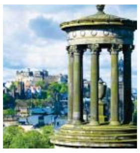

Benchmark criteria for defining a new mix design system for railway sub-ballast

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Abstract

Bituminous sub-ballast is an alternative solution to the unbound granular sub-ballast used in the railway track due to several benefits that it can provide. Indeed, it contributes to reduce the variation of the moisture content in the subgrade, slowing its deterioration process. Moreover, the presence of bituminous sub-ballast can also reduce vertical stiffness variations on the track; it can have a positive effect on the maintenance needs at the transition sections (bridge-embankment) and on the attenuation of the vibrations induced by the rail traffic. Despite the importance of the presence of the bituminous sub-ballast to conceive the construction and/or rehabilitation of sustainable infrastructure, in literature there are only fragmentary information regarding the definition of benchmark criteria for their mix design. The SUPERPAVE mix design approach is applied systematically to the railway domain, without been adjusted for the different load configuration of the rail track system. This research aims at defining the benchmark parameters for adapting the SUPERPAVE methodology to the mix-design optimization of the bituminous sub-ballast. The rail equivalent single axle load (RESAL) has been defined and the traffic spectra of the track lines have been transformed in "number of RESALs", in order to calculate the N_{design} as function of the rail traffic level (RESALs). Finally, a case study of bituminous sub-ballast mix design has been investigated for a first verification of the methodology proposed.

Keywords: sub-ballast, mix-design, tensile strain, vertical displacement, rail ESAL, N_{design}.

1. Introduction

1.1. Bituminous sub-ballast

Sub-ballast is a layer, of usually 12-15 cm thickness, interposed between the ballast and the blanket. Frequently, unbound granular materials are replaced by bituminous sub-ballast that may provide additional benefits to the subgrade protection and track performance. For instance, the bituminous sub-ballast, being almost completely water-resistant, protects the subgrade from the seasonal variations of moisture and atmospheric actions. This has an important effect in slowing down the deterioration process over the track's service life (Teixeira P.F et al. 2009). Indeed, the sub-ballast's role in reducing the seasonal amplitude of vertical displacements during its lifetime decreases the maintenance interventions, not only in the smooth parts of the track lines (Ferreira T. M. 2011) but also in the transition sections (bridge-embankment) (López A. 2007). Moreover, the bituminous sub-ballast plays an important role in distributing the load and reducing the solicitations on the subgrade. Indeed, it dissipates the stress transmitted by passing trains, ensuring a higher protection.

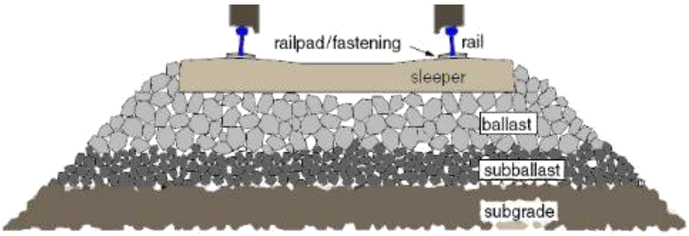
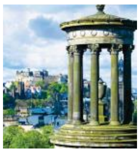


Fig. 1. Section through railway track showing the sub-ballast and formation layers.

The bituminous sub-ballast is also preferable to cement bound sub-ballast. In fact, asphalt concrete does not need an anti-evaporation protection. Nevertheless, it is important to consider the effect of the temperature on the mechanical properties of the bituminous sub-ballast which can significantly affect its service life. Recent studies (D'Andrea A. et al. 2012; Di Mino G. et al. 2012) have highlighted the capability of bituminous sub-ballast to improve the attenuation of vibrations induced by rail traffic, especially when crumb rubber is added to the mixture.

Considering all the above-mentioned aspects, the use of bituminous sub-ballasts could improve the track quality and durability (higher protection of the subgrade in term of dissipation of loads and water infiltration) improving adherence to track geometric



parameters (Rose J. G. et al. 2009).

1.2. Mix design optimization of bituminous mixtures

The bituminous sub-ballast is composed of a dense-graded bituminous mixture with a maximum aggregate size of 22–25 mm (Rose J. G. et al. 2009) similarly to the base course for road pavements. Whereas, the quantity of bitumen in the sub-ballast is normally increase of 0.5% compared to the base course and the air voids decreased to 1-3% to avoid the permeability of the layer (Rose J. G. et al. 2011). Because of the composition of the sub-ballast layer, different mix design systems should be adopted for the optimization of the asphalt mixtures when used in the railway domains. In recent years, several research efforts have been employed to refine the Superpave mix design system of Hot Mix Asphalt (HMA), that establishes a N_{design} as the design number of gyrations required to match the density of the material expected in the field and it is the parameter considered in this study. Table 1 indicates the number of cycles needed to obtain the in-place pavement density at the design traffic levels when using Superpave gyratory compactor (AASHTO R35 2001).

Table 1. Compaction parameters for SUPERPAVE gyratory compactor.

Design ESALs (10^6)	$N_{initial}$	N_{design}	N_{max}
<0.3	6	50	75
0.3 to <3	7	75	115
3 to <30	8	100	160
≥30	9	125	205

2. Problem statement and objectives

In literature, there are only fragmentary information regarding the definition of benchmark parameters for the mix design of bituminous sub-ballast. Nevertheless, to use these parameters in the railway domain it is first necessary to determine the corresponding Rail Equivalent Single Axle Load (RESAL), calculating the compression stress at the bottom of the base layer and transform the entire spectrum of traffic into the number of passages of RESALs. This paper aims at presenting a methodology to adapt the SUPERPAVE mix design approach to the railway system defining the RESAL and transforming the entire traffic spectra on the track lines of interest into number of RESALs. Afterwards, the N_{design} has been calculated as function of traffic. Indeed, the definition of a regression function of N_{design} allows assigning a specific number of gyrations for each number of RESALs.

3. Methodology

The proposed methodology is composed of different stages:

(1) Compare the solicitations induced in the sub-ballast layer with the ones produced on the road base course.

(2) Define the RESAL, i.e the rail axle load that produces the same vertical displacement (w) at high temperatures and the same horizontal tensile strain (ε_t) at low temperatures produced by the ESAL in the road structure.

(3) Convert the entire traffic spectrum into number of RESALs.

(4) Define Ndesign as function of traffic level.

3.1. RESALs

To determine the RESAL two reference sections, one for road and one for railway, have been selected. The stress-strain behaviour in both sections at the bottom of the base course and sub-ballast were defined performing several simulations using KENPAVE® and KENTRACK® software respectively. The two sections (types and thicknesses of layers) and the points where the solicitations were calculated are shown in Fig. 2.

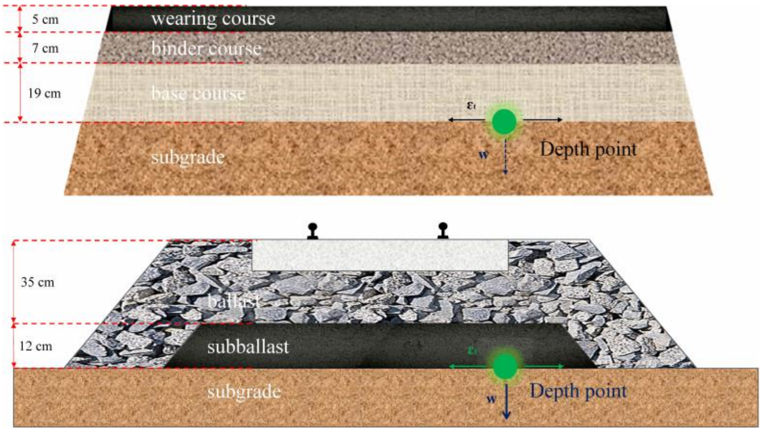
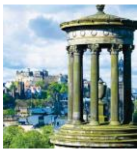


Fig. 2. Road and railway sections for simulations with KENPAVE® and KENTRACK®

KENPAVE® is a software that calculates stresses, strains and deformations in flexible pavements (Huang Y. H. 1993). KENTRACK® is the corresponding software used for the analysis and design of railway track-beds. By applying the Burmister's layered theory and the finite element method, the stresses, strains and deformations can be calculated in every point of the track-bed (Huang H. 1984). Fatigue cracking at low



temperatures and rutting at high temperatures are two of the most common causes of asphalt failure in flexible pavements. For this reason, RESAL has been defined as the rail axle load that produces the same vertical displacement (w) at high temperatures and the same horizontal tensile strain (ε_t) at low temperatures by a 80kN ESAL in roads.

Table 2. Parameters selected for KENTRACK® simulations

Type of rail:60E1 (UIC) 3141			Fastening system type: Pandrol Fastclip		
Young's modulus [MPa]	Limit of proportionality [MPa]	Limit of elasticity [MPa]	Static stiffness (Rubber pad) [MN/m]	Clamping force [kN]	Creep resistance [kN]
192000	500	600	>150	>16	>9
Sleepers in PSC wires					
Sleeper thickness [cm]	Sleeper width [cm]	Sleeper unit weight [g/cm]	Sleepers spacing [cm]	Length of sleeper [cm]	Center to center distance between rails [cm]
21	16.9	5.18	60	259	143.5
Type of axle considered for the simulations			Single		

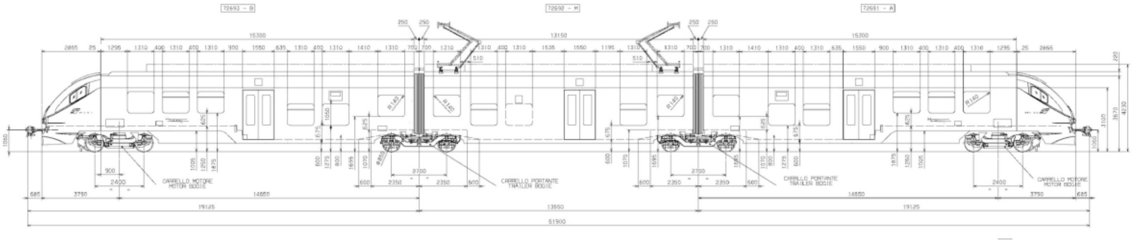


Fig. 3. Type of train considered for the rail simulations

For this purpose, it was necessary to define a complete set of information regarding all the components and the materials involved in the systems. The principal parameters (road-railway) used to create the reference sections are demonstrated in Tables 2 and 3.

Table 3. Parameters selected for KENPAVE® simulations

Road structure			
Type of material	Type of responses	Number of periods	Number of layers
Linear	Displacement	4	4
Load information			
Type of load	CR - contact radius of circular loaded areas [cm]	CP - contact pressure on circular loaded areas [psi]	NR- number of radial coordinates under a single wheel [-]
single axle with single tire	12.62	800	1

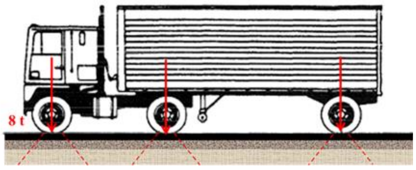
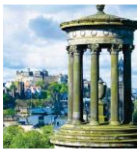


Fig. 4. Type of vehicle considered for the road simulations

The determination of the properties of the materials represents a fundamental step for



the definition of the input data of the models, implemented by KENPAVE® and KENTRACK®. Equation 1 (Barber E. 1957) expresses the temperature in the layer at the depth z and at time t.

$$T_{pav(z,t)} = T_M + R + (T_v / 2 + 3R) \cdot F \cdot e^{(-Cx)} \cdot sin[0.262t - C_x - arctg(C/(H+C))] \qquad (1)$$

Where:

$T_{pav(z,t)}$ = temperature in the pavement at the depth z and time t [°C];
T_M = mean effective air temperature [°C];
T_V = maximum variation in T^a [°C];
R = 2/3 ·(b·I)/24h_c = contribution of the solar radiation [°C];
h_c = surface coefficient depending on the wind speed [kcal/hours m^2 °C];
I = average radiation [kcal/m^2 days];
b = absorptivity to solar radiation [-];
F = H/((H+C)^2+C^2)$^{0.5}$
C = (0.131·s·w) /K [hour$^{0.5}$/m]
s = specific heat [kcal/kg °C];
w = density [kg/m^3];
H=h_c/K where K = thermal conductivity [kcal/m hour °C]; and
x = depth [m];

In the framework of this paper, Equation 1 was used to determine the temperature in the road base course and in the sub-ballast layer. The principal difference between road and railway is in the absorptivity of the surface of the structure to solar radiation. For the surface layer in the road structure the absorptivity is equal to 0.9 (Barber E. 1957), in the case of railway the coefficient of absorptivity of ballast has been estimated equal to 0.21 (Crispino M. 2001). The simulations with KENPAVE® and KENTRACK® have been set at two air temperatures, 0 and 35°C. Table 4 shows the temperatures and the properties characterizing the bituminous materials.

Table 4. Results of temperatures and properties obtained for road and railway layers

Air temperature 0°C						
		T of the layer [°C]	η [10^6 poise]	log |E*|	|E*| [MPa]	ν
Road	Wearing course	8.30	11.6057	1.1736	10282.655	0.4
	Binder course	8.30	11.6057	1.2081	11135.245	0.4
	Base course	8.30	11.6057	1.2827	13219.792	0.4
Railway	Sub-ballast	1.94	59.5026	1.4386	18929.829	0.4
Air temperature 35°C						
		T of the layer [°C]	η [10^6 poise]	log |E*|	|E*| [MPa]	ν
Road	Wearing course	43.30	0.0014	-0.1306	510.391	0.4
	Binder course	43.30	0.0014	-0.0985	549.562	0.4
	Base course	43.30	0.0014	-0.0453	621.176	0.4
Railway	Sub-ballast	36.94	0.0074	0.2354	1185.668	0.4

KENTRACK® was used to simulate the stress, strain and deformation in the sub-ballast layer under the passages of different types of axles: 8, 10, 12, 14, 16, 18 and 20 t. The results are shown in Fig. 6. As it is possible to see, 14.88t is the weight of the railway axle load that produces the same vertical displacement at high temperatures induced by

ESAL (80kN) in the road structure. 17.07t is the weight of the railway axle load that produces the same horizontal tensile strain at low temperatures produced by ESAL (80kN) in the road structure. A 16t value has been selected as the reference RESAL.

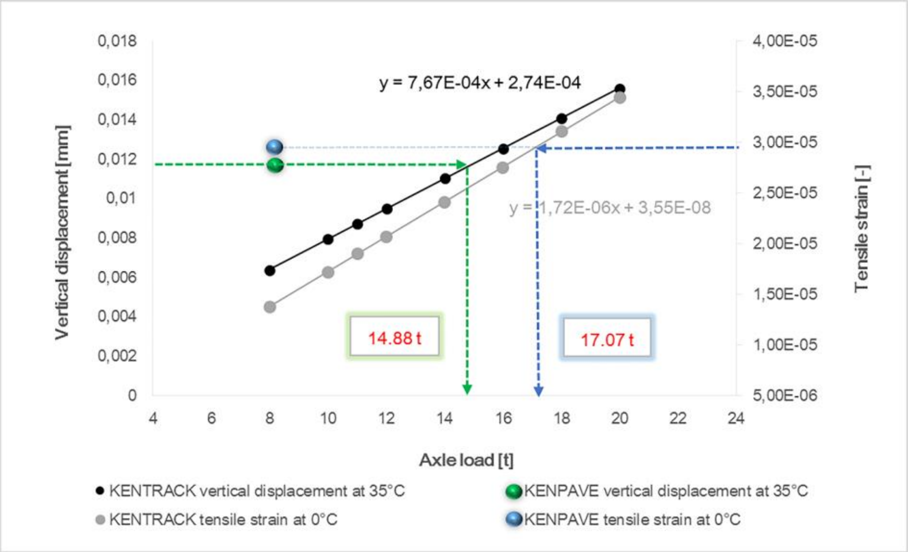


Fig. 5. Results obtained from the simulations carried out with KENPAVE® and KENTRACK®

3.2. *Conversion of the traffic spectrum in RESALs*

Once the RESAL was defined equal to 16t, the entire traffic spectrum of the railway track line was converted into numbers of RESALs to identify the traffic level and consequently the N_{design}. Three different traffic lines in the Sicilian network (*Messina-Catania; Siracusa-Catania and Caltanissetta-Catania*) were investigated and their traffic spectra were converted to RESALs. The traffic level expected over a 30-year period for the three lines is summarized in Table 5.

Table 5. Summary of the traffic levels expected on the three track-lines

RESALs at the end of the service life (30 years)			
Traffic growth rate [%]	Messina - Catania	Catania - Siracusa	Catania - Caltanissetta
0	3,171E+07	1,796E+07	3,131E+06
0.2	3,265E+07	1,849E+07	3,223E+06
0.4	3,362E+07	1,904E+07	3,319E+06
0.6	3,463E+07	1,961E+07	3,419E+06
0.8	3,568E+07	2,020E+07	3,523E+06
1	3,677E+07	2,082E+07	3,630E+06

3.3. *Estimation of N_{design}*

A logarithmic regression resulting from the interpolation of the values of Superpave (AASHTO R35-2001) has been used to determine a correspondence between the number of RESALs and the number of gyrations, N_{design} (Fig. 6).

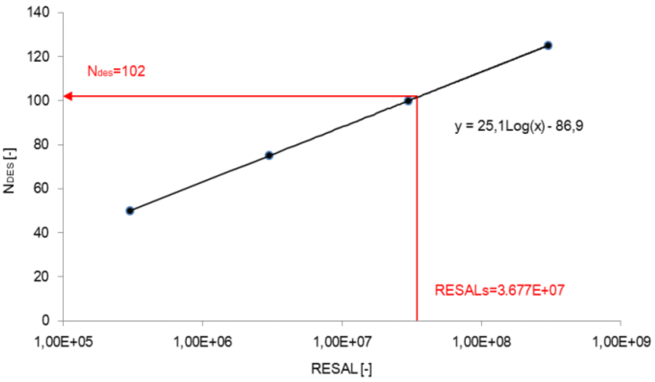


Fig. 6. Logarithmic regression obtained interpolating the values of N_{des} of SUPERPAVE

Using the logarithmic regression shown in Fig. 8, the N_{design} for the bituminous sub-ballast was calculated with each value of RESALs. A unique correspondence between the number of gyrations and the RESALs has been defined in Fig. 7.

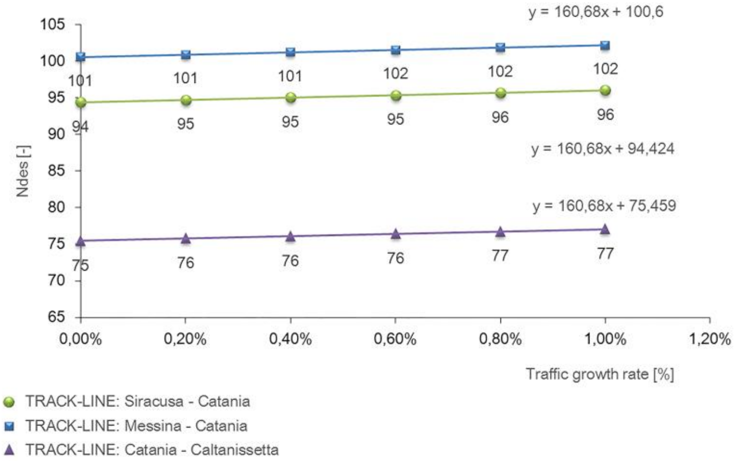


Fig. 7. N_{design} obtained for different track-lines and different values of annual traffic growth rate.

4. Case Study

The methodology was applied to determine the number of gyrations in the specific case of the track line connecting Messina and Catania (Sicily, Italy). Thus, based on the results, N_{design} is equal to 102. The Italian standard (RFI) was selected to define the target grading curve. Superpave mix-design of the bituminous sub-ballast was carried out setting the N_{design} equal to 102. The compaction temperature was set at 145°C. Four different bitumen percentages (3.6; 4.0; 4.5; 5.0 %) of the weight of aggregates were added to the mixture and compacted using the gyratory compactor. Four samples for each combination were done. 3% of air voids at N_{design} was selected. The results are summarized in Fig. 8.

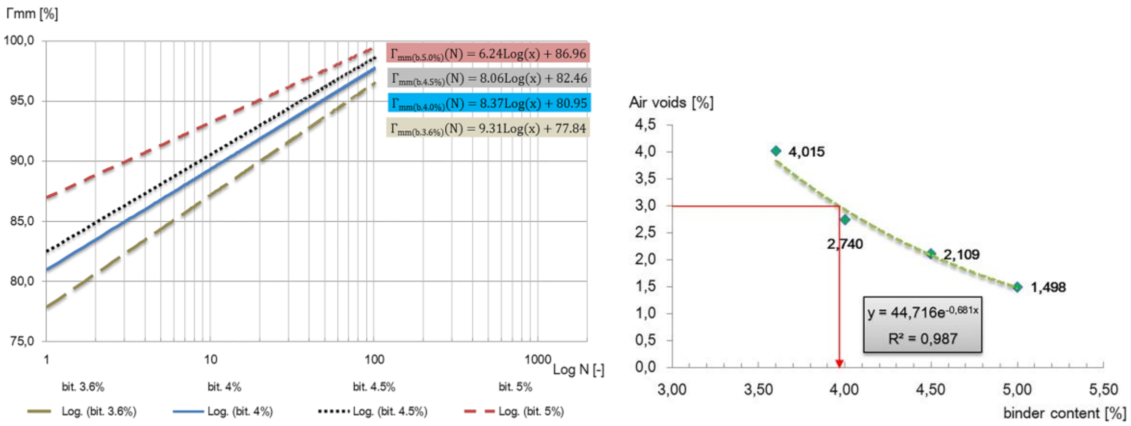


Fig. 8. A). Compaction curves of the bituminous sub-ballast mixtures fabricated with different binder contents; **b).** Plot of percent air voids versus binder content. Optimal bitumen quantity

5. Summary of findings

This study proposes a methodology to adapt the SUPERPAVE mix design approach, developed for the road domain, to the railway system, and in the process defining the "RESAL", i.e. rail equivalent single axle load. A logarithmic regression resulting from the interpolation of the N_{design} values of SUPERPAVE has been used to determine a unique correspondence between the number of RESALs and the number of gyrations.

As a further verification, the standard (RFI) requires the value of Indirect Tensile Strength Test (ITST) for the optimal recipe being higher than 0.6 N/mm^2. An ITST at 25°C was performed (ASTM D6931-2012). From the tests conducted it emerged that the sub-ballast mixture at N_{design} achieved the target voids content with 4% of bitumen in relation to the weight of aggregates. The ITS tests performed gave results higher than 0.6 N/mm^2 as required by standard (RFI) for the use of sub-ballast.

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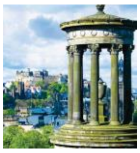

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