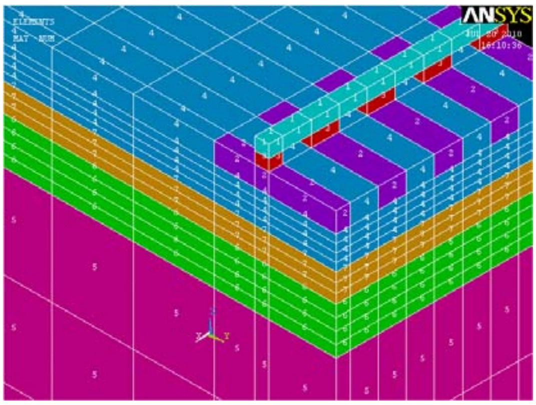

Fig. 5 – Finite element model

Table 7 – Boundary conditions[7]

Plane	Condition
x=0	u_x=0
y=o	u_y=0
x=L/2	u_x=0
y=L/2	u_y=0
z=0	u_z=0

Some characteristics of the used materials were obtained from existing literature [7], the remaining were determined in developing the study, this data set are defined in table 8. The ballast and the soils were analyzed using an elastoplastic models, the other materials were subjected to a linear elastic analysis

Table 8 – Material properties adopted in the finite element model.

Materials		E (MPa)	M_R (MPa)	v (-)	p (kg/m³)	Φ(º)	k (kN/mm)	c(kPa)	$\bar{f}_{ctk}$(MPa)
Steel rails		200.000	-	0,30	7800	-	-	-	-
Fastenings		-	-	0,35	1100	-	244	-	-
Sleepers		50.000	-	0,25	1830	-	-	-	-
Ballast		-	130	0,20	1450	45º	-	-	-
Alternative Materials	Granular sub-ballast	-	200	0,30	1800	35º	-	-	-
	Soil reinforced with cement	1600	-	0,25	1760	-	-	-	0,24
	Soil-cement	4800	-			-	-	-	0,95
	Soil-lime	250	-	0,20	1690	-	-	-	0,24
	Bituminous mixture	6000	-	0,35	2300	-	-	-	-
	Cement stabilized gravel	15.000	-	0,20	2300	-	-	-	1,32
Track Subgrade[1]	QS1 (12,5)	-	12,5	0,40	1800	10º	-	15	-
	QS2 (25)	-	25	0,30		20º	-	10	-
	QS2 (50)	-	50	0,30		20º		10	-
	QS3 (80)	-	80	0,30		35º	-	-	-

[1]In the considered soils it was added to the track subgrade a soil with QS2 properties, since the literature only addresses the case of 25 MPa.

where,

$E - Elastic\ modulus$ $\quad$ $v - Poisson's\ ratio$ $\quad$ $\emptyset - Angle\ of\ repose$ $\quad$ $c - Cohesion$

$M_R - Resilent\ modulus$ $\quad$ $p - Density$ $\quad$ $k - Stiffness$ $\quad$ $\bar{f}_{ctk} - Max. Strain\ tension$

6 Alternative design of the layers of the railway

The design using alternative materials was carried out depending on the life-time of track subgrade for traditional high-speed railway, so this chapter is divided in formulating the periods of useful life of the models and the design of the profiles.

6.1 Estimation of the useful life of track subgrade railways

In order to estimate the useful life of the of track subgrade for traditional high-speed railway their finite element model was modeled, analyzed and the vertical tension at its top surface determined. Then, the relation (1) was implemented to allow the estimating of the useful life of this structure. These values are shown in table 9.

Table 9 – Determination of the useful time of QS3's track subgrade

Subgrade soil	Vertical tension at the subgrade top (kPa)	Useful life of QS3's track subgrade N(cycles)
QS3 (80 MPa)	44,5	1,67E+07

According to the previous value, in the track subgrades of lower quality (QS1 and QS2) the maximum stresses to which each one of these track subgrades can be placed were estimated, so that there is a period of life identify with the traditional model. These analyses were made by the methods defined for the track subgrade consisting of granular or clay soils, respectively, and they are described in table 10.

Table 10 – Determination of the vertical tension at the sugrade tops

Subgrade soil	Useful life of QS3 subgrade N–(cycles)	Subgrade elastic modulus (MPa)	Vertical tension at the subgrade top (kPa)
QS2 (50 MPa)	1,67E+07	50	28,35
QS2 (25 MPa)	1,67E+07	25	14,58
QS1 (12,5 MPa)	1,67E+07	12,5	15,20

It should be noted that both methods of analysis and the process of rupture of granular soils and clay are different, and as such, similar maximum tensions between soil QS2 (25 MPa) and soil QS1 (12,5 MPa) were obtained. The method of analysis of rupture of clay soils includes in its formulation, a specific parameter for the period of life, where it was used the value defined on table 9.

6.2 Profile design

After several simulations with various types of materials of the substructure, a catalog of possible profiles of adoption was made, taking into account the use of alternative materials. In this catalog the lines differentiate the soils of the track subgrade and the columns, the type of material adopted in the sub-ballast layer or in the formation layer. The track subgrade, as defined, has a thickness of 3 meters, while the remaining layers of the sub-structure, vary with the material used, being the materials of the layers defined by colors and textures and their thicknesses labeled on the right side of each layer. Table 11 summarizes the profiles determined when the subgrades are made of granular soils.

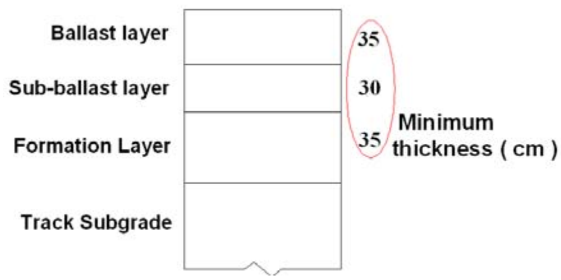

Fig. 6 – Definition of a profile type of catalog

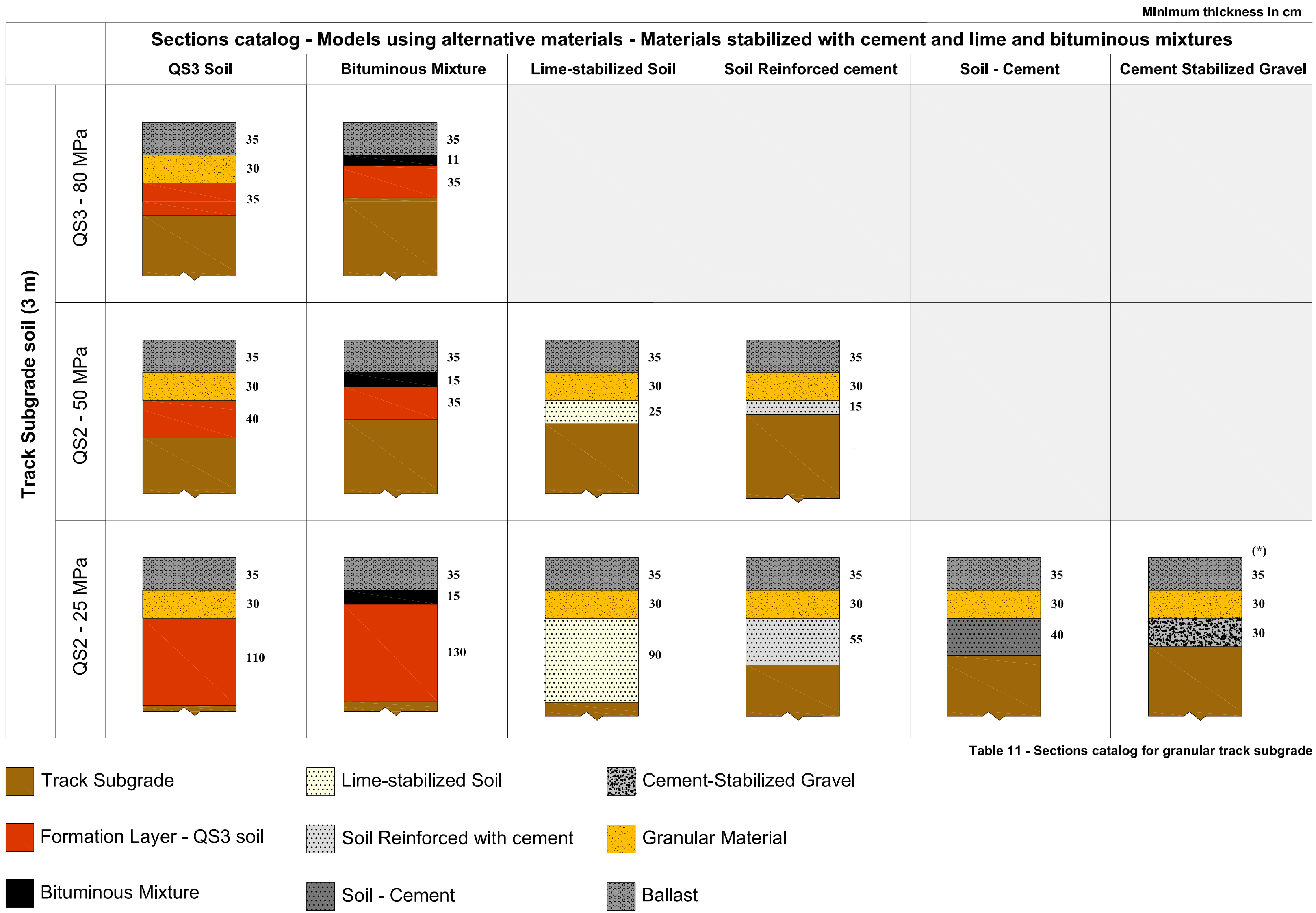

Table 11 - Sections catalog for granular track subgrade

(*) This solution may be more advantageous at both the economic and practical leves, putting the cement stabilized layer immediately below the ballast one, with an identical thickness.This mode allows the use of a formation layer on untreated granular material, being less subject to the process of structural degradation

Similarly, figure 7 shows the simulations for the case of clay subgrade. Given the differences in methods of analysis, this equivalence was defined in a separate figure. In its application, due to various approximations made to materials, this design should be applied with care and caution. This type of solution should be chosen only when there is abundance of clay soils *in situ*, so, in this case, it was only dimensioned the QS3 soils formation layer and lime-stabilized soils.

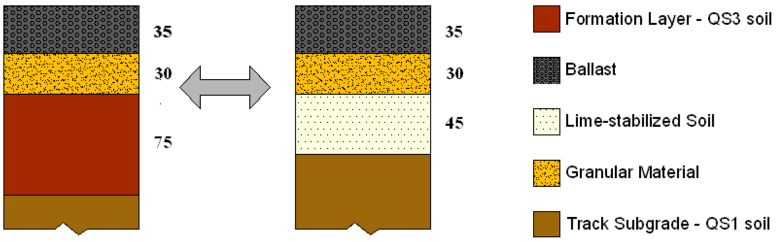

Fig. 7 Definition of sections obtained for clay subgrades

7 Conclusion

This article allowed providing a possible designer with the characteristics and methods of analysis of deterioration of alternative materials when used in layers of a high-speed rail substructure, by offering a catalog of solutions to be adopted according to the type of soil used in the design of the track subgrade.

All profiles are feasible for implementation and the evaluation of the layers of substructure in the process of structural deterioration, made with the mathematical relationships of table 6, which showed good results. The materials with better wear behavior are the granular material, bituminous mixtures, QS3 soil, lime-stabilized soil and soil-cement. The stabilized-cement gravel and soil reinforced with cement, despite having an average useful lifetime higher than the track subgrade, were very close to these values, suggesting that caution is advisable in their appliance.

From direct analysis of the table it is possible to see that it is extremely advantageous the use of treated soils compared with large thickness obtained with the use of QS3 soil's formation layers, that is the traditional method in this kind of structures. This treatment allows taking advantage of local soils, avoiding large movements of soils or the purchase of new material, being a solution that brings both environmental and economic gains. Comparing with the data of table 1, it is concluded that this type of design is conservative compared to data from the UIC.

It was also remarked that that the choice of solution to be adopted will depend on the existing soils *in situ,* that is, in an environment of granular soils it is advisable to use cement and in a clay environment using lime becomes the best option.

Finally, the fact that economic aspects inherent to every solution have not been included in the design it is suggested as a future line of investigation.

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