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Effect of Temperature and traffic on mix-design of bituminous asphalt for railway sub-ballast layer

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ABSTRACT: A wide integrated research has been carried out to assess the suitability of bituminous mixtures as the sub-ballast layer in railways. The influence of temperature on the mechanical characteristics and thermal susceptibility of the bituminous conglomerate - which forms sub-ballast layer of railway lines - has provided the motivation for carrying out a measurement of the thermal cycles in this layer. The evaluation of the average seasonal temperatures has proven to be well interpolated by sinusoidal functions, of which characteristic parameters are determined. To expand the validity of the study in different weather situations apart from Sicily, where the experiment was held, we proceeded to apply the Barber's temperature model, used to validate pavement structures, which proved to be effective for the railway superstructure. A reference bituminous mixture according the Italian standard was used applying the Superpave mix design. This article illustrates the results obtained after different simulations, following the evaluation of the average seasonal temperatures.

1 INTRODUCTION

1.1 *Bituminous sub-ballast*

The sub-ballast layer, usually 12-15 cm thick, interposed between the ballast and the blanket (Fig.1) has been pointed out as an interesting alternative to the granular sub-ballast design traditionally applied in most European railroad tracks. For instance, the bituminous sub-ballast, protects the subgrade from the seasonal variations of moisture and atmospheric actions (Teixeira P.F et al. 2009).

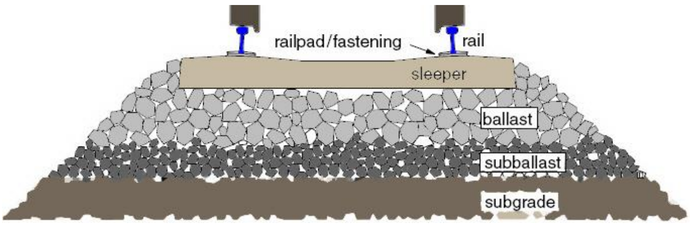

Figure. 1. Section through railway track showing the sub-ballast and formation layers.

The bituminous sub-ballast is composed of a dense-graded bituminous mixture (Rose J. G. et al. 2009). The quantity of bitumen in the sub-ballast is normally increased to 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). The use of hot mix asphalt (HMA) to replace the granular sub-ballast is a solution that has the potential to ensure the required bearing capacity and impermeability, whilst simultaneously reducing the thickness of the layer to 12 cm, compared with the 22 cm used in the conventional design. Furthermore, the use of HMA as a sub-ballast reduces noise and vibration levels throughout the track (Fang et al. 2011). Using bituminous mixtures for sub-ballast has been identified as a solution for the enhancement of the track structure (Rose & Tucker 2002). Considering all the above-mentioned aspects, the use of bituminous sub-ballast offer a higher protection of the subgrade in terms of load dissipation and water infiltration. This leads to reduced maintenance interventions (Rose J. G. et al. 2009).

1.2 *Impact of environmental conditions*

Barber (1957) was among the first researchers to study pavement temperatures based on weather reports. Pavement temperatures are of interest linking with the stabilization, curing and moisture movements of bituminous sub-ballast layer. Straub (1968) developed a computer model to predict pavement temperatures based on air temperature and solar radiation. Demsey (1970) developed a simulation model based on the heat transfer and energy balance theories to evaluate frost action in multilayered pavements. The bearing capacity of each layer is influenced by climatic conditions (air temperature, solar radiation and, wind speed) regarding the thermal regime and the moisture regime (Di Mascio et al. 2013).

1.3 *Evaluation of rail track structure design*

The purpose of the design of the rail track structure is to calculate the thickness of each layer to bear allowable stresses in the whole railway track structure and to contain the deformation due to traffic loads and temperatures variation (Esveld, 2001).

This paper deals with the distresses of the sub-ballast layer, regarding the evaluation of the temperatures from weather report and of design traffic during the life-time. After defining the temperatures of each layer, the elastic modulus of the asphalt layer can be calculated in different periods of the year. In order to extend the validity of the study, including different measured temperature values, the model to forecast temperatures proposed by Barber (1957) was calibrated and has proven to be effective for railways (Crispino 2001).

2 PROBLEM STATEMENT

2.1 *Literature review of prediction models*

Several procedures and relationships have been developed to estimate pavement temperatures from climatic data. Dempsey (1987) developed a simulation model based on the heat transfer and energy balance theories to evaluate frost action in multi-layered pavements. Diefenderfer et al. (2006) developed and validated models for predicting the daily maximum and minimum pavement temperatures. Ferreira et al. (2012) combined the mechanistic design and hydro-thermic analysis of the different railway track configurations analyzed through a three-dimensional finite-element (FEM) model.

Thus, many models are available to define the temperature into the pavements, but in this paper, there are both empirical took in consideration, Barber (1957), based on the theory of heat conduction in solids that solve the problem in a semi-indefinite body with horizontal surface in contact with air, and Marchionna et al. (1985), that proposed a climatic model for central Italy.

2.2 *Temperature profile prediction for railways*

The temperature profile in asphaltic bituminous sub-ballast is affected directly by the air-thermal environmental conditions to which it is exposed. The primary modes of heat transfer are radiation (incident solar, thermal and longwave), and convection-conduction inside the pavement (Figure 2).

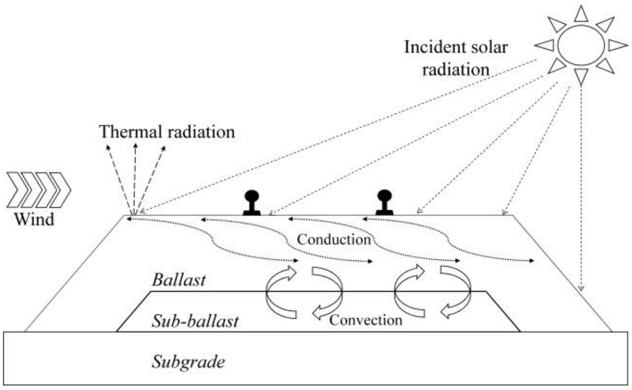

Figure. 2. Energy balance in railway track layers.

In this research, a meteorological year weather file was reproduced with a data set of hourly values of solar radiation for a one-year period, according measures by meteo-station of Palermo's airport.

Crispino (2001) illustrated the results obtained after two years measuring the thermal fluctuations to evaluate the average seasonal temperature by sinusoidal functions with a period of one day. A predicting model based on Barber (1957) was validated for road infrastructures and showed to be applicable to railway infrastructures too. See Equation 1 below that expresses the temperature in the layer at the depth z and at time t (Barber E. 1957):

$$T_{pav(z,t)} = T_M + R + \left(\frac{T_V}{2} + 3r\right) \cdot F \cdot e^{-Cx} \cdot \sin\left(0.262t - C_x - arctg\left(\frac{C}{hc/K + C}\right)\right) \tag{1}$$

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 temperature [°C]; $R = 2/3 \cdot (b \cdot I)/24h_c$ = contribution of the solar radiation [°C]; $h_c = 4.882 \cdot (1.3+0.4332 \cdot v^{3/4})$ = surface coefficient depending on the wind speed [kcal/hours m^2°C]; I = average radiation [kcal/m2day]; b = absorptivity of surface to solar radiation [-]; $F=H/((H+C)^2+C^2)^{0.5}$ *where* $C=(0.131 \cdot s \cdot w)/K$ [$hour^{0.5}$/m]; s = specific heat [kcal/kg°C]; w = density [kg/m^3]; K = thermal conductivity [kcal/mh°C]; and x = depth [m];

The principal difference between road and railway is in the absorptivity of the surface of the structure to solar radiation (b). 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). 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.

2.3 *Objectives*

The present paper focuses on the use of bituminous sub-ballast layers in railway trackbed design and the influence of the temperature on mechanical properties. The thermal susceptibility has motivated the performance of measuring the thermal cycles in this layer. The comparative analyses between Barber & Crispino are performed by simulating thermal behaviour of a sub-ballast layer for railway and a base layer for flexible roads of known thermal properties comparing the predicted max/min temperatures.

In this article, the obtained results are illustrated after different simulations, including the evaluation of the average seasonal temperatures by sinusoidal functions. It was therefore necessary to study rail traffic under various climatic situations. The application of these procedure for the mix-design of the underlayment is illustrated by an example that corresponds to three different traffic lines in the Sicilian traffic network (*Messina – Catania - Syracuse*) according to the Italian code (RFI) for bituminous sub-ballast. After defining the equivalent single axle load (E_{SAL}) and transforming the traffic spectra into number of E_{SAL}, it has been calculated the number of design gyrations (N_{des}) as Superpave parameter for railways. Finally, a case study has been investigated.

3 EVALUATION METHOD

3.1 *Design principles.*

The characterization of the linear viscoelastic behavior of a bituminous mixture is a first step to the good performance of rail-line tracks. For the elastic-plastic mechanical behavior, that characterizes sub-ballast, although its response is better described by visco-plastic constitutive laws accounting for temperature effects (Cardona et al. 2016), for this analysis is assumed a linear elastic model.

The railway structure is modeled as a multi-layer system that allows to compare the base and sub-ballasted layers to stress-strain level. The design method presented for a standard case requires to determine the thickness layer under various conditions of traffic, subgrade and climate.

After proceeding to confront both superstructures due to the similarities of thickness and properties through finite element modeling (Burmister's theory), the tensions and deformations produced by an analogous standard load can be determined. The solicitations points are shown in Figure 3.

Stresses and strains in the layers of railway track structure can be calculated by elastic multi-layer theory, defining each layer by its thickness, elastic modulus and Poisson's ratio (Witczak et al. 1999). To determine the railway equivalent single axle load (R_{ESAL}), 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® as a software that calculates stresses, strains and deformations in flexible and rigid pavements (Huang Y. H. 1993) and, KENTRACK® is the corresponding software used for the analysis and design of railway trackbeds (Rose et al. 2014). By applying the theory of stresses in layered systems by Burmister (1943) and the FEM method, the stress, strain and deformations are calculated (Huang et al. 1984) as shown in Figure 4.

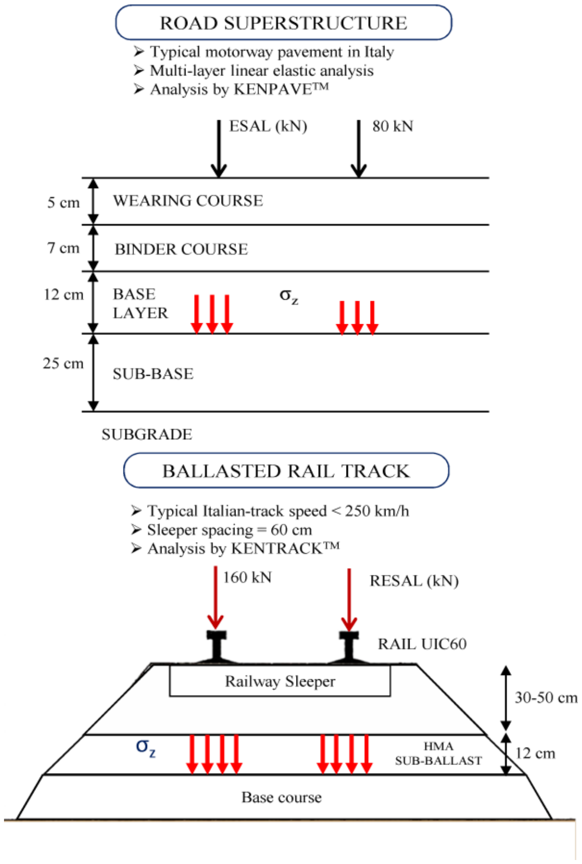

Figure 3. Road and railway sections considered.

3.1.1 *Calculation of tensions and failure criteria*

The tensile strains at the bottom of the asphalt layer, may be indicative of potential fatigue cracking at low temperatures (Rose J. 2014), which, together with the effect of rutting at high temperatures, are two of the common causes of asphalt failure in flexible pavements (Huang et al. 1987).

For this reason, in the framework of this work, the axle number, layout and load have been defined as the *rail axle load* that produces the same vertical displacement (δ) at high temperatures and the same horizontal tensile strain (ε) at low temperatures by the *road* equivalent single axle load (ESAL) (standard load is 80kN).

KENTRACK® is used under the passages of different types of axles: 8, 10, 12, 14, 16, 18 and 20 t.

3.1.2 *Trackbed model*

Rail, railpads and sleepers are modelled as prismatic elements with an isotropic linear elastic constitutive model by finite elements for trackbed design. In KENTRACK®, each section of rail between two ties is considered as a beam element with two nodes. The rails and ties are connected by tie plates modeled as a spring element (Huang et al. 1984).

Burmister multi-layer system theory is applied to calculate stresses in the trackbed. Strains at asphalt layer under multiple wheel loads are obtained by load superposition theory (Rose et al. 2010). It was found that the use of vertical compressive stress was more appropriate for railroad trackbed (Huang et al. 1984). The simulations with both software were carried out considering the air temperature equal to 0°C and 35°C (low/high temperatures respectively).

The vertical displacement was selected as the rutting parameter at high temperature. The horizontal tensile strains and deflections produced in the road and railway structures, were compared.

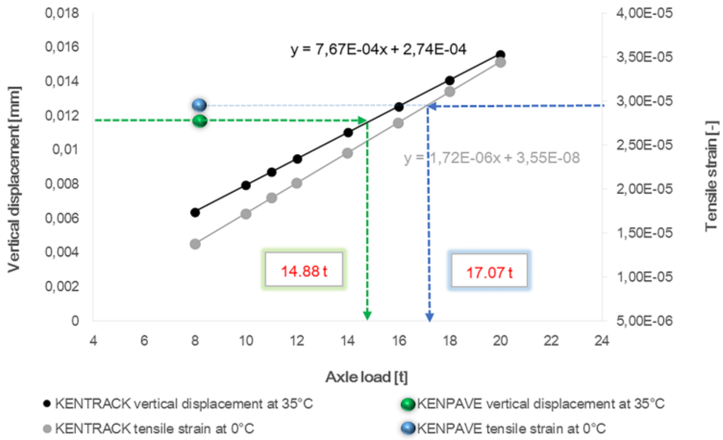

Figure 4. Results obtained from the simulations carried out with KENPAVE and KENTRACK

The tensile strain was selected at low temperature as the benchmark parameter for the definition of the railway equivalent single axle load (R_{ESAL}) because it is the critical factor governing cracking and fatigue. The results are shown in Fig. 4 and Table 1.

Table 1. Deformations results at 0ºC and 35ºC.

	Axle (ton)	T^{a} [ºC]	Tensile strain [εx]	Compressive strain [εy]	Vertical displacement [δ]
Road	8.2	0	2.940E-05	5.881E-05	4.510E-03
Railway (Sub-ballast)	8.0	0	1.380E-05	2.300E-05	5.940E-03
	10		1.720E-05	2.880E-05	7.400E-03
	11		1.900E-05	3.170E-05	8.120E-03
	12		2.070E-05	3.460E-05	8.840E-03
	14		2.410E-05	4.030E-05	1.027E-02
	16		2.750E-05	4.610E-05	1.169E-02
	18		3.110E-05	5.200E-05	1.310E-02
	20		3.440E-05	5.770E-05	1.450E-02
Road	8.2	35	2.763E-05	5.525E-05	1.169E-02
Railway (Sub-ballast)	8.0	35	2.550E-05	4.250E-05	6.390E-03
	10		3.190E-05	5.330E-05	7.950E-03
	11		3.520E-05	5.870E-05	8.720E-03
	12		3.840E-05	6.410E-05	9.949E-03
	14		4.480E-05	7.490E-05	1.10E-02
	16		5.130E-05	8.570E-05	1.256E-02
	18		5.800E-05	9.700E-05	1.409E-02
	20		6.440E-05	1.080E-04	1.560E-02

As it is possible to see from Figure 5, 14.88t is the weight of the railway axle load that produces the same vertical displacement at high temperatures induced by an 80Kn standard axle load 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 axle 80kN in the road structure. Thus, 16t has been selected as the reference R_{ESAL} in the case of Sicily.

3.1.3 *Vehicles features and axle loads*

The vehicles considered in this study were medium-speed trains in Italy, that are operating on Sicilian lines. The load for the conventional Italian passenger train consists of two (160kN) wheels in a group on each side, spaced at 60cm on centers.

The loading system of the FE model implemented in Kentrack was designed considering the *Minuetto Ale501/502-Le220* (Italian) train configuration, composed of 3 bogies (8 axles) with a static load of 16 tons per axle and a distance between axles of 2.40m. The running speed is between 130-160km/h, diesel-electric power and 1,435mm standard gauge. The dimensions are 52x2.95x3.80 m (Fig. 5):

For this purpose, it was necessary to define all the components and the materials involved in the systems. Based on the standard input parameters, asphalt underlayment trackbed can be analyzed by varying parameters such as axle load, subgrade modulus, layer thickness, etc.

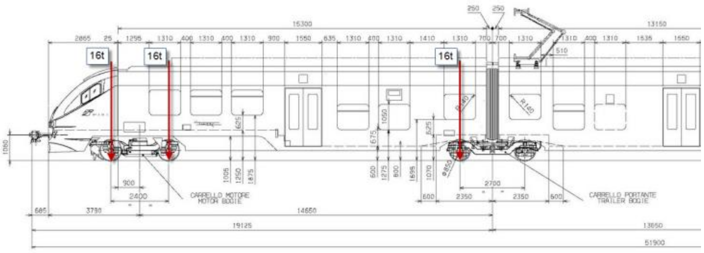

Figure 5. Convoy ALn 501-Ale Minuetto

The principal parameters (road-railway) are demonstrated in Tables 2 and 3.

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 [MN/m]	Clamping force [kN]	Creep [kN]
192000	00	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 [cm]
21	16.9	5.18	60	259	143.5
Type of axle considered for the simulations			Single		

Note: UIC = Union Internationale des Chemins de fer

Table 3. Parameters selected for KENPAVE® simulations

Road structure			
Material: Linear	Responses: Displacement	Nº Periods 4	Nº Layers 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 analysed under a single wheel [-]

3.1.4 *Analysis of traffic during design life*

The design life depends on the railway type and the traffic level. Generally, the design life is 50 years for the high-speed lines and 30 years for the ordinary lines and, it is expressed by the number of load repetitions (Sadeghi & Barati, 2010) for all the foreseen traffic load combinations and environmental conditions (temperature, moisture, etc).

The amount of traffic is measured in terms of the number of repetitions of application of loads of different axles, characteristic of the passages of vehicles on the rail-track during the service life. In this article, we have studied the Sicilian railway traffic, adopting the database provided by the Italian railway (*Rete Ferroviaria Italiana*), and considering the following types of trains (Table 4):

- *Long distance intercity (LD);*
- *Shuttle Regional Train (SR);*
- *"Minuetto EMU" ALe 501/502 (MT);*
- *Diesel Railcar "Aln 668" (AL);*
- *Wagonload freight train (WF);*

Table 4. Composition of trains in Sicily

Train / Nº coach		M [t]*	L [t]	Nº Axle	L [t]	C [t]	Nº C Axles	C [t]
LD	4	325	120	6	20	205	16	13
	5	374	120	6	20	254	20	13
SR	3	210	72	4	18	138	12	12
	4	256	72	4	18	184	16	12
MT	2	128				128	8	16
AL	1c	42				42	4	11
	2c	84				84	8	11
WF	L+7	840	120	6	20	720	36	20

**M=mass; L=locomotive; c=railcar; C=convoy; ESAL=axle load*

Three different lines in the Sicilian network were investigated and their traffic spectra were converted to R_{ESALs}, using the following equations 2, 3 and, 4:

$$T_D = 365 \times T_{HV} \times [(1+r)^n - 1]/r \qquad (2)$$

$$N_D = T_D \times \left(\sum_j^m f_j \times n_j\right) / \sum_j^m f_j) \times A \times Rt \qquad (3)$$

$$A = \sum_k^m f_k \times (P_k / P_r)^\gamma \qquad (4)$$

$$f_k = \frac{\sum_i^j (f_j \times n_j)_i}{\sum_j^m \sum_i^j (f_j \times n_j)_i} x100 \qquad (5)$$

Where T_D = total number of load passages over the service life [-]; T_{HV} = average daily traffic [-]; Rt = annual growth rate of traffic [-]; n = design life [year]; N_D = R$_{ESALs}$ at the end of the service life [-]; n_j = number of passages of the j-axle; f_j = frequency of the j-axle; Pk = k-axle load [kN]; P_r = axle load kN]; γ = coefficient for flexible railway is equal to *5 [LCPC-SETRA. (1997)]* and 6 for flexible pavements [-]; and f_k = frequency of passage 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 [-].

In order to homogenize the different axle-loads in an equivalent standard axle load (typically 80kN for road and 160kN for railway), *A* is defined as the coefficient of aggressiveness of railway traffic. An example for a highway outside cities, the coefficient of aggressiveness, A, is around 1.57. For the main railline in Sicily the value obtained is around 0.30, considering the different γ coefficient respectively. The traffic level expected over a 30-year period for the three lines is summarized in Table 5.

Table 5. RESALs at the end of the service life (30 years)

Traffic growth [%]	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

3.1.5 *Environmental conditions*

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 outcome of Barber's equation using different parameters for road and railway respectively (Table 6).

Table 6. Values adopted for Barber's equation

Parameters	Value	Units
T_M	0-10-20-30-35-40	(°C)
T_V	10.5	(°C)
I	5398	(kcal/m^{2}h)
v	17.5	(km/h)
hc	24.25	(kcal/m^{2}h,°C)
v	17.25	(km/h)
H	16.17	(1/m)
C	6.71	(hour$^{0.5}$/m)
b$^{(*)}$	0.21-0.9	
F	0.68	
K	1.5	(kcal/m,h,°C)
s	0.21	(kcal/kg,°C)
w	2500	(kg/m^3)
R	8.35	(°C)
x	47	(cm)

$^{(*)}$ *Values of absorptivity in the case of railway ballast, equal to 0.21 (Crispino M. 2001) and, 0.9 (Barber E. 1957)*

3.1.6 *Mechanical properties*

The material characteristics to be determined are the hot mix asphalt modulus, the subgrade modulus and the nonlinear elastic constant of ballast. The railroad trackbed is considered as a three-layer elastic system composed of ballast, HMA and subgrade, characterized by a modulus of elasticity and a Poisson's ratio. The bedrock is assumed incompressible with a Poisson's ratio of 0.5 (Table 7).

Table 7. Standard layer properties for default case.

Layer	Thickness		Poisson's ratio	Young's (E)
	mm	inches		psi(x 6.89kN/m^2)
Concrete Tie	210	8.27"	0.3	4000000
Ballast	350	13.78"	0.2	18490
Sub-ballast	120	4.72"	0.4	1305000
Subgrade	300	11.81"	0.4	21350
Bedrock	---	---	0.5	10000000000

Kentrack 4.0. (Liu S. 2013) incorporates the functions of asphalt binders, mix properties, viscosity and loading rates. The Witczak-E* predictive model (Andrei D. et al. 1999) for asphalt was incorporated to calculate the mechanical characteristics of the bituminous materials (Equation 6):

$$\log|E^*| = -1.249937 + 0.02923\varphi_{200} - 0.00167\varphi_{200}^2 - 0.002841\varphi_4 - 0.058097V_a - 0.802208\,V_{beff}/(V_{beff} + V_a) + \frac{3.971977 - 0.0021\varphi_4 + 0.003958\varphi_{38} - 0.000017\varphi_{38}^2 + 0.00547\varphi_{34}}{1 + e^{(-0,6033 - 0,3133\log(f) - 0,3935\log(\mu))}} \tag{6}$$

where $|E^*|$= Asphalt dynamic modulus [10^5 psi]; ρ_{200}= % passing to the sieve 0.075mm; ρ_4= % retained to the sieve 4.75mm; ρ_{38}= % retained to the 9.5mm sieve; ρ_{34}= % retained to the 19mm sieve; V_{beff}= effective binder content [% by volume]; V_a= air voids [% by volume]; f= frequency [Hz]; and μ= binder viscosity [10^6 poise].

The important parameter to evaluate asphalt properties is dynamic modulus (Witczak, 2006). In applying the equation, it was assumed that the HMA has a bitumen content of 5.5 percent by volume and an air voids content of 4 percent, the mineral aggregates have 6 percent passing the No.200 sieve and, the load is applied at a frequency of 28Hz. These values are random because the objective, in this case, is to represent a point of comparison between the road model and the railroad. The value adopted for the bituminous Poisson ratio (ν = 0.4) is the same value used by Rose et al. (2004). Table 8 shows the properties characterized.

Table 8. Main parameters for road and railway layers

Air T^a 0ºC		Layer [°C]	η [10^6poise]	log |E*|	|E*| [MPa]	ν
Road	WC	8.30	11.6057	1.174	10282.65	0.4
	BC	8.30	11.6057	1.208	11135.24	0.4
	BA	8.30	11.6057	1.283	13219.79	0.4
RaiL	SB	1.94	59.5026	1.434	18929.83	0.4
Air T^a 35ºC		Layer [°C]	η [10^6poise]	log |E*|	|E*| [MPa]	ν

Road	WC	43.3	0.0014	-0.130	510.39	0.4
	BC	43.3	0.0014	-0.098	549.56	0.4
	BA	43.3	0.0014	-0.045	621.17	0.4
RaiL	SB	36.9	0.0074	-0.235	1185.68	0.4

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

4 VALIDATION OF TEMPERATURE MODEL

4.1 *Temperature results*

The operating methodology to calculate the temperature gradients is composed of different stages:

- *Acquisition from the last 30-years of temperature values* (operated by Sicilian Information Service (SIAS) by the Regional Agriculture and Forestry);
- *Meteorological data processing,* dividing the year and calculate the T_{max_min} for each year-period.
- *Calculate the average air temperature $T_{a(p)}$;*
- *Temperature inside each layer*;

Then the results of calculations for different temperatures are performed. Each simulation has considered that in the case of roads and rail, the depth of interest is 31cm and 47cm respectively, as shown in Figure 3. Tables 9 and 10 show the results.

Tables 9-10. Results of $T^a_{pav(z,t)}$ obtained for road base and railway sub-ballast layers

Air Tª	0ºC		10ºC		20ºC		35ºC	
Nº hour	Road	Rail	Road	Rail	Road	Rail	Road	Rail
0	6.68	2.04	16.68	12.04	26.68	22.04	41.68	37.04
1	6.26	1.96	16.26	11.96	26.26	21.96	41.26	36.96
2	5.99	1.88	15.99	11.88	25.99	21.88	40.99	36.88
3	5.87	1.80	15.87	11.80	25.87	21.80	40.87	36.80
4	5.93	1.73	15.93	11.73	25.93	21.73	40.93	36.73
5	6.15	1.68	16.15	11.68	26.15	21.68	41.15	36.68
6	6.52	1.64	16.52	11.64	26.52	21.64	41.52	36.64
7	7.02	1.63	17.02	11.63	27.02	21.63	42.02	36.63
8	7.60	1.64	17.60	11.64	27.60	21.64	42.60	36.64
9	8.24	1.66	18.24	11.66	28.24	21.66	43.24	36.66
10	8.89	1.71	18.89	11.71	28.89	21.71	43.89	36.71
11	9.49	1.78	19.49	11.78	29.49	21.78	44.49	36.78
12	10.02	1.85	20.02	11.85	30.02	21.85	45.02	36.85
13	10.44	1.94	20.44	11.94	30.44	21.94	45.44	36.94
14	10.71	2.02	20.71	12.02	30.71	22.02	45.71	37.02
15	10.82	2.10	20.82	12.10	30.82	22.10	45.82	37.10
16	10.76	2.17	20.76	12.17	30.76	22.17	45.76	37.17
17	10.54	2.22	20.54	12.22	30.54	22.22	45.54	37.22
18	10.17	2.25	20.17	12.25	30.17	22.25	45.17	37.25
19	9.67	2.27	19.67	12.27	29.67	22.27	44.67	37.27
20	9.08	2.26	19.08	12.26	29.08	22.26	44.08	37.26
21	8.45	2.23	18.45	12.23	28.45	22.23	43.45	37.23
22	7.80	2.18	17.80	12.18	27.80	22.18	42.80	37.18
23	7.20	2.12	17.20	12.12	27.20	22.12	42.20	37.12
Δ	8.35	1.95	18.35	11.95	28.35	21.95	43.35	36.95

NOTE: Road base layer depth 31.5cm; Sub-ballast railway depth 47cm; Values of absorptivity in the case of railway = 0.21 (Crispino M. 2001) and of road = 0.9 (Barber E. 1957)

According to the depth of each layer showed in Figure 3, was calculated the temperature at depth 0, 5, 12, 19 and 31cm for roads and 0, 10, 35, 47cm for railways. The following graph shows 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 a sinusoidal cycle marked by the daily hours (Figure 6).

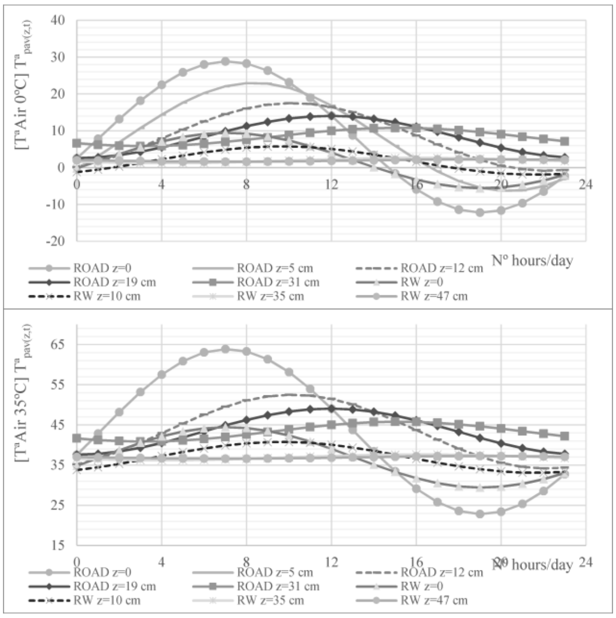

Figure 6. 24hour-Tª variation in the pavement at different depths [Air Tª 0°C-35°C] between road and railways

5 EXPERIMENTAL RESEARCH

5.1 *Analogy between road-railway through the ESALs for adequate use of Superpave*

Under NCHRP (2007), additional laboratory analysis tests were developed to further determine the performance of Superpave mixtures for the specific project design traffic and climatic condition. Traffic levels are defined by intervals counting the number of passages of equivalent single axle loads (ESALs) accumulated during a 20-year design life. Different climates were expressed by the average 7-day high air temperature recorded at the project site. N_{design} increased as design ESALs and high air temperature increased. Table 11 shows the compaction parameters to be set up (AASHTO R35, 2001).

Table 11. Compaction parameters for SUPERPAVE.

E_{SALs} (10^6)	N_{ini}	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

Using the values as shown in Table 4, the N_{design} for the bituminous sub-ballast was calculated with each value of RESALs. Thus, based on the results for the Sicilian traffic and temperatures, the energetic parameter for compaction is equal to 102 cycles.

5.2 *Case study*

The Superpave Gyratory Compactor (SGC) was applied to determine the number of gyrations in the specific case of the track line connecting *Messina-Catania*, with a traffic growth rate selected equal to 1%. The specifications for the bituminous sub-ballast are defined by the Italian standard (RFI). The main components are summarized in Table 12.

Table 12. Characteristics of the materials used.

Properties Bitumen		Standard	Value
Penetration at 25°C		EN1426:2007	53
Penetration index [-]		EN12591Annex A	-0.575
Softening point [°C]		EN1427:2007	50
Bulk specific gravity (SG) [g/cm^3]		EN 15326:2007	1.033
Viscosity at 150ºC [Pa·s]		ASTMD2493M-09	0.195
Equiviscosity values by	0.28Pa·s	EN 12695:2000	143.1
Brookfield viscosim. [°C]	0.17Pa·s	AASHTOT316-04	156.2
Properties Aggregates *(limestone)*		Standard	Value
Los Angeles abrasion loss [%]		EN 1097-2:2010	20.8
Bulk SG coarse aggreg. [g/cm^3]		EN 1097-3:1998	2.82
Bulk SG sand [g/cm^3]		EN1097-6:2013	2.84
Bulk SG filler [g/cm^3]		EN1097-7:2009	2.70

(*)Superpave mix-design of the bituminous sub-ballast was carried out setting the N_{design} equal to 102 (see Figure 6. Track line Messina-Catania, annual traffic growth rate: 1%).
The reference mix in this study was a bituminous dense graded hot mix asphalt with a maximum size of 31.5mm coarse aggregate. Limestone for the fine fraction and, a 6.75% amount of filler passing sieve 63μmm (72% had a size smaller than 0.17mm) according *RFI (Capitolato costruzioni opera civili, 2016).*

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 (ASTM D2493). Four bitumen percentages (3.6; 4.0; 4.5; 5.0 %) of the total weight of aggregates were added to the mixture and compacted. Four samples for each mix were fabricated. The specimens were developed with 12cm of height after compaction in analogy of the real thickness of the sub-ballast layer, and a diameter of 15cm according the gyratory compactor machine. A value of 3% of air voids at N_{design} was selected as the target value (AASHTO R35). The results are summarized in Figure 7.

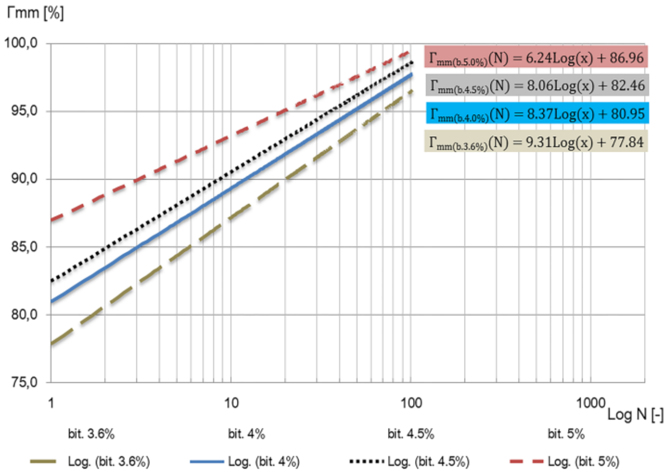

Figure 7. Compaction curves of bituminous sub-ballast mixes

6 CONCLUSIONS

It has been proceeded to the calibration of the model to forecast temperatures of Barber-Crispino, both for the road-railway structures considering the main parameters of surface temperature, wind speed, precipitation, air temperature, and solar radiation, as controlled by the thermal properties of the pavements.

The verification of the applicability of Barber forecasting model, which is widely used in the field road, to the case of the railway superstructure based on a complete temperature data, provides to be available as a measure to estimate temperatures in sub-ballast for different weather conditions.

The Superpave Gyratory Compactor (SGC) has been used to determine the optimum mixture. Once the overall procedure for the mix design was defined, a laboratory verification was conducted. Thus, this research, in parallel, provides an advance for the development of a methodology to adapt the mix-design by gyratory compactor to the railway system.

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