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CHARACTERIZATION OF RUBBERIZED ASPHALT FOR RAILWAYS

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ABSTRACT
Rubberized asphalt mixtures are regarded as a solution for improving the strength of the rail-track section. The recycled rubber has become an enhancer of the modified bituminous mixtures. In this work, it has been shown as a sustainable improvement option in HMA mixes due to the elastic behavior exposed by the rubber particles. The impact of thermal susceptibility on the mechanical properties of the railway bituminous sub-ballast layer has served to the advanced measurement of the thermal cycles inside the rail track. Different simulations following the Kentrack and Kenpave software were employed to be effective with the best mix-design for railways. According to weather situation, reviewed temperature models were used to prove the effectiveness of the railway superstructure. It is included the assessment of improved modified asphalt mixes with coarse rubber from scrap tires, containing 1.5-3% of rubber (sizes 0.2-4mm) by weight of the total mix. Adopting the Volumetric mix-design by the dry process was enhanced the characterization of rubberized materials after computer simulations to evaluate stresses derived from the rail traffic and the average seasonal temperatures. The stiffer-elastic sustainable rubberized mixes showed that is useful in the reduction of rail track damping vibrations.

KEYWORDS: Rubberized asphalt; Sustainability; Thermal susceptibility; Crumb rubber; Superpave; Railways.

I. INTRODUCTION
The sub-ballast layer is the critical element of the track. Its performance dramatically affects the reliability and durability of the whole infrastructure, which plays a vital role as a foundation for the superstructure (i.e., rails, sleepers, and ballast) and carries the vehicle loads to the ground [1]. The blanket is a layer, or several layers, of granular material laid over the subgrade which conforms and creates its desired properties. Frequently, unbound granular materials are replaced by bituminous sub-ballast, being almost entirely water-resistant, that may provide additional benefits to the subgrade protection and track performance, because of the effect on slowing down the deterioration process over the track's service life [2-3]. The bituminous sub-ballast is composed of a dense-graded bituminous mixture similar to the base course for road pavements [4-5]. The bitumen in the sub-ballast usually is increased to 0.5% compared to the base layer, and the air voids decreased to 1-3% to enhance the impermeability of the layer resulting in a mixture characterized by a medium permanent deformation resistance [6]. However, rutting does not represent a primary concern in the track-bed because the presence of the ballast distributes pressures of axle loads over a wider area. Other studies have observed that the use of HMA as a sub-ballast allows for a reduction in vibration levels throughout the track, therefore reducing noise [7]. Considering these aspects, the use of bituminous sub-ballasts improves the track quality and durability (higher protection of the subgrade regarding load dissipation) leading to reduced maintenance interventions, improving adherence to track geometric parameters [8-9].

Advantages of bituminous sub-ballast
Traditional railway track consists of rails, sleepers, fastenings, ballast and a formation layer over the ground (Fig. 1). The materials and the thickness of track layers composing the railway structures are allocated by practice [10], but the constant demand for high speed and loading capacity increasing, involve the incorporation of the required sub-ballast layer. The thickness of sub-ballast and ground layers have been enlarged in modern tracks with the aim of obtaining higher bearing capacity, and durability of the system [11]. In line with this objective, the novel

sustainable and environmental solution is the road with bituminous sub-ballast, widely used in the construction of new high-speed railway lines [12-13].
About this trend, it should also be measured that all these changes in the railway section lead to the increase in the load capacity and the modification of other relevant parameters of the rail track such as vertical stiffness [14-15], and deflection caused by the load.

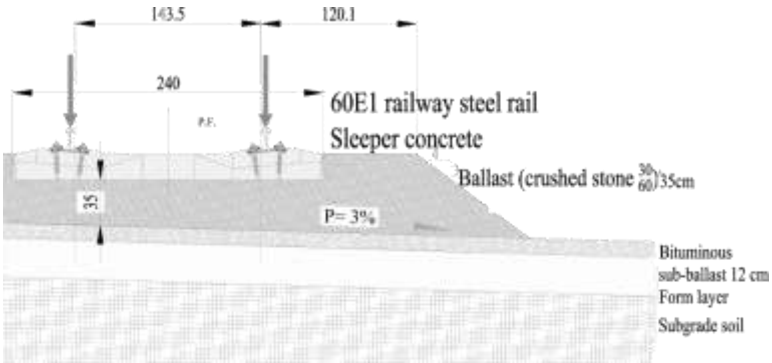

Fig. 1. Section through railway track showing the sub-ballast and formation layers.

In the case of ballasted tracks, sub-ballast layers are determining elements in the mechanical performance of the rail track and for the protection of the ballast. Using a bituminous sub-ballast layer has been recognized as an environmental solution for the necessary enhancement of the track structure. Substantial development research has been conducted during the last years [16-17]. Asphalt underlayment has shown to apply to track features with weak subgrades, soft soils, and poor drainage.

A review of model factors

The performance of asphalt pavements is influenced by temperature distribution and environmental conditions to which it is exposed. Barber [18] observed that pavement temperature fluctuations roughly followed a sine curve with a period of one day. A reasonable estimation of asphalt surface temperature was observed by including both the solar radiation and the air temperature in the model.
Pavement temperatures are of interest linking with the stabilization, curing and moisture movements of bituminous sub-ballast layers [19]. Straub et al. (1968) developed a computer model to predict pavement temperatures based on air temperature and solar radiation [20]. He showed that the surface measurements of the temperature showed a good correlation with solar radiation. Even these temperatures varied independently depending on the depth and conditioned by the layer thickness. Furthermore, the results indicated that solar radiation had a significant effect on pavement surface temperatures than air temperatures. Williamson (1972) developed a model to predict pavement temperature at various depths using a FEM model including climatic parameters as well as the thermal properties of the layer [21].
One of the most critical environmental factors that significantly affect the mechanical properties of asphalt mixtures is temperature [22-23]. Therefore, it is essential to predict the temperature distribution under the pavement layers. The properties of asphalt mixtures change significantly with temperature variation. Bituminous mixtures suitable for railway sub-ballast are susceptible to cracking at low temperatures. Precise prediction of asphalt pavement temperature at different depths based on air temperature measurements can help to perform retroactive calculations of the bituminous mixtures module and to estimate pavement deflections. Thus, the temperature is critical to the selection of the long-term grade performance values of the pavement. The bearing capacity of each layer is predisposed by climatic conditions regarding the thermal regime and moisture damage [24-25].
Climatic factors that may influence the pavement thermal regime of the railroad are air temperature, solar radiation and, wind speed. The railway structure seeks to optimize a reliable performance while at the same time with a minimum thickness it is possible to resist the stresses-deformations allowed along the railway due to traffic and temperature variations. The use of different types of sub-ballast caused low variations in bearing capacity. The incorporation of an elastic rubberized asphalt sub-ballast causes a decrease in the bearing capacity [26].

II. SCOPE AND OBJECTIVES

Background of temperature profile models

Temperature models based on mechanical methods, energy balance and finite difference equations are purely empirical regressions. Computer modeling has validated its use under certain doubts about the experimental methodology. Recent work provides with guidelines on how to determine input parameters (convection, air temperature, material unit weight, moisture content, material classification, and thermal conductivity) which are difficult to obtain [27-28]. Hermansson (2001) presented a FEM model that predicts pavement temperatures during summer condition based on the heat transfer [29]. The input data per hour per day are solar radiation, air temperature, and wind speed, observing a concordant relationship between measurements. In this experiment, the effects of solar radiation and depth were added to the analysis layer. Ferreira (2012) analyzed through a finite-element (FEM) model, the long-term behavior of the deformation of the sub-ballast layer, evaluating the effect on different configurations of the railway section [30]. As a result of the environmental effects (atmospheric actions and changes in the water table), they optimized the modeling of surface drainage systems. Numerical models have been developed since years to address the mechanistic analysis of the railway track.

The Strategic Highway Research Program (Superpave) went in a slightly different direction [31-32]. The performance-type specifications developed for asphalt cement required that a particular grade of asphalt binder perform over a given range of temperatures. Considering the solar-thermal radiation between the railway, the climatic zone, the heat-convection between the surface of the pavement and the air, an exact calculation of thermal prediction model could be accomplished in the sub-ballast after knowing the max/min temperatures on the railway trackbed [33-34].

In this research, the conventional measures of temperature, relative humidity, atmospheric pressure, wind speed, and, hours of sunlight during12-months were selected from statistics determined by using the global horizontal-direct standard radiation, and wind speed for simulation of solar energy conversion systems. Crispino [35-36] measured the thermal fluctuations of the sub-ballast layer evaluating the average seasonal temperature. The analytical model to forecast temperatures proposed by Barber [18] is used to analyze rail stresses on railway tracks.

Objectives

The present study is divided in a first part, that studies the aspects of traffic and temperature using modeling with the aim of representing the real conditions in that layer of the rail track. Secondly, the volumetric mix-design of the mixtures in the laboratory using the gyratory compactor (SGC) is developed in this work exclusively for the railway sector, since until now it was applicable only on roads. In this research, the critical issue is to evaluate the distresses inside the sub-ballast layer, regarding the prediction of temperature profile (from weather report and of design traffic-loads and number of repetitions) during the lifetime.

The framework is focused on the thermal susceptibility of bituminous materials to predict layer temperature profile [37-38]. Thus, it is needed to know the temperature within the layer and the relationship with the mechanical characteristics. Barber´s theory was used to find the temperature in the road base course and, the modifications purposed by M. Crispino (1998) were used in the sub-ballast layer [39-40]. Using comparative analysis by simulating the thermal sub-ballast and road-base layer behavior respectively, of known thermal properties, was possible to predict the pavement temperatures including the average seasonal temperature evaluation, which result is presented after different computer simulations. Inside the methodology, is illustrated a case study that corresponds to different traffic in the Italian main rail lines, and according to the Standard code for bituminous mixes in the sub-ballast layer [41-42].

This investigation, therefore, evaluates the best parameters of temperature and traffic that characterize the optimal mixture for a sub-ballast layer. Also, it gives an advance in the development of a new method for the bituminous sub-ballast to adapt the SGC method focused exclusively for roads but now in the railway field. This procedure is needed for the volumetric mix-design of the underlayment rail-track [43].

For this purpose, a study was conducted with a hot mix asphalt (HMA) conventional (reference mixture) and three different rubber modified asphalt concrete mixtures (RUMAC). It was used coarse rubber from scrap tires, having 1.5 to 3 percent of rubber (particle sizes between 0.2-4mm) by weight of the total mix. The primary aim is to optimize the sub-ballast layer in the railway layers and the base layer on roads with similar characteristics but varying the mixtures according to the type of coarse aggregate and the amount of rubber used.

III. MATERIALS AND METHODS

Methodology for a Temperature-Traffic model

The linear viscoelastic behavior is a first step to understand the mechanical performance of high-speed line tracks with bituminous layers. The rail sub-ballast purpose requires the determination of temperature by the prediction model reviewed. Due to the extensive analysis of the road model, we have validated the railway model by adopting a multi-layer system comparing the base road and the sub-ballast layer to stress-strain level.

The track system model is divided in rails, tie plates, pads, and sleepers, which are modeled as prismatic elements with an isotropic linear elastic constitutive model by finite elements for trackbed design [44-45].
The railway and road structures respond to a multilayer model from which the properties of each layer can be defined. The two sections (types and thicknesses of layers) and the solicitations points are shown in Fig. 2.

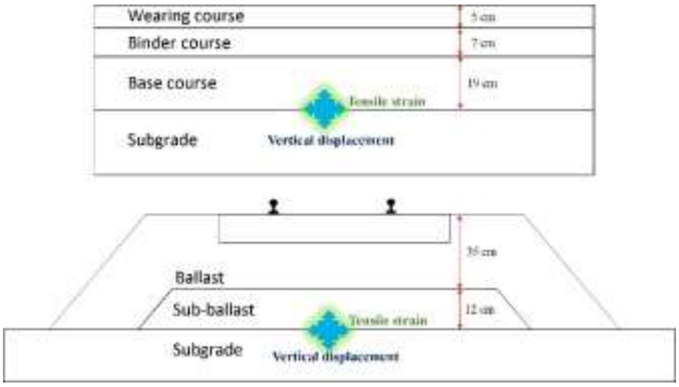

Fig. 2. Road and railway sections considered

Stress-strain behavior of railroad layers
Railway track structure can be calculated by flexible multi-layer theory, defining each layer by its thickness, elastic modulus and Poisson's ratio [46-47]. The pressure transmitted from trains by rail, sleepers and ballast can be considered uniformly distributed over a circular area (vertical, shear stress, and radial displacement). Strains can be considered in railroad materials for each layer of the track formation using structural analysis by Burmister [48]. Thus, tensions and deformations were calculated at every point of the track-bed [49-50] as shown in Fig. 3.

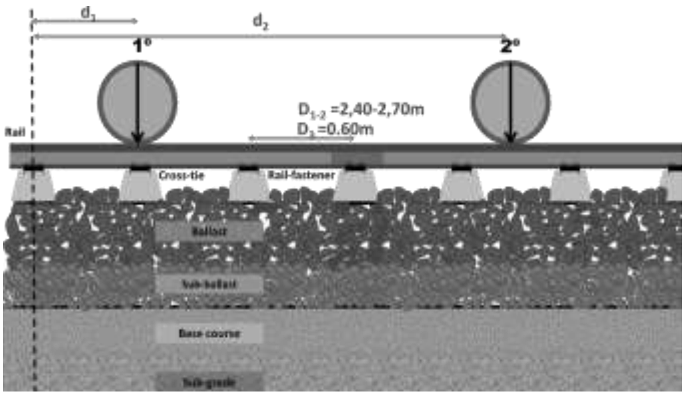

Fig. 3. Positioning the loads concerning the ties in rail-track

KENPAVE® is a software that finds stress-strain-deformations in flexible-rigid pavements [51]. KENTRACK® is for the analysis of railway track-beds [52-53], which provides a rational method for designing a railway track for different loadings and layer materials. It is a layer elastic finite element-based computer program that can be applied for a performance structural design and analysis of railroad track beds. Kentrack, as a computer program for HMA in ballast railways, determines the tensile strains at the bottom of the asphalt layer, a reliable indicator of potential fatigue cracking at low temperatures [54].
The standard axle load for railways that produces the same solicitations in road pavements, after several simulations were obtained using both computer programs. It were considered axle-passages between 80kN (roads) until 180kN (railways), a design number (N_{des}) of one hundred cycles were imposed to avoid the cumulative damage effect into the Superpave gyratory compactor for laboratory mixes (Fig. 4) [55-56]. The software considered the air temperatures equal to 0°C until 35°C (high temperature). The horizontal tensile strains and the deflections produced in the road and railway structures were compared. The tensile strain at low temperature defines the railway equivalent single axle load (RESAL) because it is the critical factor governing cracking and fatigue [57].

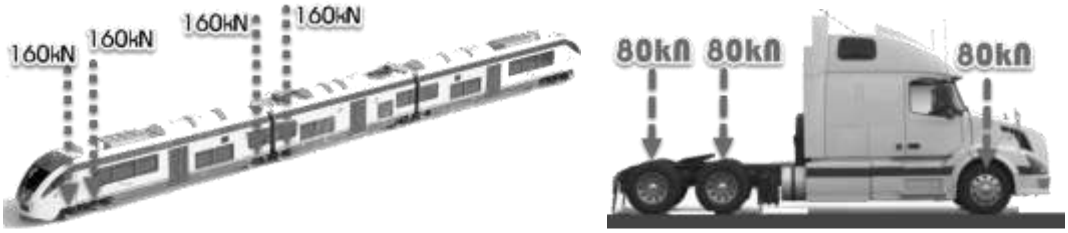

Fig. 4. (a) Convoy Aln 501- Ale Minuetto (train for simulations); (b) Vehicle considered for road simulations

Materials: Laboratory mixtures with "Volumetric mix-design" for railways

During the study, different mixes were characterized by volumetric mix-design, obtaining optimal mixes with different amounts of asphalt binders (4%, 5%, 5.5%, 6%, 6.5% and 7% of total binder weight). Also, the different quantity of rubber proportion (0%, 1.5%, 2% and 3% of the total weight of the aggregates in volumetric substitution) was studied.

Using six different bituminous mixtures (HMA binder 4%, DRY 1.5% b. 5%, DRY 1.5% b.5.5%, DRY 2% b.6%, DRY 2% b. 6,5%, DRY 3% b. 7% mixtures) was studied the influence of the rubberized asphalt materials by dry process for a bituminous sub-ballast layer. The reference mixture (HMA) was a dense-graded hot mix asphalt with a limestone nature of aggregates and a 4% of a conventional bitumen B50/70 in accord with satisfactory previous studies. The manufacturing process with the rubber mixtures (called DRY or RUMAC, rubber modified asphalt concrete) involved a protocol to homogenize the aggregates with rubber by dry technology better and enhance the digestion process providing a final cohesion and optimal compaction.

These mixtures were optimized in the laboratory after testing different binder's content to relate the compaction and volumetric characteristics with changes in the coarse-fine gradations and the corresponding ratios of filler-aggregates. The dust proportion (DP) was measured as a parameter that affects the mix properties. Excessive dust dries out the mix reducing asphalt film thickness and durability. DP is determined as the ratio between Ø0.075, the aggregate content passing the 0.075 mm (75 µm) sieve and, P_{be}, effective asphalt binder content, both as percent by mass of aggregate, to the nearest 0.1%. For each mixture, the values of DP were between 0.7 to 1.4, within the acceptable values required for optimum durability for sub-ballast.

IV. RESULTS AND DISCUSSION

Application of AASHTO mechanistic-empirical pavement design approach to railways

The sustainable design method is the one proposed by the compaction methodology "Superpave" to be used in asphalt mixtures for rail transport, considering the equivalent axial loads for the railway lines [58]. The vertical displacement at high temperature is the reason that exemplifies the rutting distress.

The results with both software are shown in Fig. 5 and Table 1.

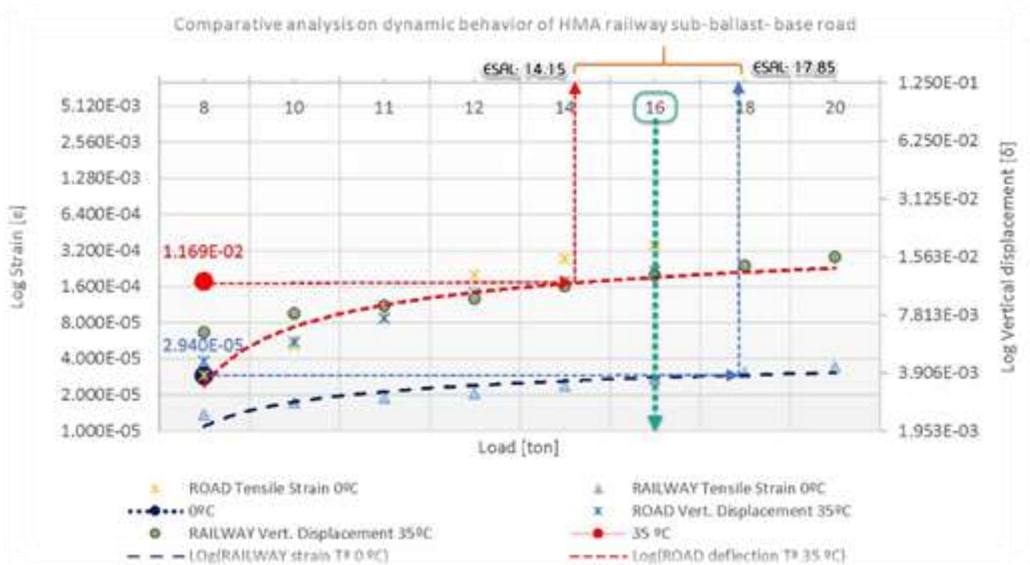

Fig. 5. Results obtained from the simulations with KENPAVE-KENTRACK software

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Table 1. Deformations results at 0ºC and 35ºC

	Axle (ton)	Tª [ºC]	Tensile strain [εx]	Vertical displacement [δ]
Road (Base layer)	8.2	0	2.940E-05	4.510E-03
Railway (Sub-ballast)	8.0	0	1.380E-05	5.940E-03
	10		1.720E-05	7.400E-03
	11		1.900E-05	8.120E-03
	12		2.070E-05	8.840E-03
	14		2.410E-05	1.027E-02
	16		2.750E-05	1.169E-02
	18		3.110E-05	1.310E-02
	20		3.440E-05	1.450E-02
Road (Base layer)	8.2	35	2.763E-05	1.169E-02
Railway (Sub-ballast)	8.0	35	2.550E-05	6.390E-03
	10		3.190E-05	7.950E-03
	11		3.520E-05	8.720E-03
	12		3.840E-05	9.949E-03
	14		4.480E-05	1.103E-02
	16		5.130E-05	1.256E-02
	18		5.800E-05	1.409E-02
	20		6.440E-05	1.560E-02

As it is possible to see from Fig. 4, the road deformations find the homolog for railways with an axle between 14 to 18 ton; the average weight is equal to 15.98t. Thus 16 ton has been selected as the reference standard axle-rail predominant in the case study of Italian main rail lines.

Traffic spectrum and project traffic of rail lines

For the case study, operating high-speed trains on Italian lines were considered.The load for the regular passenger train consists of two (160kN) wheels in a group on each side, spaced at 60cm on the rail. The loading system of the Kentrack model was designed considering the Long-distance intercity train configuration, composed of 1 locomotive plus four bogies (16 axles) with a static load of 16 tons per axle and a distance between axles (wavelength of vibration) of 14,65m. The running speed is between 200-250km/h, diesel-electric power and, 1,45mm standard gauge.

It is considered an equivalent frequency equal to the ratio between average train speed, v, and wavelength, λ. Thus, a five-hertz frequency value (ratio between the maximum speed of a long-distance train 250km/h or 69.45m/s, and the wavelength characterized by the axle distance-tandem wheel, in this case, 14.65m, where f=v/λ (see Fig. 6).

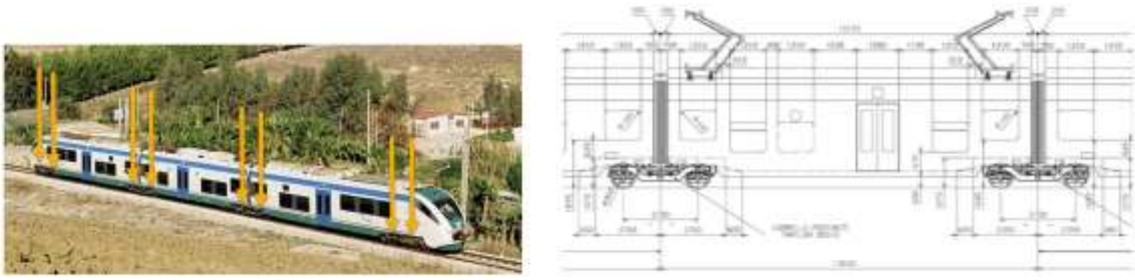

Fig. 6. (a) Long-distance intercity example train (250km/h); (b) distance between axle tandem wheels

The definition of project traffic must include a condition of practical loads and the number of movements of each train that will use the infrastructure during its useful life. Traffic forecasts are then determined to differentiate the stresses to which it is subjected the formation of sub-ballast.

Based on the standard input parameters, asphalt underlayment trackbeds can be examined by varying parameters such as axle load, subgrade modulus, and layer thickness.

The principal parameters (road-railway) used to create the reference sections are demonstrated in Tables 2 and 3.

Table 2. Parameters selected for KENTRACK simulations

Type of rail: 60E1			Pandrol Fastclip system		
Young's modulus [MPa]	Limit of proportionality [MPa]	Limit of elasticity [MPa]	Static stiffness [MN/m]	Clamping force [kN]	Creep [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]	Rail distance [cm]
21	16.9	5.18	60	259	143.5
Type of axle considered for the simulations				Single	

Table 3. Parameters selected for KENPAVE® simulations

Road structure			
Material:	Response	Nº Periods	Nº Layers
Linear	Displacement	5	4
Load information			
Load	CR*	CP**	NR***
single axle	12.62	800	1

* Contact radius of circular loaded areas [cm];
** Contact pressure on circular loaded areas [psi];
*** Nº of radial coordinates to be analyzed under a single wheel [-]

The amount of traffic is measured regarding the number of repetitions of application of loads of different axles. So, the assessment of traffic implies knowledge of:

- the number of vehicles by year and the growth rate of the rail industry;
- the average number of axles/vehicle and the spectrum of axle loads;
- the transverse distribution of loads and the time horizon of the useful life;

The different traffic spectrum for rail lines was converted to RESALs. The frequency of the passage (f_k) of the k-axle load, defined as the ratio between the number of axle-steps and the total number of the axle-passages for 100 vehicles passing, was calculated using the following equations:

$$T_D = 365 \times T_{HV} \times [(1+r)^n - 1]/r \quad (1)$$

$$N_D = T_D \times (\sum_j^m f_j \times n_j) / \sum_j^m f_j) \times A \times Rt \quad (2)$$

$$A = \sum_k^m f_k \times (P_k / P_r)^\gamma \quad (3)$$

$$f_k = \frac{\sum_i^j (f_j \times n_j)_i}{\sum_j^m \sum_i^j (f_j \times n_j)_i} x100 \quad (4)$$

Where:
T_D = total number of load passageways expected over the entire service life [-];
T_{HV} = avg. daily traffic in the year of rail creation [-];
Rt = annual growth rate of traffic [-];
n = 30 years design life [year];
N_D = RESALs at the end of the service life [-];
n_j = number of ways of the j-axle;
f_j = frequency of the j-axle;
P_k = k-axle load [kN];
P_r = axle load [kN];
A = aggressiveness coefficient of railway traffic[1];
γ = coefficient for the flexible bituminous railway – base course [5-6, respectively]; and
f_k = passage frequency of the k-axle load [-].

Railway traffic design life

The design life depends on the railway type and the traffic level it is longer for the railroads with significant traffic to cause the least interference to the exercise due to rehabilitation maintenance works. The design life is 50 years for the high-speed lines and 30 years for the regular lines. It is stated by the number of load repetitions for all the

[1] According to 1993 AASHTO Guide for Flexible Pavement Structural Design for a highway outside cities, the coefficient of aggressiveness, A, is around 1.57. For the main rail-line, the value obtained is around 0.30, considering the different γ coefficient respectively.

traffic load and environmental conditions. Prediction of structure distresses and maintenance throughout its lifetime can be performed according to the allowable number of load repetitions (Sadeghi & Barati, 2010).

Table 4. RESALs at the end of the service life (30 years)

Traffic growth [%]	Palermo Messina	Catania Messina	Siracusa Catania
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

The traffic level over a 30-year period for the main-lines considered is summarized adopting a traffic growth rate equal between 0% to 1% (Table 4).
Considering an average of increased rate industrial traffic of 1%, and service life of 30 years, the rail equivalent single axle load (RESAL) obtained is $3.7x10^7$ (Level 3 of "volumetric mix-design method"). The results of the traffic spectrum for the mainline considered are shown in Fig. 7 and Table 5.
Therefore, considering the logarithmic regression from the interpolation of the values of ESAL-N_{des} (AASHTO R35-2015), it has been determined the correspondence between the RESALs and number of gyrations (Fig. 8).

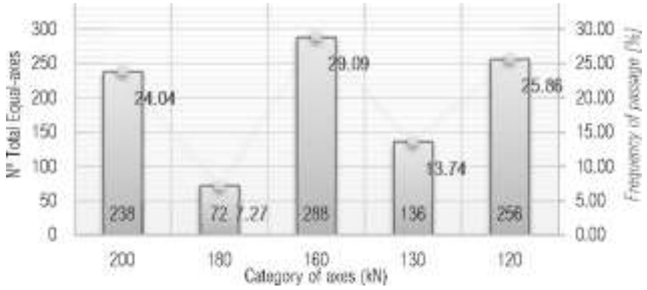

Fig. 7. Traffic spectra of main railway line

Table 5. Traffic levels

Category of axes		N° Total Equal-axes	fk [%]	N° Passages x 100 trains	N°passages / N° axes	Avg. N° axles for train, n [%]	Coefficient of aggressiveness A
₸	200	238	24.04	57.22	0.240	0.57	0.734
₸	180	72	7.27	5.24	0.073	0.05	0.131
₸	160	288	29.09	83.78	0.291	0.84	0.291
₸	120	256	25.86	66.20	0.259	0.66	0.061
Total ₸		990	100	231.12	1.00	2.31	1.27

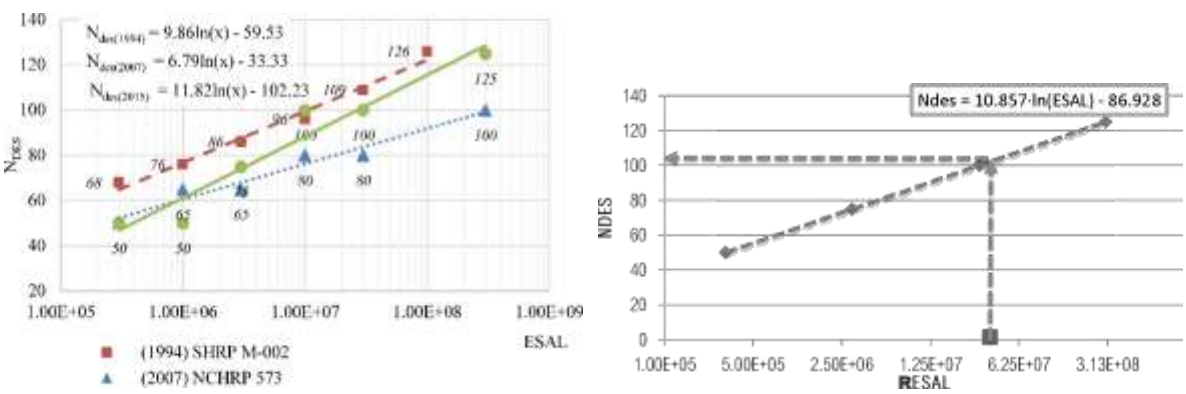

Fig. 8. (a) N_{design} recommended by Superpave standards; (b) Logarithmic regression by interpolation of N_{des}

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A unique correspondence between the number of gyrations and the RESALs has been defined. In this lab-research, the "volumetric mix-design method" requires specimen compaction with SGC at the design number of gyrations of N_{des}=102; N_{init}=8 and N_{max}=162 gyrations.

The design asphalt content is selected at 3% air voids at N_{des}. Thus, a new table of values is used in a volumetric mix-design for railways, and it has been determined from the rail traffic level expected and the design air temperatures for the site. Once the overall procedure for the mix design was defined, a laboratory verification has been conducted with a conventional HMA mixture and different rubberized asphalt solutions by a dry process.

Examination of thermal contribution and mechanical properties

Due to the existence of ballast aggregates for underlayment, the hot mix asphalt and subgrade in railroad trackbed are better protected from environmental effects as compared to highway pavements. The simulations with KENPAVE and KENTRACK have been set at 0ºC and 35°C, which representatives of low and high temperatures respectively. Consequently, two different temperatures (0-35ºC) within the bituminous layers at the depth "z" and at time "t" were calculated as the outcome of Barber's equation using different parameters for road and railway respectively (Eq. 5).

$$T_{pav(z,t)} = T_M + R + (\frac{T_V}{2} + 3R) \cdot F \cdot e^{-Cx} \cdot \sin\left(0.262t - C_x - arctg\left(\frac{C}{hc/_K + C}\right)\right) \quad (5)$$

Where:

$T_{pav(z,t)}$ = pavement temperature at the depth z and time t [°C];
T_M = mean effective air temperature[0-35°C];
T_V = maximum variation in temperature [10.5°C];
$R = 2/3 \cdot (b \cdot I)/24h_c$ = contribution of the solar radiation [8.35°C];
$h_c = 4.882 \cdot (1.3+0.4332 \cdot v^{3/4})$ = surface coefficient depending on the wind speed [24.25 kcal/hours m^2°C];
(*) Values of absorptivity in the case of railway sub-ballast, equal to 0.21 (Crispino M. 2001) and, 0.9 (Barber E. 1957).

v = wind speed [17.25km/h];
I = average radiation [5398 kcal/m^{2}day];
b = absorptivity of surface to solar radiation [0.21];*
$C=(0.131 \cdot s \cdot w)/K$ [6.71 hour$^{0.5}$/m];
s = specific heat [0.21 kcal/kg°C];
w = density [2500 kg/m^3];
K = thermal conductivity [1.5 kcal/mh°C]; and
x = depth [0.47 m];

The most important effect is the temperature of bituminous sub-ballast, which affects its elastic modulus. Consequently, two different temperatures within the bituminous layers were calculated as the outcome of Barber's equation using various parameters for road and railway respectively (Table 6).

Table 6. Values adopted for Barber's equation

Parameters	Value	Units		Parameters	Value	Units
T_M	0-10-20-30-35-40	ºC		F	0.68	_
T_V	10.5	ºC		C	6.71	hour$^{0.5}$/m
I	5398	kcal/m^{2}h		R	6.71	hour$^{0.5}$/m
v	17.25	km/h		K	1.5	kcal/mhºC
h_c	24.25	hour$^{0.5}$/m		s	0.21	Kcal/kgºC
H	16.17	1/m		w	2500	Kg/m^3
B_{barber}	0.9	_		$B_{Crispino}$	0.21	_

Sub-ballast and subgrade are measured as linear elastic materials. The bedrock is assumed incompressible with a Poisson's ratio of 0.5. Ballast in a newly constructed trackbed behaves non-linearly while in an old trackbed it behaves linearly due to being well compacted. In the asphalt layer, the tensile strain at the bottom of the asphalt layer controls its service life. The design method presented was used under the following conditions of traffic and climate (Table 7).

Table 7. Standard layer properties

Railway track	Layer (mm)	Thickness (inch)	Poisson's ratio	Young's modulus (psi) (× 6.89 kN/m^2)
Concrete tie	210	8.27"	0.3	4,000,000
Ballast	350	13.78"	0.2	18,490

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Sub-ballast	120	4.72"	0.4	1,305,000
Subgrade	300	11.81"	0.4	21,350
Bedrock	-	-	0.5	10,000,000,000

The dynamic modulus of HMA is calculated using the method developed by Witczak (1979) [59-60]. To accurately model the asphalt, different temperatures should be utilized for the various periods since the dynamic modulus is dependent on the temperature. Witczak E* predictive model was incorporated into KENTRACK to calculate asphalt dynamic modulus [61]. The equation is expressed as Eq. 6:

$$\log\left|E^*\right| = -1.249937 + 0.02923\rho_{200} - 0.00167\rho_{200}^2 - 0.002841\rho_4 - 0.05809\cdot V_a - \ldots$$

$$\ldots 0.802208\cdot V_{beff}\,/\,(V_{beff}+V_a) + \frac{3.971977-0.0021\rho_4+0.003958\rho_{38}-0.000017\rho_{38}^2+0.00547\rho_{34}}{1+e^{(-0,6033-0,3133\log(f)-0,3935\log(\mu))}} \tag{6}$$

Where:

- *|E*|= Asphalt dynamic modulus [10^5 psi];*
- *ρ200= % passing to the sieve 0.075mm;*
- *ρ4= % retained to the sieve 4.75mm;*
- *ρ38= % retained to the 9.5mm sieve;*
- *ρ34= % retained to the 19mm sieve;*
- *Vbeff= effective binder content [% by volume];*
- *Va= air voids [% by volume];*
- *f= frequency [Hz]; and*
- *μ= binder viscosity [10^6 poise].*

Table 8 shows the temperatures and the properties characterizing the bituminous materials.

Table 8. Parameters inserted in the Witczak formula

	Layer	Ẋ Tª [°C]	μ [10^6 poise]	log |E*|	|E*| [MPa]	ν
Air temperature 0°C						
Road	WC	8.34	11.6057	1.174	10282.6	0.4
	BC	8.34	11.6057	1.208	11135.2	0.4
	BA	8.35	11.6057	1.283	13219.8	0.4
Rail	SB	1.94	59.5026	1.434	18929.8	0.4
Air temperature 35°C						
	Layer	Ẋ Tª [°C]	μ [10^6 poise]	log |E*|	|E*| [MPa]	ν
Road	WC	43.34	0.0014	-0.130	510.39	0.4
	BC	43.34	0.0014	-0.098	549.56	0.4
	BA	43.35	0.0014	-0.045	621.17	0.4
Rail	SB	36.95	0.0074	-0.235	1185.68	0.4

(*) *WC: wearing course; BC: binder course; BA: base course; SB: sub-ballast layer.*

Temperature validation results

The thermal regime, within the pavement, is governed by the physical, chemical and thermal properties of the layer materials, as these affect the process of propagation of the temperature in the sub-ballast and the substrate. The operating methodology to calculate the temperature gradients is composed of different stages:

- Acquisition from the last 30-years of meteorological temperature values (operated by Sicilian and meteorological Information Service, SIAS);
- Meteorological data processing, dividing the year and calculate the average max/min temperatures $T^a_{max/min}$ for each year-period.
- Calculate the average air temperature T_a(p) of the seasonal periods;
- Temperature inside each layer, in function of the relative average air temperature for each period, using Barber equation;

Certain limitations are solved such as the fluctuations in temperatures that can significantly affect the layer stability, or the different conductivity of the materials. Each simulation for various temperatures (0, 10, 20, 30, and 35ºC), has considered that in the case of roads and rail, the depth of interest is 31cm and 47cm respectively. In table 9 are shown the temperature gradients for each layer.

Table 9. Results Tª pav(z,t) obtained for road base and railway sub-ballast layers

Air Tª	0ºC		10ºC		20ºC		30ºC		35ºC	
Nº hour	Road	Railway	Road	Railway	Road	Railway	Road	Railway	Road	Railway
0	6.68	2.04	16.68	12.04	26.68	22.04	36.68	32.04	41.68	37.04
1	6.26	1.96	16.26	11.96	26.26	21.96	36.26	31.96	41.26	36.96

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2	5.99	1.88	15.99	11.88	25.99	21.88	35.99	31.88	40.99	36.88
3	5.87	1.80	15.87	11.80	25.87	21.80	35.87	31.80	40.87	36.80
4	5.93	1.73	15.93	11.73	25.93	21.73	35.93	31.73	40.93	36.73
5	6.15	1.68	16.15	11.68	26.15	21.68	36.15	31.68	41.15	36.68
6	6.52	1.64	16.52	11.64	26.52	21.64	36.52	31.64	41.52	36.64
7	7.02	1.63	17.02	11.63	27.02	21.63	37.02	31.63	42.02	36.63
8	7.60	1.64	17.60	11.64	27.60	21.64	37.60	31.64	42.60	36.64
9	8.24	1.66	18.24	11.66	28.24	21.66	38.24	31.66	43.24	36.66
10	8.89	1.71	18.89	11.71	28.89	21.71	38.89	31.71	43.89	36.71
11	9.49	1.78	19.49	11.78	29.49	21.78	39.49	31.78	44.49	36.78
12	10.02	1.85	20.02	11.85	30.02	21.85	40.02	31.85	45.02	36.85
13	10.44	1.94	20.44	11.94	30.44	21.94	40.44	31.94	45.44	36.94
14	10.71	2.02	20.71	12.02	30.71	22.02	40.71	32.02	45.71	37.02
15	10.82	2.10	20.82	12.10	30.82	22.10	40.82	32.10	45.82	37.10
16	10.76	2.17	20.76	12.17	30.76	22.17	40.76	32.17	45.76	37.17
17	10.54	2.22	20.54	12.22	30.54	22.22	40.54	32.22	45.54	37.22
18	10.17	2.25	20.17	12.25	30.17	22.25	40.17	32.25	45.17	37.25
19	9.67	2.27	19.67	12.27	29.67	22.27	39.67	32.27	44.67	37.27
20	9.08	2.26	19.08	12.26	29.08	22.26	39.08	32.26	44.08	37.26
21	8.45	2.23	18.45	12.23	28.45	22.23	38.45	32.23	43.45	37.23
22	7.80	2.18	17.80	12.18	27.80	22.18	37.80	32.18	42.80	37.18
23	7.20	2.12	17.20	12.12	27.20	22.12	37.20	32.12	42.20	37.12
Δ	8.35	1.95	18.35	11.95	28.35	21.95	38.35	31.95	43.35	36.95

The results after comparison between railway sub-ballast bottom layer and road base bottom layer are represented in Fig. 9. The experimentation conducted has allowed the determination of the temperatures in the sub-ballast layer of the asphalt mixture. The variation of temperatures during the year is found to be approximated by a sinusoidal function. It has been found that the wind speed and depth have a positive effect on the pavement temperature predictions, the maximum daily temperature increases by increasing the wind speed and depth.

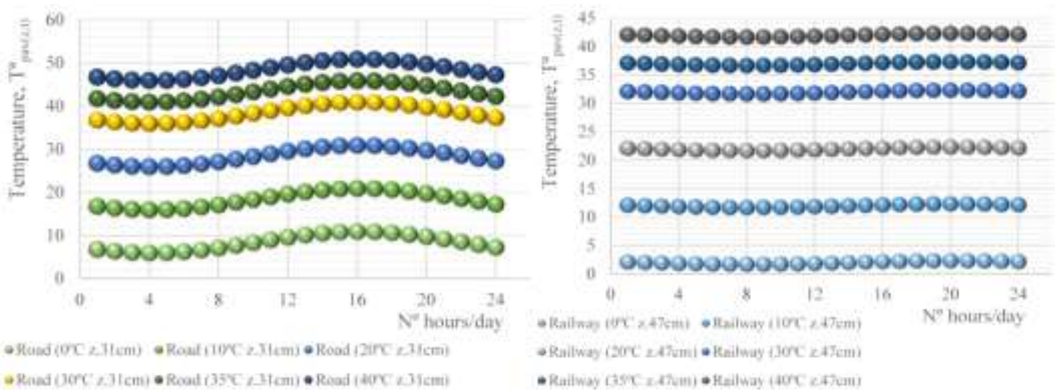

Fig. 9. Daily variation of T^a in the pavement at the depth z and time t [°C] between road and railways

Air temperature and solar radiation were found to have the main positive impact, and pavement temperature fluctuations follow a sine curve with a period of one day. Based on the acquired measurements we determined the average seasonal temperatures in the layer, for the spring, summer, autumn, and winter respectively, related to climatic conditions.

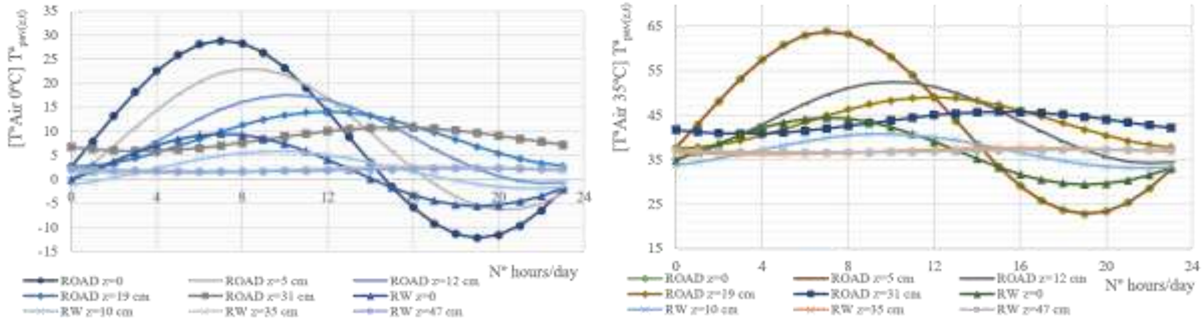

Fig. 10. 24hour-Tª variation at different depths [Air Tª 0°C-35ºC] between road and railways

In the Fig. 10 is shown the evolution of the temperature in each layer for the most representative air temperatures (0ºC and 35ºC) in each section of pavement and railway, along with a sinusoidal cycle marked by the daily hours.

Laboratory experimental results

Materials and mixture design

Volumetric mix design with gyratory compactor (SGC) is the crucial step in a well-performing asphalt mixture according to NCHRP (2007). It was developed as the optimal laboratory tool that more closely simulates field compaction of asphalt mixtures. The SGC is a 1.25º fixed angle, 600kPa pressure and rate of gyration (30rev/min) compactor that creates samples of Ø150x120mm in target height. The compacted samples are measured for specific gravity, and the volumetric properties are calculated. The SGC also provides the ability to investigate the aggregates properties at void levels representing construction throughout its intended life cycle.The specifications for the bituminous sub-ballast are defined by the Italian standard (void content of 4-6%, a Marshall stability of 10kN, and a higher indirect tensile strength at 15ºC of 0.6N/mm^2).

The Volumetric mix design system contains specific characteristics related to select acceptable aggregate materials (washed sieve analysis, mineral dust filler, control points, and Fuller's curve). The grading curve of aggregates (Fig.11) was precise adopting the optimal percentages to produce asphalt mixtures which exhibit controlled levels of coarse aggregates interlock.

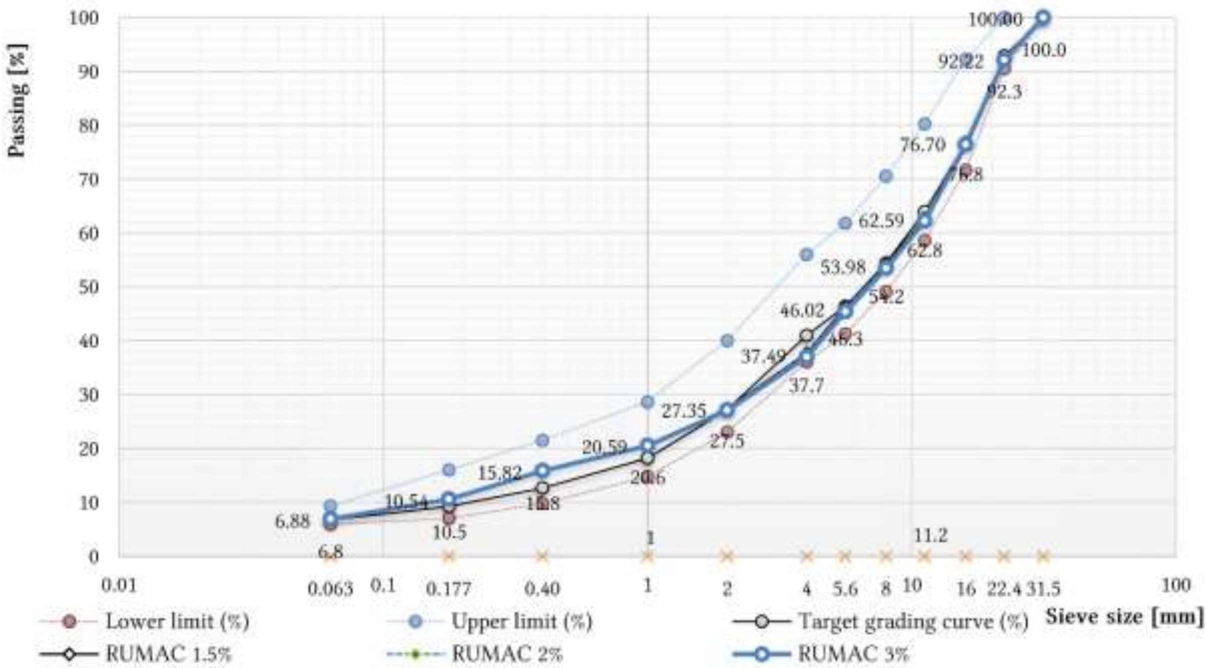

Fig. 11. Grading curve of the mixtures

The content of bitumen based on the total mass of the aggregates will have to correspond to the optimum content obtained in the laboratory, with a tolerance of ± 0.5%. The characteristics of the materials used for the fabrication of the bituminous sub-ballast are summarized in Table 10.

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Table 10. Characteristics of the materials used for the bituminous sub-ballast production

Bitumen Properties		Standard	Value
Penetration at 25°C		EN1426:2007	53
Penetration index [-]		EN12591 Annex A	-0.575
Softening point [°C]		EN1427:2007	50
Bulk gravity [g/cm^3]		EN 15326:2007	1.033
Viscosity at 150ºC [Pa·s]		ASTM D2493M-09	0.195
Equiviscosity values by Brookfield viscosim. [°C]	0.28Pas	EN 12695:2000	143.1
	0.17Pas	AASHTO T316-04	156.2
Aggregates properties		Standard	Value
Los Angeles abrasion loss [%]		EN 1097-2:2010	20.8
Density of aggregates [g/cm^3]		EN 1097-3:1998	2.82
Density of sand [g/cm^3]		EN1097-6:2013	2.84
Density of filler [g/cm^3]		EN1097-7:2009	2.70
Resistance to fragmentation (%)		EN1097-2	20.83
Determination of particle shape		EN 933-3 (%)	10
Sand equivalent (>45) (%)		EN 933-8	61
Total sulphur content (<0.5) (%)		EN 1744-1	0
Rubber properties			
Color	Black		
Particle morphology	Irregular, undisclosed		
Moisture content (%)	<0.75		
Textile content (%)	<0.65		
Metal content (%)	<0.10		
Maximum density according proportion 60% Ø0.4-2mm ; 40% Ø2-4mm). Standards: C.N.R. UNI-1 ; ASTM C128 ; UNE 12597-5:2009			
Tª water: 27ºC *(density 1.00025 gr/cm^3)*		Pycnometer test	
Weight of sample (gr)			500
Weight of pycnometer, m1(gr)			767
Weight of pycnometer with sample mass, m2 (gr)			1270
Weight of pycn. + sample ssd + water, m3 (gr)			3106
Weight of pycnometer filled of water, m4 (gr)			3039
Maximum Specific Gravity of rubber (g/cm^3)			1.1536

The crumb rubber used by the dry process had two particle sizes of 0.2-4mm and 2-4mm (sieving process and grading curve are shown in Fig. 12). The rubber aggregate with gap-gradation is a two-component system in which the finest gradation is believed to interact with the asphalt cement while the coarse rubber performs as an elastic aggregate in the hot mix asphalt mixtures [62].

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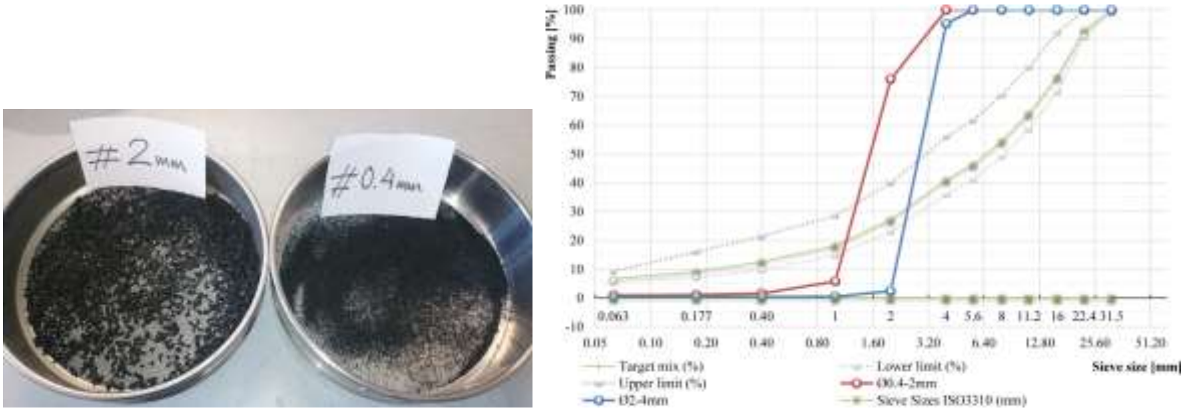

Fig. 12. (a) Sieve analysis for grading; (b) Rubber sieve analysis (Grading curves Ø2-4mm; Ø0.4-2mm)

The volumetric mix design characteristics are explained in the next table 11:

Table 11. Volumetric mix design characteristics

N_{des}	102	150	180	290
Characteristics of the mixtures	RFI b.4%	DRY1.5% b.5,5%	DRY2% b.6,5%	DRY3% b.7%
Mixture weight (*)	5460	5460	5460	5460
Aggregrate mass	5250	5176	5127	5103
SG Aggregates	2.809	2.808	2.808	2.808
%Inert part	96.15%	94.79%	93.89%	93.45%
Bitumen mass	210.0	284.5	333.4	357.4
S. Gravity binder	1.033	1.033	1.033	1.033
% binder	3.85%	5.21%	6.11%	6.55%
γ_{max} [g/cm^3]	2.634	2.577	2.541	2.524

(*) Optimal inert part for a specimen of Ø150x120mm

Laboratory results and discussion

The reference mix was a bituminous dense graded mixture of sub-ballast layers according to RFI (2016). It was a hot mix asphalt with a maximum size of 31.5mm coarse aggregate, a limestone fraction and a 6.75% amount of filler passing sieve 63μmm. An amount of 72% of filler had a particle size smaller than 0.177mm. The mixtures were designed with a fine-aggregate fraction less than 2mm to guarantee excellent adhesion and chemical bonding, The manufacturing temperature for a conventional B50/70 bitumen was 160ºC, and the compaction temperature was set at 145°C, were carried out with the Brookfield viscometer, according to the viscosity values (ASTM D2493, 2009). The higher temperature thus guaranteed the workability of the mix.

Previously, for the HMA selected, to obtain the target air voids percentage of 3%, a volumetric mix design procedure was developed with four different bitumen percentages (3.5%, 4%, 4.5%, and 5%) of the total weight of aggregates compacted using the gyratory compactor (SGC). Between three and four samples for each combination were manufactured for determination of the maximum theoretical specific gravity.

Finally, for a 4% of binder content, a 2,74% of air voids at Ndesign was achieved as the target value (AASHTO R35, 2001) in the case of HMA mixtures. For mixtures with rubber, the percentage of voids varied between 3.01% and 3.37%. Therefore, it is never possible to exceed the maximum value of an established 4% of voids for a suitable bituminous mixture in sub-ballast. The dry-process mixes were manufactured with a digestion time between 60, 90 and 120min. The digestion time enhanced the interaction between binder and rubber modifying the mechanical properties of the mixes.

An essential step inside the volumetric compaction by Superpave is the optimal finding of the relationship between mass inert part and height of the final specimen, in that case, cylindrical specimens of Ø150x120mm for gyratory compaction were selected. The specimens, as a valid criterion of orientation, were developed with 120mm of height after compaction in analogy of the real thickness of the sub-ballast layer.

According to the sub-ballast optimal thickness of the layer, as we can see before, a height of 120mm value corresponds with sub-ballast layer modelized in rail track, so for optimal compaction, it was needed to find the optimal relation binder content-amount of aggregates.

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After compacting the specimens to 102 cycles (N_{des}), it has been determined the bulk specific gravity (Γ_{mb}) and the theoretical maximum specific gravity (Γ_{mm}) of each of the mixtures (EN 12697-6) [63]. A densification curve for each mixture is plotted indicating the measured relative density at each number of gyrations, % Γ_{mm} vs. the logarithm of the number of gyrations (Fig. 13a). To ensure compaction and densification, for each mixture were observed the aggregate interlock and, the air void content around 3%. So, this is reflected in the logarithmic trend equations (Fig. 13b):

$HMA\ (b.4\%) \rightarrow \Gamma mm = 3.633 \ln(x) + 80.954$
$DRY1.5/5.0 \rightarrow \Gamma mm = 3.426 \ln(x) + 80.964$
$DRY1.5/5.5 \rightarrow \Gamma mm = 3.277 \ln(x) + 81.595$
$DRY2.0/6.0 \rightarrow \Gamma mm = 2.359 \ln(x) + 86.209$
$DRY2.0/6.5 \rightarrow \Gamma mm = 2.306 \ln(x) + 86.864$
$DRY3.0/7.0 \rightarrow \Gamma mm = 1.806 \ln(x) + 86.955$

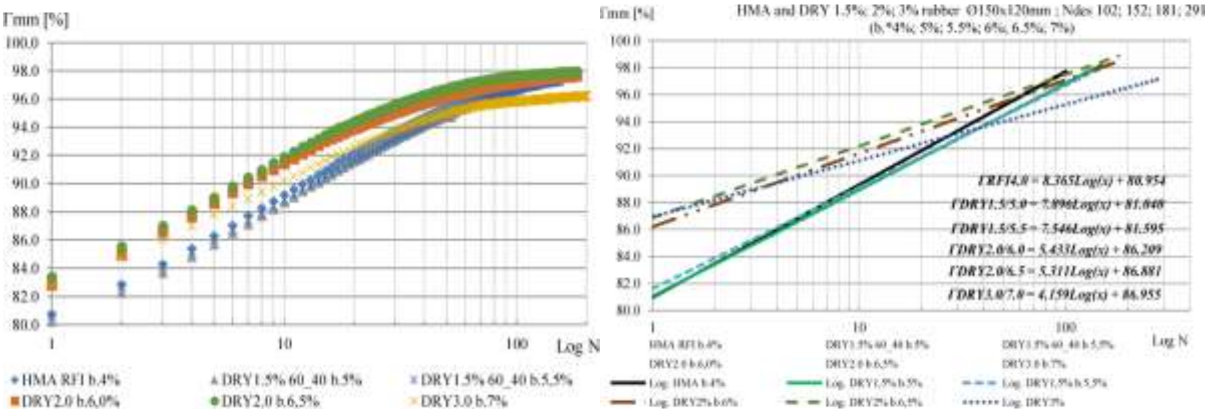

Fig. 13. (a) Comparison between compaction curves; (b) Trend lines of final compaction curves

For each specimen prepared, the asphalt binder (135-150ºC), aggregates (160-190ºC) and compaction molds (150ºC) were heated to the proper mixing temperature according to the mixture type. After compaction, each sample was 24h cooled to room temperature (20ºC) without being removed from the mold with the purpose to avoid the bounce back effect due to the swelling of rubber. Because it was observed a dilatation (expansion) of the specimens after seven days, final air voids are considered to explicit the optimal binder content (Fig. 14 and Table 12).

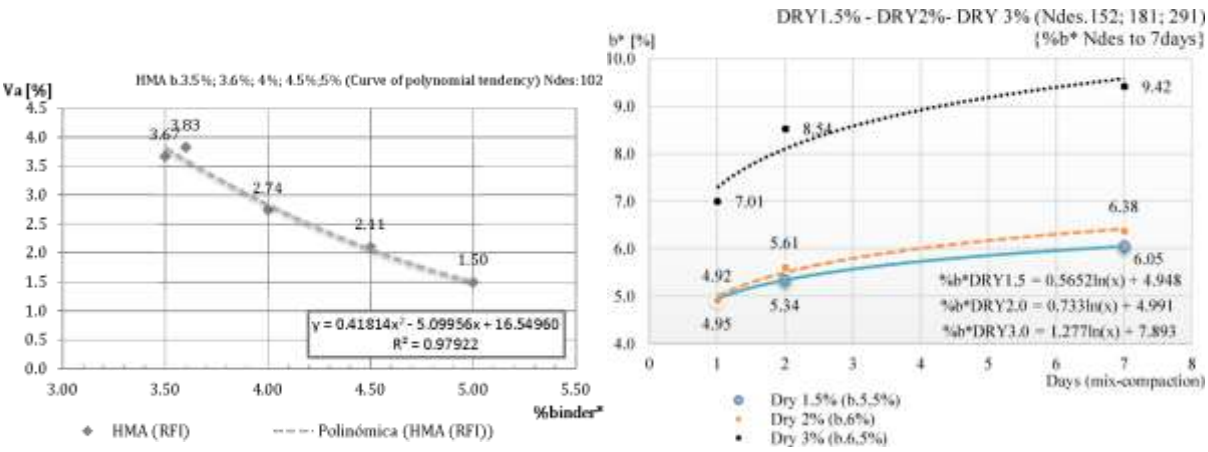

Fig. 14. (a) HMA plot of air voids vs. binder content; (b) Optimal binder content after one week due to the swelling effect of rubberized compacted specimens

Table 12. Optimal binder content to achieve a target value of 3% of air voids by dry process

Mixture	%Va*	$\%b^*_{(Ndes)}$	$\%b^*_{(24h)}$	$\%b^*_{(7d)}$
Dry 1.5%	3.0%	4.95%	5.34%	6.05%
Dry 2%	3.0%	4.92%	5.61%	6.38%

Dry 3%	3.0%	7.01%	8.54%	9.42%

During mixing period, rubber swells and the amount of bitumen absorbed increased which causes a stiffer residual bitumen that must be controlled. This fact responds to the need to comply with the following optimum manufacturing protocol [64], with the aim of avoiding the absorption effect of the rubber and subsequent structural internal swelling, which leads to deterioration of the specimen.
From the tests conducted it emerged that the sub-ballast mixture at N_{design} 102 cycles achieved the target voids content with 4% of bitumen about the weight of aggregates, for a conventional mixture without rubber. An example of the compacted samples is shown in Fig. 15.

Figure 20. Compacted SGC Specimens of HMA_RFI 15x12cm and DRY mixtures

V. CONCLUSION

It has been proceeded to the calibration of the model to forecast temperatures of Barber and Crispino, both for the road-railway structures respectively. The main parameters of pavement temperature, wind speed, precipitation, air temperature, and solar radiation were controlled by the thermal properties of the layers. The verification of the applicability of Barber forecasting model to the case of the railway by the complete temperature data (so the four seasons), provides to make available an appropriate measure to estimate temperatures in sub-ballast for different weather conditions.
It has been necessary to understand the effects of the various track components to develop a rational structural design method for railroad trackbeds. These factors include axle load, subgrade modulus, etc. A trackbed that has strong load-bearing capacity of subgrade should be able to support heavy tonnage and wheel loads without excessive deformation. KENTRACK has shown to be applicable for cal-culating stresses and strains in the trackbed and pre-dicting associated design lives for a specific set of design parameters.
An experiment was conducted through SGC to determine Ndes. It was found a relationship between pavement densification and accumulated traffic through the densities of samples compacted in the SGC with/without rubber, and there was a linear re-lationship between N_{design} and rail design traffic.
The Superpave Gyratory Compactor (SGC) has been used to determine an optimal mixture. After that, the global procedure for the mix design and a laboratory verification were conducted. Based on the results, the methodology proposed is considered auspicious in estimating the optimal ratio binder-voids percentage in the studied case.
A railway equivalent single axle load has been defined, which produces the same vertical displacement (w) at high temperature (35°C) and the same horizontal tensile strain (εt) at low temperature (0°C) produced by the ESAL (80 kN) in the road structure.
The tensile strain was selected at low temperature as the benchmark parameter for the comparison and the definition of RESAL because it is the critical factor governing fatigue cracking. According to this procedure, the RESAL has been defined equal to 16 ton.
The rubberized mix-results obtained and the comparison with a conventional HMA show that these dry rubber bituminous mixtures are particularly useful in damping vibrations. The purpose of using rubber modifiers in HMA to obtain a stiffer-elastic sustainable material has been achieved for the assessment of its behavior in sub-ballast/base layers.

VI. ACKNOWLEDGEMENTS

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VII. COMPLIANCE WITH ETHICAL STANDARD

The author(s) declare(s) that there is no potential conflict of interest, also confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us and, that we have followed the regulations of our institutions concerning intellectual property.

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