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IMPROVEMENTS IN THE MIX-DESIGN, PERFORMANCE FEATURES AND RATIONAL METHODOLOGY OF RUBBER MODIFIED BINDERS FOR THE THERMAL EVALUATION OF THE RAILWAY SUB-BALLAST

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Abstract
The objectives of this study are focused on the ideal methodology and the dimensioning of the railway super-structure, involving the use of a bituminous sub-ballast layer modified with recycled natural rubber tire out-of-use. The previous study of the thermal transmission in each Railtrack layer, the analysis of the traffic in high-speed lines and the revision of the thermal-mechanical models have motivated this research. An experimental methodology has been optimized for the application of the volumetric mix-design with the gyratory compactor (SGC). According to the meteorological situation and applying experimental models based on thermal conductivity interpolated by sinusoidal functions, a laboratory study of conventional bituminous mixtures and improved mixtures of asphalt modified with coarse rubber waste tires is illustrated. The enhanced methodology entails a case study where compacted mixes are used by SGC, replacing rubber between 1.5 and 3 percent of rubber (particle size 0.2-4 mm) in the total weight of the blend. After the evaluation of the average seasonal temperatures, the mixtures were designed considering the dry process, as an advanced measure of sustainability and for their demonstrated improvements in thermal behavior and resistance to fatigue. A step-by-step manufacturing process is provided to avoid swelling problems in the post-compaction phase characteristic of dry mixes. The purpose of using rubber modifiers in the hot mix asphalt has been achieved to obtain an elastic sustainable material for the evaluation of its behavior in sub-ballast layers.

Introduction
The fine-coarse crumb rubber incorporated into asphalt mixes by using "dry process" method which refers to technology that mixes the recycled tire rubber out of use with the aggregates before mixing it with asphalt binder. Two aggregate gradations were considered under this investigation, dense graded (asphaltic concrete with 22.4mm nominal maximum aggregate size) and gap graded (stone mastic asphalt with 31.5mm maximum aggregate size). For each particle size distribution, of an aggregate sieving process, the percentages of crumb rubber added varied from 1.5 % to 3 % by weight of the total aggregates. The European standard for sub-ballast in high-speed rail-lines as grading curve and Superpave gyratory compactor technique as mix-design were used. This article describes the benefits that can be derived from conducting the Volumetric mix-design with Superpave gyratory compactor (SGC) analysis developed as a reviewed method for railways. The rubberized sustainable solution can offer advantages such as reducing greenhouse emissions, fuel consumption and, a suitable performance as sub-ballast for railways tracks from mechanical behavior.
The tires at the end of their suitable life are among the most problematic waste sources due to the large volume produced, their durability and their components are ecologically questionable. However, their availability, size, and recovery ability also make them highly profitable targets for recycling. Therefore, the material recovered from waste tires, known as "crumb rubber," is usually used in road surface layers and railway sub-ballast, in fuel derived from tires, in agricultural products, and materials in sports areas [1-6].

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Scrap tire rubber (STR) can be incorporated into asphalt mixtures in two different methods or techniques, which are referred to as the wet-dry process [7-12]. The blending of recycled rubber with asphalt cement has been used for years, and several manufacturing processes have been developed in Europe as well as in the United States. The use of a bituminous sub-ballast layer has been pointed out as an exciting alternative to the granular sub-ballast design traditionally applied in most European railroad tracks [13-15]. Frequently, unbound granular materials are replaced by bituminous sub-ballast that provide additional benefits to the subgrade protection. Much research has been conducted on finding other alternative material to be used as a modifier in asphalt mixes to improve its properties [16-18]. Rubberized asphalt mixtures are regarded as a proper solution for improving the strength of the rail-track section. In comparison with traditional granular sub-ballast, these materials allow an increase in bearing capacity and more excellent protection of the substructure. The recycled rubber has become a significant enhancer of the modified bituminous mixtures, and in this work, it has been shown as a sustainable improvement [19-20] option in Hot mix asphalt (HMA) mixes due to the elastic behavior exposed by the rubber particles especially in reducing the fatigue cracking potential [21-25].

Volumetric mix-design: a review

The Volumetric blend design method provides a complete means for creating asphalt blends that will achieve a performance level consistent with the unique demands of traffic, weather, pavement structure and reliability for the project [26-27].

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. Rubber-Asphalt mixes (RUMAC) have shown a higher resistance to fatigue cracking compared to the conventional blends without rubber [28-29].

The Volumetric mix design procedure [30] developed in the Asphalt Research Program of the Strategic Highway Research Program (SHRP) does not include a simple, mechanical "proof" test analogous to the Marshall stability and flow tests method [31]. Instead, the original "Volumetric mix-design" method relied on strict conformance to the material specifications and volumetric mix criteria to ensure satisfactory performance of mix design intended for higher traffic (NCHRP 513). Cracking performance is significantly affected by the pavement structure and traffic [32-33]. This analysis procedure required a rigorous evaluation of the mix design's potential for fatigue cracking (Fig. 1).

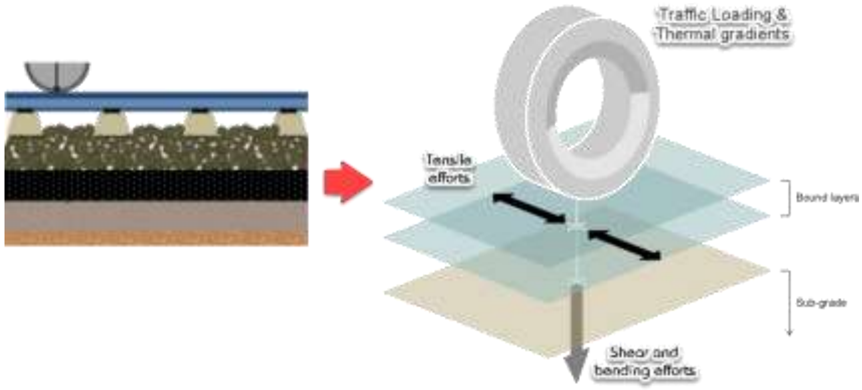

Fig. 1. Movements due to thermal variations and traffic loads

The Volumetric mix-design [34-35] is the crucial step in developing a well-performing HMA_DRY mixture according to NCHRP (2007) [31]. Under SHRP, additional laboratory analysis tests and material performance models were developed to determine the capabilities of Superpave mixtures further to perform well for the specific project design traffic and climatic condition. The values established in the first regulations of Superpave contemplated several levels of gyration, that represent seven traffic levels for each of four climates. In the years following the improved N_{design} value, the climatic region factors were eliminated and incorporated in the bitumen selection process depending on the performance grade [29]. For the past years, trackbed construction has used the Superpave Performance Graded (PG) system based asphalt binders.

Kentrack@ software [48] is used to consider the asphalt grading trackbed system and their properties inside the computer program. Therefore, the program maintains the previous asphalt grading system and incorporates information of the new asphalt grading system for comparison purposes (NCHRP 2007). In this study, the recent updates of Superpave values were applied (Fig. 2).

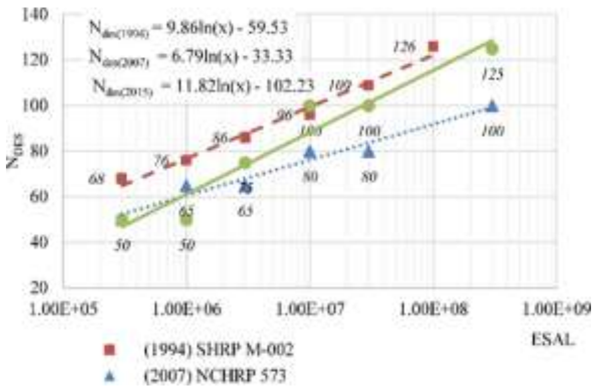

Fig. 2. N$_{design}$ recommended by Superpave standards

During a previous investigation [36], a new methodology to characterize bituminous mixtures has recently been accepted through the methodology of the gyratory compactor (SGC) suitable for the section of high-speed railway layers (Fig. 3). The Superpave system developed for railways [37-38], considering the necessary parameters of the temperature profile, rail traffic and thermal gradient in the multi-layer system, has proved to be efficient and therefore applicable to HMA with or without modification of scrap tire rubber (SCR).
At the higher traffic levels, extensive performance testing is recommended to assure the highest reliability. A unique feature of the Superpave test is its performing at temperatures and aging conditions that more realistically represent those encountered by in-service sub-ballasts [39].

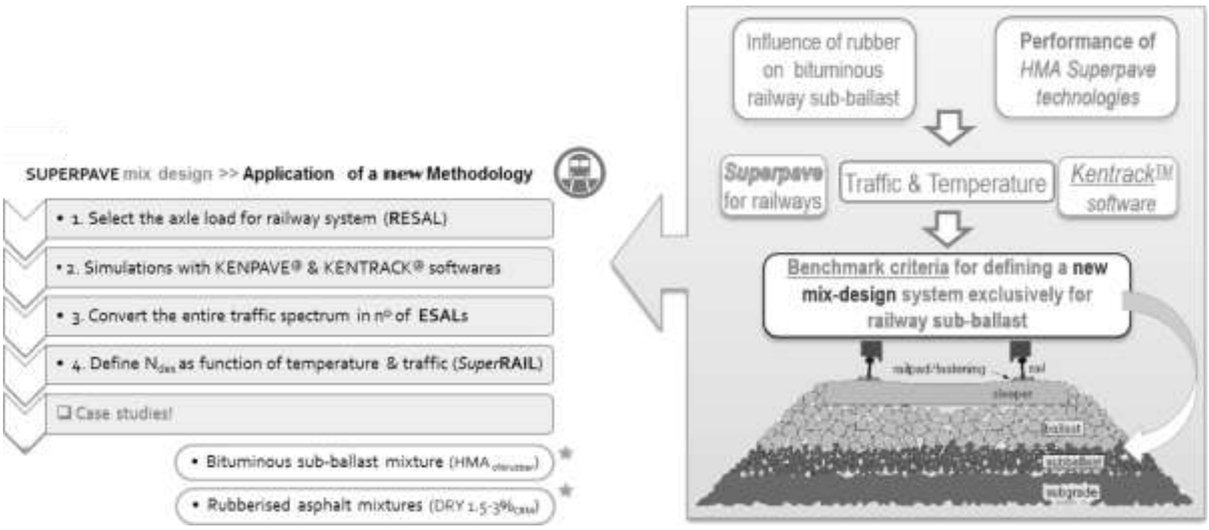

Fig. 3. Steps procedure of Super-rail mix-design methodology proposed

In recent years, several researchers have investigated and refined the Superpave mix design system of Hot Mix Asphalt (HMA) for new construction [40-41]. In predicting performance for multilayer, specific ground rules govern the treatment of the primary layer distresses: permanent deformation, fatigue, and low-temperature cracking. Superpave allows to identify the input for the material properties for each layer below the asphalt layer and would be extended to the prediction of fatigue cracking distress.

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Improvements in the railway sub-ballast

Traditional railway track consists of rails, sleepers, fastenings, ballast and a formation layer over the ground (Fig. 4). The materials and the thickness of track layers composing the railway structures are assigned by practice [42-43], 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 increased in modern tracks with the aim of obtaining higher bearing capacity, and durability of the system [44].

The bituminous sub-ballast is composed of a dense-graded bituminous mixture similar to the base course for road pavements [45-46]. 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 an intermediate permanent deformation resistance [47-48].

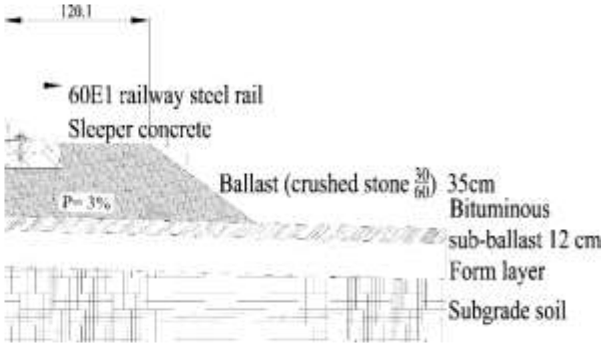

Fig. 4. Section of railway track showing the multi-layer system [29]

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 showed during the last years [49]. Asphalt underlayment has shown to apply to track features with weak subgrades, soft soils, and poor drainage [50]. 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 [51-52].

Temperature profile models

Some of the temperature models based on mechanical methods, energy balance and finite difference equations are purely empirical regressions. The use of computer modeling is validated under certain misgivings about the experimental methodology. Recent additions to real practice provide 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 [53].

A FEM model that predicts pavement temperatures during summer condition based on the heat transfer was presented by Hermansson (2001) [54]. The input data per hour per day are solar radiation, air temperature, and wind speed, seeing a concordant relationship between measurements. In this experiment, the effects of solar radiation and depth were added to the analysis layer. Crispino (2001) measured the thermal fluctuations of the sub-ballast layer, to evaluate the average seasonal temperature [55-56]. Barber´s theory [57] was used to find the temperature in the road base course and, the modifications purposed by M. Crispino were used in the sub-ballast layer [58-59].

Ferreira et al. (2012) [60] 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. Because of the environmental effects (atmospheric actions and water changes), they perfected the modeling of surface drainage systems. The Strategic Highway Research Program (Superpave) went in a slightly different direction [61-62]. The performance-type specifications developed for asphalt cement required that a 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 carried out in the sub-ballast after knowing the max/min temperatures on the railway trackbed [63-64].

Traffic spectrum

The amount of traffic is measured regarding 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. The traffic information to be used for the thickness design includes the magnitude of wheel loads and the number of repetitions per year. Considering an average of increased rate industrial traffic of 1%, and service life of 30 years, the rail equivalent single axle load (ESAL) obtained for high-speed lines with 160kN/axle tandem in long-distance trains is $3.7x10^7$ (Level 3 of "volumetric mix-design method"). Therefore, considering the recently logarithmic regression from the interpolation of the values of ESAL-Ndes (AASHTO R35-2015) showed in Fig. 2, a correspondence between the number of N_{des} gyrations and the rail axle load value has been well-defined. Due to the imprecision of N_{des} values between 100 and 125 gyrations inside the SGC, it has been chosen to interpolate the values in the Fig. 2, and obtain the regression trendline. Using the regression equation proposed by the number of Energetic parameters, Ndes =10,857·Log (ESAL)-86,928, the N_{des} is 102 cycles (Fig. 5).

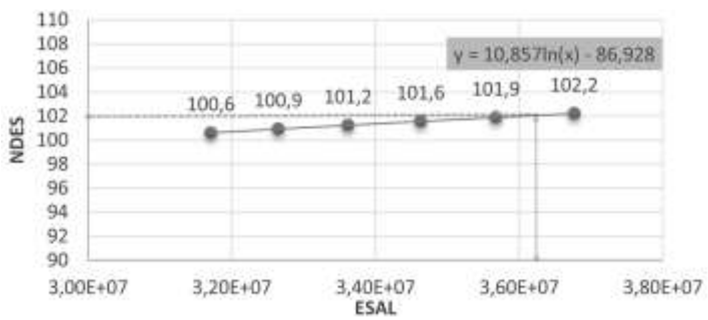

Fig. 5. Logarithmic regression by interpolation of Ndes values

During the development of this methodology of "Volumetric mix-design" for railways, we have analyzed the main European high-speed lines considering a 16ton equivalent axle. The advantage and more magnificent achievement with this study are that it offers a unique solution for the traffic-temperature predictive model of any other world zone. It is possible to develop real values of N_{des} for the bituminous mixtures in each particular case.

Scope and Objectives

The goal of the present research study is to analyze the behavior of asphalt rubber mixtures (ARC) obtained by the dry process compared with a conventional HMA through different rubberized mixtures (DRY) by reducing and controlling the fatigue life and cracking effect. The purpose is to optimize the reference conventional HMA and the rubber-aggregate blends DRY 1.5%, DRY 2%, and DRY 3% according to the optimal recipes found in the laboratory after trial mixtures with SGC under cyclic loads for a 30-year life cycle for railways [65].

The present study, therefore, is divided into different steps (Fig. 6), that studies the aspects of traffic and temperature profile using the AASHTO mechanistic-empirical pavement design approach to railways with the aim of representing the real conditions in the sub-ballast layer of the rail track. Secondly, a general framework is intensive on bituminous materials because of stress-deformation and thermal susceptibility.

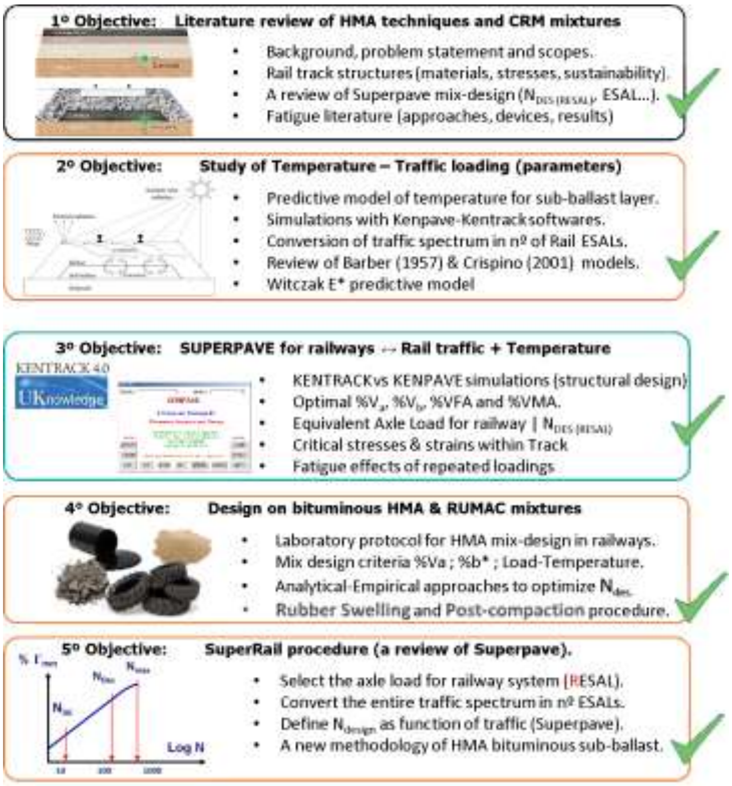

Fig. 6. Different steps in the study

Thus, it is needed to know the temperature within the layer and the relationship with the mechanical characteristics. Barber´s theory was used to determine the temperature in the road base course and, the modifications purposed by Crispino were applied in the sub-ballast layer. Using the average seasonal temperature analysis by simulating the thermal sub-ballast and road-base layer behavior respectively, was possible to predict the medium-layer temperatures, which obtained results are shown after different computer simulations [28-29].

The last section is dedicated to exploring through the optimized mixtures obtained with the gyratory compactor [66-67], whose experimental details are widely reported in previous research [68-69]. 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.

This investigation, therefore, evaluates the optimum parameters of temperature and traffic that characterize the optimal mixture for a sub-ballast layer [63-64]. Also, it provides the development to adapt the SGC methodology focused exclusively for roads but now in the railway field. The application of this procedure is needed for the volumetric mix-design of the underlayment rail-track [70-71].

Methodology

Analyzing the model factors

The performance of asphalt pavements is influenced by temperature distribution and environmental conditions to which it is exposed [72]. Barber (1957) observed that pavement temperature fluctuations roughly followed a sine curve with a period of one day. A reasonable estimation of asphalt surface temperature was seen 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.

The properties of asphalt mixtures change significantly with air temperature variation, solar radiation, and wind speed [73]. Bituminous mixtures suitable for railway sub-ballast are susceptible to cracking at low temperatures [74].

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 thermal and moisture regimen is critical to the choice of the long-term performance grade on the mechanical properties of the bituminous materials [75-76].
In this research, the conventional measures of temperature, relative humidity, atmospheric pressure, wind speed, wind direction, precipitation and, hours of sunlight during 12-months were chosen from statistics determined by using five elements: global horizontal radiation, direct standard radiation, dry bulb temperature, dew point temperature, and wind speed.

Temperature-traffic modelization
The linear viscoelastic behavior is a first step to understand the mechanical performance of high-speed line tracks with bituminous layers although its response is better described by viscoelastic constitutive laws [77-78]. The rail sub-ballast purpose needs the determination of temperature by the prediction model reviewed.
The track system model is divided from top to bottom into rails, springs, ties, and sleepers, which are modeled as prismatic elements by finite elements for trackbed design. The railway structure responds to a multilayer model from which the properties of each layer can be defined. The section (type and thicknesses of layers) and the solicitations points are shown in Fig. 7.

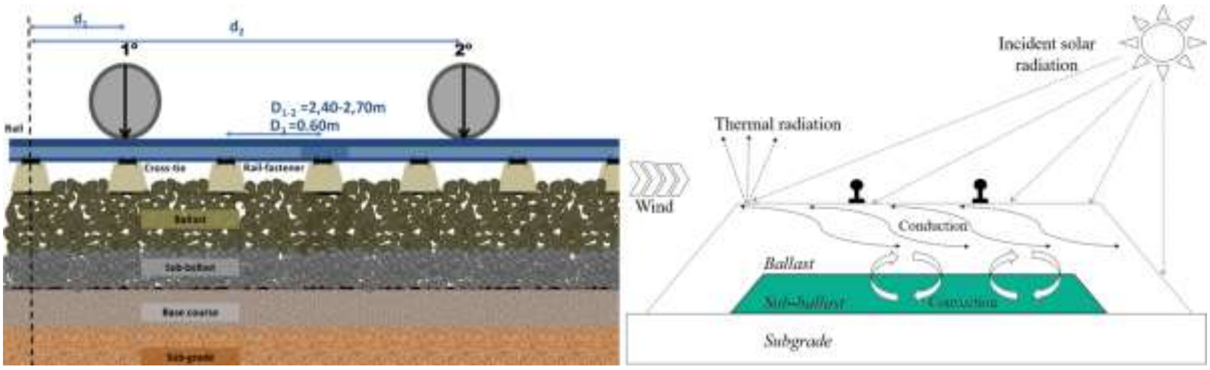

Fig. 7. (a) Rail-track considered with the loads concerning the ties; (b) Energy balance in railway track

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 standard axial load for the railway lines (R_{ESAL} [36]). 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 [29].
In this lab-research, the “volumetric mix-design method” requires specimens compacted 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 with a target air voids content of 3% at Ndes. Thus, the recent values are used in the volumetric mix-design for railways, and it has been determined from the rail traffic level expected and the design air temperatures for the site.
The dynamic modulus of HMA was calculated using the method developed by Witczak (1979) [79-80] to model the asphalt accurately; different temperatures should be utilized for the various periods since the dynamic modulus is dependent on the temperature.
Witczak-E* predictive model was merged into KENTRACK software [78-80], which was developed by the University of Kentucky, to calculate asphalt dynamic modulus [81-82].
With KENTRACK 4.0 (2014) the underlayment configuration is analyzed for the critical horizontal tensile strain at the bottom of the HMA sub-ballast and the critical vertical compressive stress on the top of the subgrade.
Table 1 shows the temperatures and the properties characterizing the bituminous materials.

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Table 1. Parameters inserted in the Witczak formula

Air temperature 0°C		Layer $\dot{X}$ Tª [°C]	μ [10^6 poise]	log |E*|	|E*| [MPa]	ν
Rail	SB	1.94	59.5026	1.434	18929.8	0.4
Air temperature 35°C		Layer $\dot{X}$ Tª [°C]	μ [10^6 poise]	log |E*|	|E*| [MPa]	ν
Rail	SB	36.95	0.0074	-0.235	1185.68	0.4

(*)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. First, the acquisition from the last 30-years of meteorological temperature values; then, a meteorological data processing, dividing the year and calculate the average max/min temperatures $T^a_{max/min}$ for each year-period. The following graph shows the evolution of the temperature in each layer of railways (RW) for the most representative air temperatures (0ºC and 35ºC). It was applied based on the simulations made with the computer program, along with a sinusoidal cycle marked by the daily hours and the depth (z) to the layer bottom (Fig. 8).

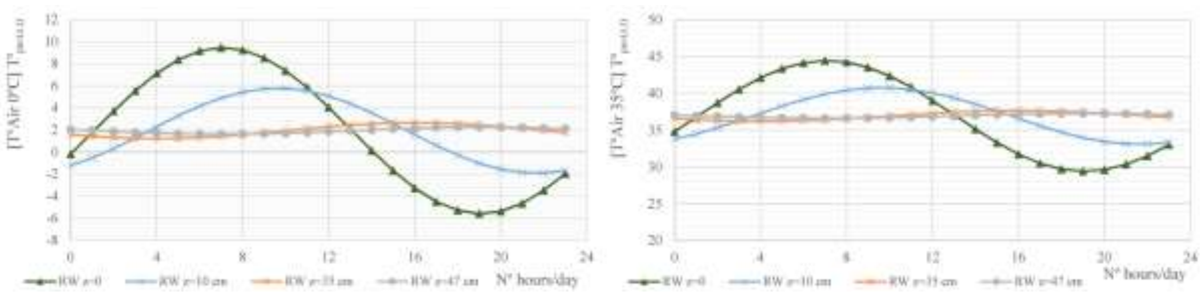

Fig. 8. 24hour-Tª variation at different depths [Air Tª 0°C-35ºC]

Finally, it was made the average air temperature $T_a(p)$ of the seasonal periods, and the temperature inside the sub-ballast layer, in function of the relative average air temperature for each period, using Barber's equation. Each simulation for various temperatures (0, 10, 20, 30, and 35ºC), has considered that in the case railways, the depth of interest is 47cm (bottom of the sub-ballast layer).
The simulations with KENTRACK® have been set at two air temperatures, 0ºC, and 35°C, based on low and high temperatures respectively, and applying only 100 cycles to avoid the cumulative effect of damage. Subsequently, it was possible to calculate the mechanical characteristics of the bituminous materials with the Witczak predictive model based on the volumetric properties of the mixture and the characteristics of the binder.

Once the overall procedure for the temperature profile inside the sub-ballast layer was defined, a laboratory verification has been conducted with a conventional HMA mixture and different rubberized asphalt solutions by a dry process with gap-dense gradation mixtures.

Materials

Volumetric mix design with gyratory compactor (SGC), adopting a well-performing asphalt mixture according to NCHRP (2007), it was established 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 gives 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 European standard (void content of 4-6%, a Marshall stability of 10kN, and a higher indirect tensile strength at 15ºC of 0.6N/mm²).

The content of bitumen based on the total mass of the aggregates will have to correspond to the excellent content obtained in the laboratory, with a tolerance of ± 0.5%.

The features of the materials used for the production of the bituminous sub-ballast are concise in Table 2.

Table 2. Characteristics of the materials used for the bituminous sub-ballast mixtures

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 viscosimeter [°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: 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 pycnometer + sample ssd + water, m3 (gr)			3106
Weight of pycnometer filled with water, m4 (gr)			3039
Maximum Specific Gravity of rubber (g/cm$^{3)}$			1.154

The Volumetric mix design system has 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. 9) was perfected through the selected percentages of each aggregate fraction to produce asphalt mixtures which exhibit controlled levels of coarse aggregates interlock.

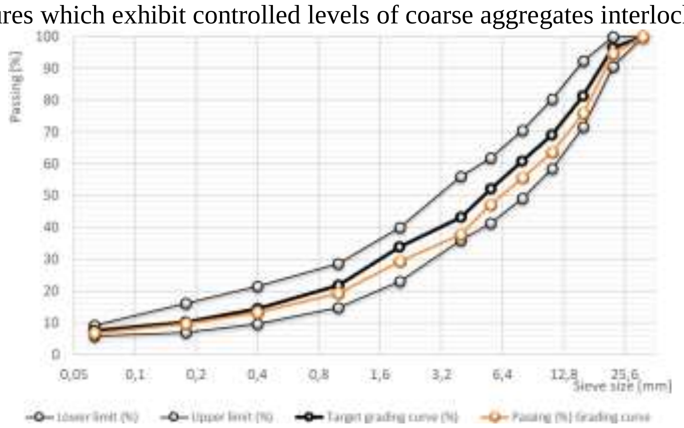

Fig. 9. Grading curve (Upper-lower limits)

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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. 10).

The rubber aggregate with gap-gradation is a two-component system in which the fine aggregates portion interacts with the asphalt cement while the coarse rubber performs as an elastic aggregate in the hot mix asphalt mixtures [83].

The percentage of rubber used in these mixes varies from 1 to 3 percent by the total weight of the mix. The mixes are not considered to be asphalt rubber since rubber is not blended with the asphalt cement before mixing it with aggregates.

The rubber-asphalt mixes which are produced by first mixing CRM and aggregates followed with an intimate mixing with asphalt cement are mentioned as “asphalt concrete rubber filled” or “rubber modified asphalt concrete mixes (RUMAC)” [84].

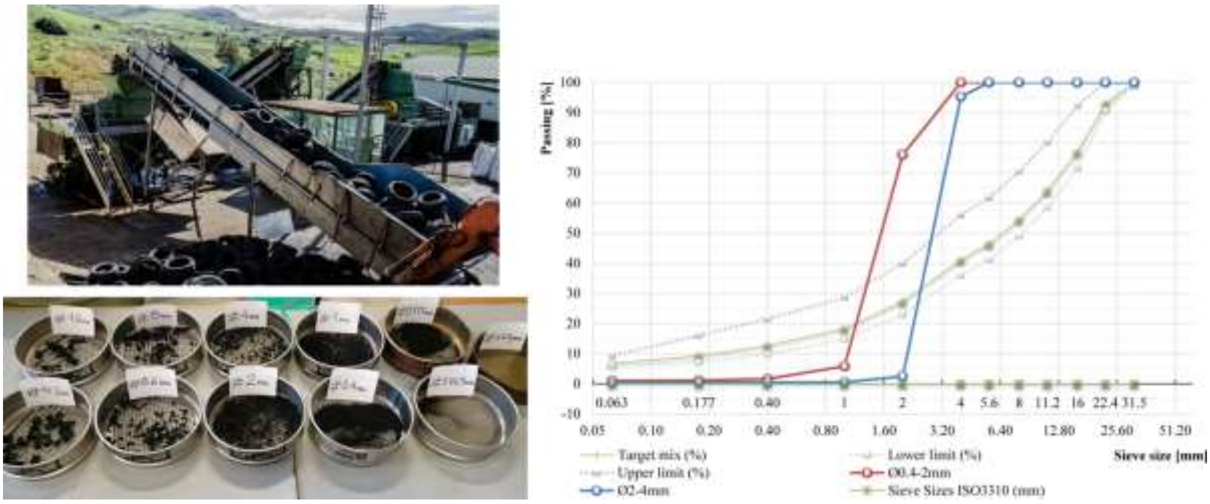

Fig. 10. (a) Sieve analysis for grading; (b) Rubber sieve analysis (Grading curves Ø2-4mm; Ø0.4-2mm)

Therefore, the following blends were considered in the development of the study once already made using the methodology of previous chapters (Fig. 11).

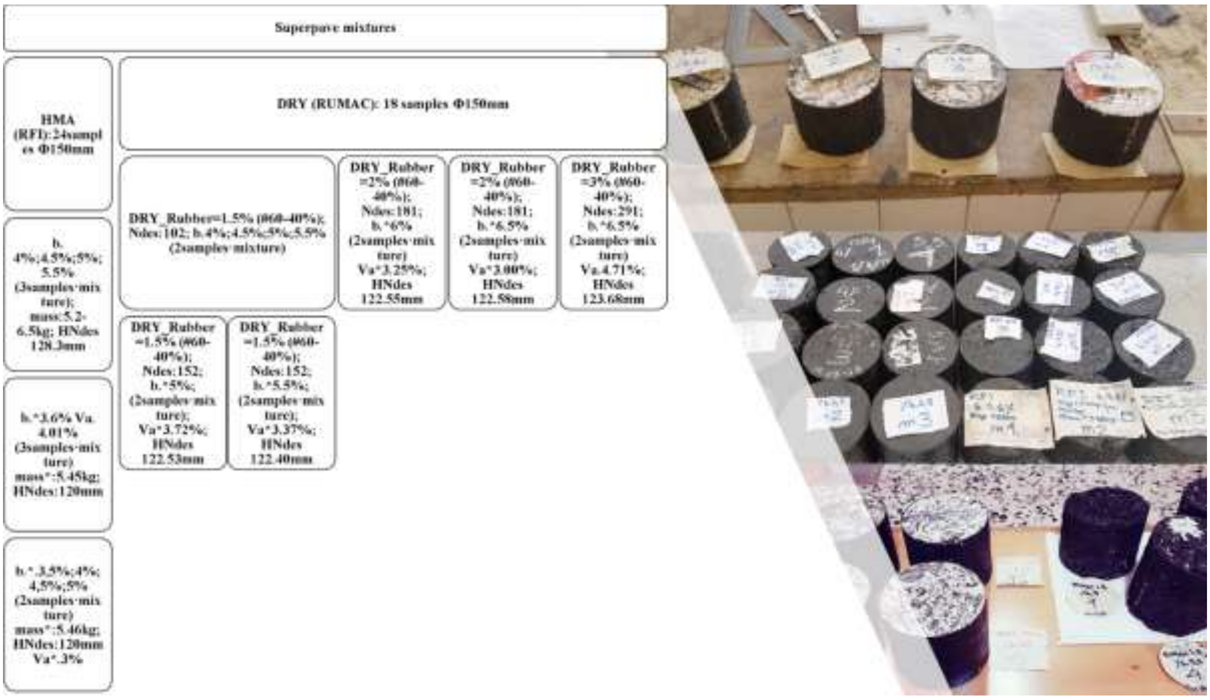

Fig. 11. (a) Materials and mixtures specifications on this research; (b) HMA_DRY Specimens developed

The reference mix was a bituminous dense-graded mixture of the sub-ballast layer according to European High-Speed Rail Lines [85]. 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.

Laboratory results and discussion

The manufacturing temperature for a conventional B50/70 bitumen was 160ºC, and the compaction temperature was 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 blend were mass-produced for determination of the maximum theoretical specific gravity. Initially, for a 4% of binder content, a 2,74% of air voids at N_{design} was achieved as the target value in the case of HMA mixtures [86]. The volumetric mix-design is clarified in Table 3:

Table 3. Volumetric mix design characteristics

Samples dimensions	Ø150x120mm			
N_{design} = 102 cycles	HMA b.4%	DRY 1.5% b.5,5%	DRY 2% b.6,5%	DRY 3% b.7%
Mixture weight [gr]	5460	5460	5460	5460
Aggregrate mass [gr]	5250	5176	5127	5103
Density of Aggregates γ_{max} [g/cm^3]	2.809	2.808	2.808	2.808
% Inert part	96.15%	94.79%	93.89%	93.45%
Bitumen mass [gr]	210.0	284.5	333.4	357.4
% binder	3.85%	5.21%	6.11%	6.55%
Max. density, γ_{max} [g/cm^3]	2.634	2.577	2.541	2.524

For mixtures with rubber, the percentage of voids varied between 3.01% and 3.37%. Therefore, it was never possible to exceed the maximum value of an established 4% of voids for a suitable bituminous mixture in sub-ballast.

Testing program for HMA Mixtures

Each HMA specimen was compacted to the maximum number of gyrations, with data collected during the compaction process. During the post-compaction phase, the height of the specimen was frequently monitored. The density has been continually monitored knowing the initial weight of the mix, the fixed volume of the mold, and the measured height (Table 4).

Table 4. HMA final recipe. Volumetric analysis of recipes for laboratory

Sample	H [mm]	Mass Aggr. [gr]	Binder [%]	Sample mass [gr]	Binder mass [gr]	Sample mass [gr]	Binder mass [gr]	Filler [gr]	Sand [gr]	fØ5-10mm [gr]	fØ10-15mm [gr]	fØ20-25mm [gr]	fØ25-30mm [gr]
b.3.5%	120	5101	*3.5*	5280	179	5280	185	646	1162	380	1093	951	1047
b.4.0%	120	5250	*4.0*	5460	210	5350	214	655	1178	385	1108	963	1061
b.4.5%	120	5225	*4.5*	5460	235	5325	240	652	1172	383	1103	959	1056
b.5.0%	120	5167	*5.0*	5425	258	5270	264	645	1160	379	1091	949	1045

Table 5. HMA final recipe. Results after compaction

Ø150xh (mm)	Binder (%)	Sample mass [gr]	HN_{des}[mm]	H_{24h} [mm]	Eff. binder [gr]	M_1 24h [gr]	M_2 24h [gr]	M_3 24h [gr]	ϒapp [g/cm^3]	Γ_{max} [g/cm^3]	Γ_{mb*} [g/cm^3]	Γ_{mm} [%]	Va [%]	VMA [%]	VFA [%]	Δ%b*
$HMA_{3.5\_1}$	3.5	5280	116.1	116.3	178.4	5280	3227	5284	2.557	2.656	2.565	96.6	3.65	12.10	69.87	3.36
$HMA_{3.5\_2}$	3.5	5275	116.4	116.1	177.7	5262	3216	5267	2.556	2.656	2.557	96.3	3.70	12.15	69.58	3.38
Averaged	3.5	5277.5	116.25	116.2	178.07	5271	3221	5275	2.556	2.656	2.561	96.4	**3.68**	12.12	69.73	3.37
$HMA_{4.0\_1}$	4.0	5250	114.3	113.33	201.3	5239	3202	5240	2.561	2.636	2.577	97.8	2.78	12.40	77.59	3.51
$HMA_{4.0\_2}$	4.0	5250	115.9	115.50	200.2	5209	3189	5214	2.563	2.636	2.553	96.8	2.70	12.32	78.12	3.48
Averaged	4.0	5250	115.1	144.40	200.73	5224	3195	5227	2.562	2.636	2.565	97.3	**2.74**	12.36	77.86	3.49
$HMA_{4.5\_1}$	4.5	5225	114.3	113.3	223.8	5201	3178	5204	2.558	2.617	2.567	98.1	2.15	12.90	83.30	3.76
$HMA_{4.5\_2}$	4.5	5224	114.2	112.9	224.3	5214	3186	5215	2.561	2.617	2.572	98.3	2.06	12.82	83.94	3.72
Averaged	4.5	5225	114.2	113.2	224.0	5208	3182	5209	2.559	2.617	2.569	98.2	**2.11**	12.86	83.62	3.74
$HMA_{5.0\_1}$	5.0	5452	119.5	116.33	258.6	5436	3322	5438	2.561	2.598	2.567	98.8	1.39	13.24	89.74	3.94
$HMA_{5.0\_2}$	5.0	5557	121.3	117.50	262.8	5525	3361	5526	2.544	2.598	2.561	98.5	2.05	13.82	85.44	4.21
Averaged	5.0	5452	119.3	116.11	258.1	5425	3312	5426	2.558	2.598	2.565	98.7	**1.50**	13.34	89.11	4.07

Table 6. Determination of air voids in HMA mixes

HMA	Sample	Wair (m1)	Wdry (m3)	Wwater (m2)	ϒw (Kg/m^3)	%b	ϒb (Kg/m^3)	ϒaggr (g/cm^3)	ϒbulk (Kg/m^3)	ϒbulk (Ẋ)	%Va (N_{des})	%Va	%Va (Ẍ)	%b* (Ẍ)
binder 3.5%	$HMA_{3.5\_1}$	5280	5284	3227	996.30	3.5	1033.3	2807.9	2556.9	2556.30	3.65	3.65	3.67	3.37
	$HMA_{3.5\_2}$	5262	5267	3216					2555.7		3.69	3.70		
binder 4.0%	$HMA_{4.0\_1}$	5239	5240	3202	996.30	4.0	1033.3	2807.9	2560.7	2561.74	2.78	2.79	2.74	3.49
	$HMA_{4.0\_2}$	5209	5214	3189					2562.8		2.70	2.71		
binder 4.5%	$HMA_{4.5\_1}$	5201	5204	3178	996.30	4.5	1033.3	2807.9	2558.1	2559.39	2.15	2.17	2.12	3.74
	$HMA_{4.5\_2}$	5214	5215	3186					2560.7		2.06	2.07		
binder 5.0%	$HMA_{5.0\_1}$	5436	3322	5438	996.30	5.0	1033.3	2807.9	2560.6	2557.85	1.39	1.39	1.50	4.00
	$HMA_{5.0\_2}$	5525	3361	5526					2543.6		2.04	2.05		

Once the experimentation on the sample range with different binder ratios was accomplished, the %Va-%b graph was constructed. The optimum binder content was established with a 4%. From this relationship, exponential and polynomial regression curves, and an optimal bitumen percentage of 3.91% to 4% was obtained to get a 3% air voids (Fig. 12). Volumetric characteristics, that is, air voids, VMA, VFA, and density were determined for each specimen at 102 N_{design} gyrations. After compacting the specimens to N_{des} gyrations, it has been found the bulk specific gravity (Γ_{mb}) and the theoretical maximum specific gravity (Γ_{mm}) for two samples of each blend for the four different HMA mixtures (Tables 5-6).

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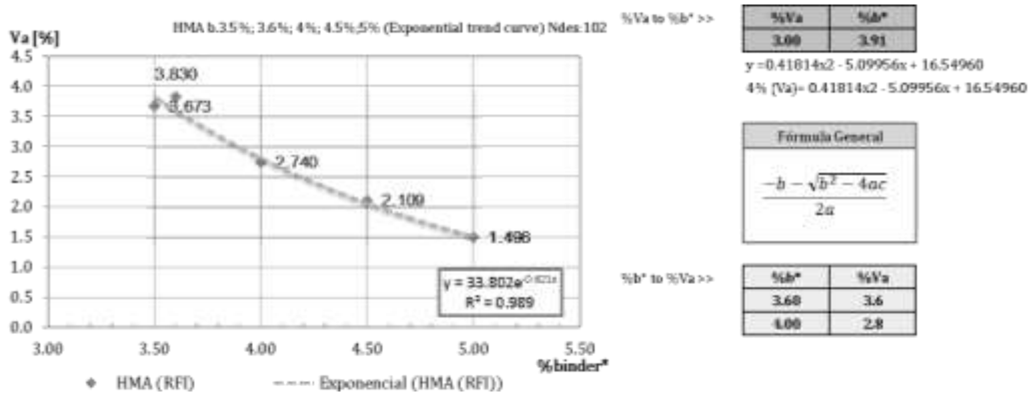

Fig. 12. Air voids vs. Binder content in HMA samples (Ndes.102; φ150x120mm)

Densification curves were plotted for each mixture that stands for the measured relative density at N_{des} or N_{max} cycles (%Γ_{mm}) versus the logarithm of the number of gyrations (Fig. 13).

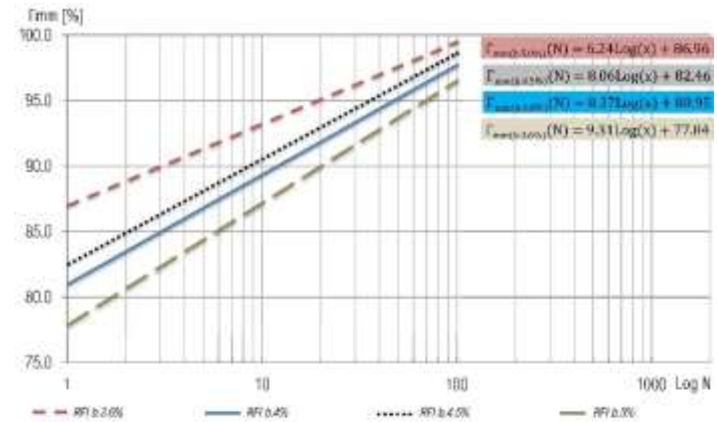

Fig. 13. Densification curves for optimal HMA mixtures φ150·120mm

Testing program for DRY mixtures

As has been done with the conventional HMA blend, test mixtures with different bitumen content are made for DRY 1.5%, 2%, and 3% mixtures. The dry-process mixes were human-made with a digestion time between 60, 90 and 120min.

It was observed that the swelling effect in the specimens appeared at the end of the compaction with the SGC during 24h. In this case, in dry mixtures with a higher amount of rubber was greater the swelling effect in comparison with the mixtures at 1.5% and 2% of scrap tire rubber. Therefore, the increase in volume due to "swelling and rebounding effect" is solved increasing the number of gyrations in each case.

Thus, the method by which the number of gyrations to N_{des} (102, 182, and 291) is modified in each case, it is developed to better adjust to the requirements of each mixture with recycled rubber. In conclusion, the final regression equations are (Table 7, Fig. 14).

Table 7. Regression equations according to Superpave compaction curves

HMA $_{(b.4.0\%)}$ → Γ_{mm} ($N_{des.}$ 102) = 8.365Log(x) + 80.954
DRY1.5 $_{(b.5.0\%)}$ → Γ_{mm} ($N_{des.}$ 152) = 7.896Log(x) + 81.040
DRY1.5 $_{(b.5.5\%)}$ → Γ_{mm} ($N_{des.}$ 152) = 7.546Log(x) + 81.595
DRY2.0 $_{(b.6.0\%)}$ → Γ_{mm} ($N_{des.}$ 181) = 5.433Log(x) + 86.209
DRY2.0 $_{(b.6.5\%)}$ → Γ_{mm} ($N_{des.}$ 181) = 5.311Log(x) + 86.881
DRY3.0 $_{(b.6.5\%)}$ → Γ_{mm} ($N_{des.}$ 291) = 4.161Log(x) + 86.955
DRY3.0 $_{(b.7.0\%)}$ → Γ_{mm} ($N_{des.}$ 291) = 3.848Log(x) + 89.432

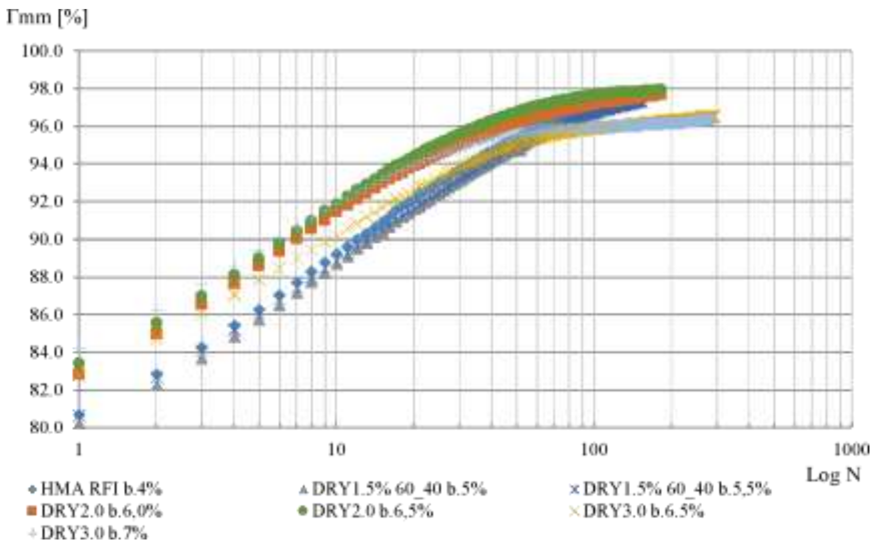

Fig. 14. (a) Densification curves for all SGC mixtures; (b) Trendline and regression equations

The compatibility of these mixes is entirely different even though 3% of air voids is the target value, being more sensitive to the gyration levels than the other. Another relevant aspect that can be observed in the results is that as the rubber content in the mixture increases, the workability (slope of the trend line) decreases (higher densification), due to several reasons:

- The increase of bitumen content and the reaction of ground rubber – bitumen;
- The adjustment of the grain size curve to introduce the optimal volumetric proportion of rubber replacing part of the unbound aggregates.

By analyzing the results obtained for each of the mixtures, we can determine the optimum bitumen content to make any mix based on the percentage of rubber required.

Analyzing the regression curves of Fig. 14, the relationship between the proportion of voids and optimum asphalt content is obtained (Table 8).

Table 8. Air voids vs. Binder content in HMA_DRY samples (Optimal binder content)

	%Va	%b*$_{(Ndes)}$	%b*$_{(24h)}$	%b*$_{(7d)}$
Dry 1.5%	3.0%	4.95%	5.34%	6.05%
Dry 2%	3.0%	4.91%	5.61%	6.38%
Dry 3%	3.0%	6.70%	7.13%	7.27%

(Averaged)

	%Va*	%b*$_{(Ndes)}$	%b*$_{(24h)}$	%b*$_{(7d)}$
Dry 1.5%	3.0%	4.95%	5.40%	6.1%
	Def. %b	5.0%	5.5%	6.0%
Dry 2%	3.0%	5.00%	5.70%	6.4%
	Def. %b	5.0%	6.0%	6.5%
Dry 3%	3.0%	6.70%	7.20%	7.3%
	Def. %b	7.0%	7.5%	7.5%

Conclusion

The present research proposes an experimental approach for the optimization of the volumetric mix-design of HMA and DRY blends for sub-ballast in railways. The methodology adopted was the SGC (Superpave gyratory compactor) with a different number of gyrations according to the mixture. It has been proposed a method that considers the elastic behavior of the rubber and calculates its release of deformation after compaction.

However, additional work is needed to verify the robustness of the methodology using other materials and different sizes of recycled rubber, other ratios. Also, the procedure based on experimental approximations still lacks strong aspects of turning it into a widely accepted method. In fact, this work has considered a simplified system of a bituminous matrix (aggregates, bitumen, air voids and rubber) and has been considered the compression as a determining factor that is exerted in compaction. It is proposed as a future line to carry out studies to decide the effect of real temperature according to the climatic zone, the behavior of rubber and the mutual interactions between rubber and bitumen.

To prove a repeatable laboratory procedure is necessary to control all the variables to keep the mixing and compaction conditions consistent. Even if this methodology represents the first step towards a new SCR blends design approach, it provides promising results in estimating the final void content after thermal stabilization and curing in mixtures of asphalt with rubber.

The protocol followed during the mix production of test specimens in the laboratory has been justified, with a section, since the behavior of the rubber requires care in the post-compaction phase that does not occur in conventional HMA mixtures.

A key point was the fact that the binder exerts a high influence on the final mechanical response of all the mixtures studied. The service life of asphalt pavements will directly depend on the type of binder used, and thus an adequate choice is crucial to design more durable sub-ballast layers. Using rubber in railways construction is a sustainable solution that ensures consumption of massive quantities of these waste materials.

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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