

Optimizing Volumetric Mix-Design of Bituminous Rubber Mixtures for Enhanced Railway Sub-Ballast Performance

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ABSTRACT

The design of an unmodified bituminous mixture and three rubber-aggregate mixtures containing rubber-aggregate by a dry process (RUMAC) was evaluated, using an empirical-analytical approach based on experimental findings obtained in the laboratory with the volumetric mix design by gyratory compaction.

A reference dense-graded bituminous sub-ballast mixture (3% of air voids and a bitumen 4% over the total weight of the mix), and three rubberized mixtures by dry process (1,5 to 3% of rubber by total weight and 5-7% of binder) were used applying the Superpave mix-design for a level 3 (high-traffic) design rail lines. The railway tracked section analyzed was a granular layer of 19cm compacted, while for the sub-ballast a thickness of 12cm has been used. To evaluate the effect of increasing the specimen density (as a percent of its theoretical maximum specific gravity), in this article, are illustrated the results obtained after different comparative analysis into the influence of varying the binder-rubber percentages under the sub-ballast layer mix-design.

This work demonstrates that rubberized blends containing crumb and ground rubber in bituminous asphalt mixtures behave at least similar or better than conventional asphalt materials. By using the same methodology of volumetric compaction, the densification curves resulting from each mixture have been studied. The purpose is to obtain an optimum empirical parameter multiplier of the number of gyrations necessary to reach the same compaction energy as in conventional mixtures. It has provided some experimental parameters adopting an empirical-analytical method, evaluating the results obtained from the gyratory-compaction of bituminous mixtures with an HMA and rubber-aggregate blends.

An extensive integrated research has been carried out to assess the suitability of rubber-modified hot mix asphalt mixtures as a sub-ballast layer in railway underlayment tracked. Design optimization of the mixture was conducted for each mixture and the volumetric properties analyzed. Also, an improved and complete manufacturing process, compaction and curing of these blends are provided. By adopting this increase-parameters of compaction, called "beta" factor, mixtures modified with rubber with uniform densification and workability are obtained that in the conventional mixtures. It is found that considering the usual bearing capacity requirements in rail track, the optimal rubber content is 2% (by weight)

KEYWORDS: Empirical approach, Rubber-asphalt, Sub-ballast, Superpave mix-design, Railways, Hot-mix asphalt.

I. INTRODUCTION

THE entire mix design system, including field control, is based on the use of the Superpave gyratory compactor (SGC), which estimates the binder demand needed for the selected aggregate structure, and proceeds with preparing a maximum specific gravity sample and a set of 15 cm specimens for compaction in the gyratory compactor device [1]-[2]. The performance properties of the compacted specimens simulate the mechanical behavior of flexible HMA layers constructed with an asphalt-aggregate combination. The SGC also allows the best compaction of the mixture, including an estimation of the final air voids content under rail-traffic (the probability of the mix becoming plastic under traffic), and a measure of the structuring of the aggregate.

The gyratory simulates the mix densities achieved under the actual climate and loading conditions. This device can accommodate large aggregate, recognizing potential tender mix behavior and similar compaction problems, and is well suited for mixing plant quality control operations.

Now, it has been described the Superpave volumetric mix design (SGC) as the key to develop a well-performed asphalt mixture [3]. It is the optimal laboratory tool that more closely simulates field compaction of asphalt mixtures.

Mixture composition, preparation, and curing are significant elements in the production phase that affect mixture performance in service. Currently, no widely accepted mixture design method has been developed for rubber-

modified asphalt mixtures. PlusRide® and Generic-dry® methods [4]-[5] are the two most commonly used dry process technologies in North America for wearing course applications. However, their field and laboratory performance are inconsistent [6]-[7] with limited fundamental research to understand the mixture's mechanical properties. Consequently, the dry process has become less popular, although it has a high potential to consume larger quantities of scrap tires and is also logically easier compared to the wet process [8]-[9].

The literature review revealed that irrespective of mixture gradation (gap or dense graded), early life cracking is the main distress mechanism that occurs in the dry process with crumb rubber modifier (CRM) asphalt in road layers or sub-ballast railways [10]. Therefore, in this research, the mixture was designed as a dense-graded HMA (conventional for the base course in roads, and also as sub-ballast underlayment [11]-[12]) to avoid direct impact of mechanical weathering and fatigue cracking.

Also, different rubber modified asphalt concrete (RUMAC) mixtures were designed using a sub-ballast grading curve based on [13] (RFI) but enhance with other sieves according to European standards [14], [15], [16] to minimize the extra effort required in the material design stage. As the material gradation and mixture design used in this study were different from other types of CRM mixtures available, the terms "HMA" and "DRY1.5%", "DRY2%", and "DRY3%" were adopted as acronyms to represent the mixtures throughout this research.

A. Problem statement

Among the two widely known techniques for the introduction of recycled rubber in bituminous mixtures, the dry process has been shown to be less commercially popular due to the problems arising from its manufacturing process compared to the wet process. One of these concerns, not so well-known, refers to the rubber-bitumen interaction that causes swelling of the rubber particles within compacted asphalt mixture [17] (Fig. 1)



Fig. 1 Swelling effect on rubber-modified HMA samples of Ø150x120mm manufactured according to SGC

The rubber increases the demand of bitumen, and this could have an adverse effect on the mechanical characteristics of the asphalt mixture. The resilient modulus of the rubberized asphalt decays, and this implies an increase of layer thickness, compared with conventional mixtures. On the other hand, an interaction was observed between bitumen and rubber: the volatile components of bitumen are transferred to the rubber. The absorption of lighter components (paraffin and maltenes) is part of the maturation process "maceration," it causes the swelling of the crumb rubber particles and leads to having a more viscous bitumen.

It is common not to achieve uniform distribution of the rubber particles throughout the mix when adding it as a dry-filler inside an HMA mixture (120-190°C). That is because there is not enough time for a reaction to take place between binder and fine-rubber, consequently there is no modification of the resulting binder, diffusion or the imbibition process, so the solvent into the polymer is not happening [18].

A fundamental investigation of the mechanical properties of rubber-bitumen was carried out to solve the interaction rubber-bitumen, understanding the rebounding ("bounce-back") effect, and non-uniform post-compaction, which are considerable distresses in laboratory HMA-DRY specimens [19]. This study aims to prove a different thought by controlling the reaction rubber-bitumen.

B. Optimization of the manufacturing process

The dry process is usually used as a fraction of the coarse-fine aggregate [16]. Recent studies have been carried out with the aim of finding an alternative material that is used as a modifier improving mechanical properties of the asphalt mixtures. Scrap tire rubber (STR) is selected as the best option since it contributes to the reduction of fatigue and rutting pathologies because of the elastic behavior of the rubber [20].

The increasing usage of STR in asphalt pavements requires a better understanding of its effects on the physical, chemical, and performance properties of rubber-modified hot-mix asphalts. Several studies show that the

properties of some binders are improved by the addition of rubber particles of recycled rubber at ambient temperature, among which the reduction of the thermal susceptibility of bitumen and the increase of the viscosity according to the rubber-bitumen interaction [21].

Rubber in asphalt mixtures improves the elasticity of the binders and the mixtures, but it requires attention, mainly because of the amount of rubber, the design of the mix, the compaction temperature, the time of digestion and, the way in which the recycled rubber reacts with the bitumen at high temperatures [22].

In this case, one of the main purposes of this research was the development of an optimal Superpave mix-design of bituminous hot mix asphalt and rubberized-dry mixtures for railways, including its subsequent curing, minimizing the effects derived from the rubber-bitumen interaction.

Despite the many efforts employed in improving the mix design system for bituminous mixtures, individual limitations emerge when the traditional SUPERPAVE is applied to CRM mixtures. The biggest problem is that the rubber is an element involved in the mixture that has a different behavior from the other components (bitumen, filler, and aggregates) and this affects the mix design optimization process. First, during the mixing and compaction phase, the rubber mixture needs a certain curing time to complete the swelling and stabilize.

This curing time is influenced by temperature and rubber particles size [23]. The swelling is partly due to the chemical interaction between rubber and bitumen that leads to an increase in asphalt demand. Moreover, especially in the case of the dry process, the swelling after compaction is mostly due to the mechanical behavior of the rubber.

It is important to understand the interaction process or reaction between asphalt cement and crumb rubber modifier ($\varnothing 0.2-4$ mm) when blended. Therefore, when a stress is applied is subjected to a deformation, but once the pressure is removed, it returns to its original configuration. Thus, the crumb rubber releases the distortion accumulated during the compaction process that may turn out in a non-negligible swelling of the asphalt mixture sample.

The presence of STR can cause an increase of voids in the post-compaction phase, exceeding the range of the admissible voids content for asphalt mixtures. Therefore, it is necessary to quantify the recovered deformation and the energy stored by the rubber to control this phenomenon by changing the compaction process adequately. In the study carried out in this work, the effects due to swelling, rebounding and non-uniform post-compaction stages are analyzed from a practical point of view (Fig. 2).

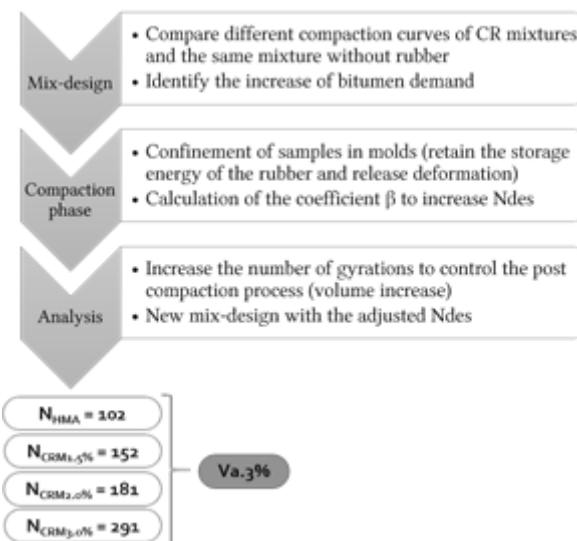


Fig. 2 Schematic representation of research stages

The increasing usage of STR (Scrap Tire Rubber) in asphalt pavements requires a better understanding of its effects on the physical, chemical, and performance properties of rubber-modified hot-mix asphalts. Several studies [23]-[24] show that the properties of some binders are improved by the addition of rubber particles of recycled rubber at ambient temperature, among which the reduction of the thermal susceptibility of bitumen and the increase of the viscosity according to the rubber-bitumen interaction.

II. METHODOLOGY

Having at the end of the compaction phase the same voids content for both HMA conventional and CRM mixtures, it consents the same starting point of comparison for both mixtures. This allows highlighting the contribution in increasing the void content due to the deformation release of the rubber in the post-compaction phase.

The analysis of the post-compaction phase leads to the definition of a coefficient (β) to multiply the standard number of gyrations to achieve, at the end of the curing time, the same void content obtained for the traditional HMA mixture. In other words, an analytical-comparative method has been defined by the same void content (Va.3%) after compaction (in bituminous mixtures with/without recycled rubber).

The purpose is to calculate how compaction should be increased ($N^o N_{design}$) for mixtures with CRM considering that after compaction during the thermal stabilization and curing phase, the release of rubber deformation will cause an increase in volume and additional voids. The aggregates and bitumen are considered as a unique element that does not recover after compaction. Thus, the difference between the recovery of traditional and CRM mixtures can be attributable only to the presence of the rubber

A. Empirical approach

The crumb rubber could be considered an elastic material, but it is significantly less stiff than aggregates. Therefore, when a stress is applied is subjected to a deformation, but once the pressure is removed, it returns to its original configuration. Thus, the crumb rubber releases the distortion accumulated during the compaction process that may turn out in a non-negligible swelling of the asphalt mixture sample [24]-[25]. This can cause an increase of voids in the post-compaction phase, exceeding the range of the admissible voids content for asphalt mixtures. Therefore, it is necessary to quantify the recovered deformation and the energy stored by the rubber to control this phenomenon by modifying the compaction process adequately.

An empirical approach to quantify the recovered deformation of the crumb rubber in the post-compaction phase has been developed to adjust the number of gyrations proposed by Superpave mix-design with the final aim of meeting the requirements of voids content.

The research steps are well-defined in three main phases:

- *Preliminary phase*: Comparative study of the densification curves obtained in each optimum mixture.
- *Compaction phase*: Definition of a coefficient beta (β) for increasing N_{design} considering the elastic recovery of the rubber and calculation of the rubber storage energy.
- *Post-compaction phase*: Thermal stabilization, and confinement. The curing phase is defined as the time necessary for the rubber to recover its first volume after the compaction.

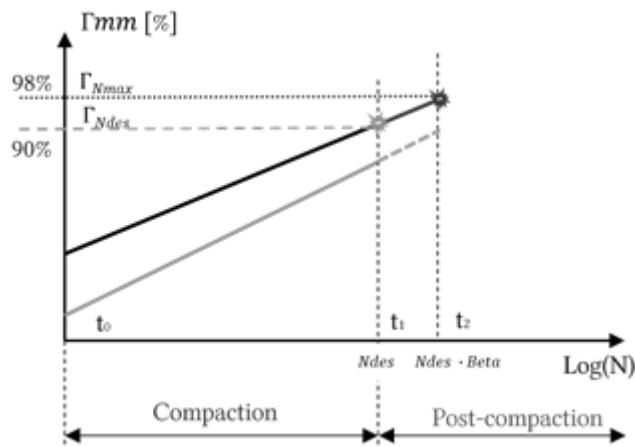


Fig. 3 Preliminary stage of comparison densification curves

B. Preliminary Phase

In the first step of the research, it is necessary to understand how the demand of bitumen increases when the rubber is added to the mixture to obtain the same workability and compaction curve of the corresponding traditional mixture without the addition of rubber. A reference mixture without the rubber and three with rubber have been fabricated with different percentages of bitumen, and they were compacted at the same N_{design} used for the traditional blend. The compaction curves obtained are compared (Fig. 3).

C. Compaction phase

In the second step of this approach, the difference between the compaction of a traditional and CRM mixture is expressed by a correction factor for N_{design} denoted as β . In the framework of this work, “beta” is defined as the coefficient that multiplies the design number of gyrations ($\beta \cdot N_{\text{design}}$) necessary to compact a sample of traditional asphalt mixture to obtain the *design number of gyrations required to compact a sample of CRM mixture* (N_{CRM}):

$$N_{\text{CRM}}^i = \beta \cdot N_{\text{des}}^i \quad i = 1, 2, \dots, \text{samples} \quad (1)$$

$$\beta = \frac{\% V_a^{\text{CRM}}}{\% V_a^{\text{HMA}}} \text{ if } V_a = 3\% \rightarrow \beta = \frac{\Gamma_{\text{mm97\%}}^{\text{CRM}}}{\Gamma_{\text{mm97\%}}^{\text{HMA}}}$$

Where:

- N_{CRM} = design number of gyrations optimized for rubber-aggregate mixtures;
- $\Gamma_{\text{mm97\%}}^{\text{mix}}$ = average specimen density at 97% ($V_a = 3\%$).

The above mathematical process allows to find a low factor between conventional mixtures and those with recycled rubber in the case according to the percentage of rubber but must be combined with a limitation of compaction. N_{CRM} must have an upper bound (N_{limit}) defined to perform compaction with a reasonable number of turns.

In fact, even if the N_{CRM} does not have a physical limit, the design of the asphalt mix can not contemplate an infinite number of turns; indeed, it must be compatible with compaction on field sub-ballast layers.

D. Post-compaction phase

After compaction, prepared specimens undergo a dilation (a bounce-back effect) during the curing period (first 24 h at temperature 145 °C to ambient 20 °C). After compaction, the sample is cooled to room temperature. The real air void content is determined after extrusion, not after applied compaction at N_{des} (*energetic parameter of Superpave*).

After compaction is complete, the specimen is extruded, and the *bulk specific gravity* is determined (Γ_{mb}) by AASHTO T166 in the case of the conventional HMA mixture [26]-[27].

On the other hand, for mixtures with recycled rubber, since they require a higher compaction energy to reach the percentage of target voids, a minimum period of stabilization of the mix (post-compaction) is necessary to maintain a thermal equilibrium and homogeneous expansion.

During the 24 hours after the mixing, it is observed that the rubber mixtures undergo an expansion in the vertical direction internal to the compacting molds (thermal stabilization phase).

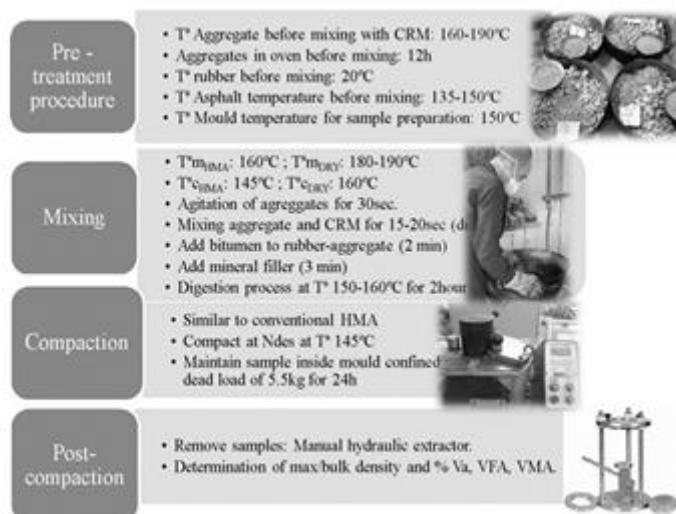


Fig. 4 Operational framework. Basic rules

Immediately after compaction, a dead load equivalent to the sample weight ($\pm 5.5\text{kg}$ thus limiting a possible post-compaction that reduces the final void percentage) must be applied for a further 24 hours to allow the mixture to

cool down to ambient temperature, and bitumen to gain stiffness to reduce rubber rebounding, considering that after compaction during the thermal stabilization the rubber deformation release will cause an increase in volume and more air voids.

Due to the increase in compaction energy, the compactability is greater initially by having mixtures which, within the first 24 hours, experience a strong swelling effect in the case of not following the protocol of manufacturing suggested in Fig. 4.

As an example of the consequences of not following the post-compaction process suggested in Fig. 4, a plot of the maximum theoretical density versus the number of gyrations for the mixture made with recycled rubber at 1.5% is shown in Fig. 5, following the number of gyrations of N_{des} and with two percentages of bitumen at 5% and 5.5%. The difference is that the same mixture was performed with the conventional Superpave procedure (*without the confinement of the specimen in the mold for 24 hours*) and on the other hand, following the protocol suggested.

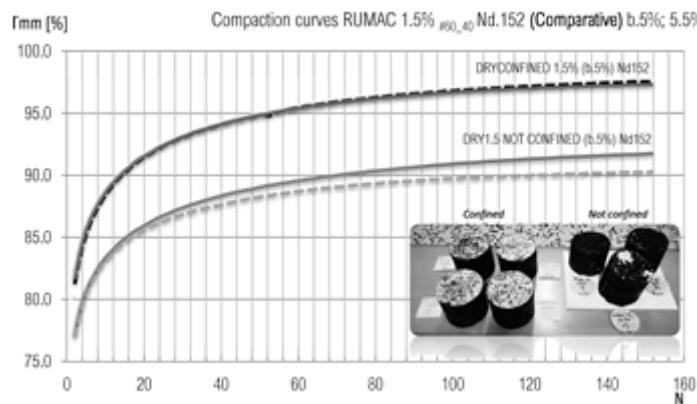


Fig. 5 Maximum specific gravity vs. Number of gyrations under DRY 1.5% mixtures confined/unconfined in molds during 24h

The final aim is to provide the beta parameters that we must apply to N_{des} established in the existing regulations to be able to implement the exact number of gyrations in the mixtures with recycled rubber to reach the objective of the optimal 3% of air voids in rail sub-ballast.

Thus, a fundamental investigation on the mechanical properties of rubber-bitumen was carried out to understand the interaction rubber-bitumen, to solve the rebounding (“bounce-back”) effect, and non-uniform post-compaction, which are considerable distresses in laboratory HMA-DRY specimens.

III. MATERIALS

Superpave volumetric mix design (SGC) was conceived as the optimal laboratory tool that more closely simulates field compaction of asphalt mixtures [28]. The next step in the mixing procedure is to define the specimens with diameter $\phi 150\text{mm}$, and the final desirable height at N_{des} of 120mm. Thus, we manufactured a conventional HMA mixture and rubber modified asphalt concrete mixes (DRY) with a final void percentage of $\pm 3\%$.

In previous publications [29]-[30], N_{des} for the bituminous sub-ballast was calculated with an equivalent standard axle load higher than 30 RESAL. In that work, the conventional HMA mixtures will be developed with a $N_{des}=102$; $N_{init}=8$ and $N_{max}=162$ gyrations. Subsequently, the mixtures with recycled rubber will be elaborated between 1% and 3%. A different methodology manufacture and compaction are proposed to achieve the target percentage voids:

- Experimentally, for an HMA at Va. 3%, it is needed a binder content of 4%, an aggregate mass of 5250 gr, a binder weight of 210 gr of the total mixture (sample mass of 5460 gr).
- For a RUMAC at Va. 3%, it is needed a binder content of 6% in mixtures DRY with rubber 1.5%; and a binder content of 6.5% with DRY 2%. An aggregate mass of 5380 gr.

For HMA and DRY mixtures, the target specimens are diameter 150mm and height 120mm (N_{des}) in both cases.

During these study, different mixes were analyzed by volumetric mix-design, obtaining optimal mixes with various amounts of asphalt binders| :

- A dense-graded mix type (onwards HMA or reference mixture, with bitumen B50/70 and a content of 4% according to [31]);

- A gap-graded Plusride mixture with 1.5% of rubber and binder 5 to 5.5% (from now on DRY 1.5);
- A gap-graded Plusride mixture (DRY 2.0) with binder content of 6 to 6.5% and;
- A Generic dry dense-graded mixture (DRY 3.0) with a 3% of rubber and 6 to 7% of optimal binder.

Each mixture has a different proportion of rubber, to be representative of the real conditions in industry and to ensure the homogeneity of the reaction between rubber-bitumen. Thus, the distribution is:

- For *Plusride* mixes: #60-40 (60% of fine powder-crumb rubber of Ø0.4 to 2mm and, 40% of coarse or ground rubber of Ø2 to 4mm) and;
- For *Generic-dry* mixture: #80-20 (20% of fine powder-crumb rubber of Ø0.4 to 2mm and, 80% of coarse or ground rubber of Ø2 to 4mm).

A. Mix-design of conventional Hot mix asphalt (HMA)

The first phase of the experiment involved the study of the volumetric mix-design of the traditional HMA (RFI) bituminous conglomerate. The conglomerate mix preparation method follows the standards [32]-[33], which describe the laboratory mixing of bituminous materials for the manufacture of specimens. Also, it specifies the reference compaction temperatures for mixing based on the grade of the binder for paving grade.

The stone material, before mix stage, is placed in the oven for 24 h at a temperature of 20°C above the *c* temperature, which is between 150 and 170 °C; while that of the binder must be 5°C higher than that of the aggregates. The split molds available for the gyratory compactor (SGC) model (Fig. 6) are those with an inside diameter of 150 mm and a height of 250 mm.

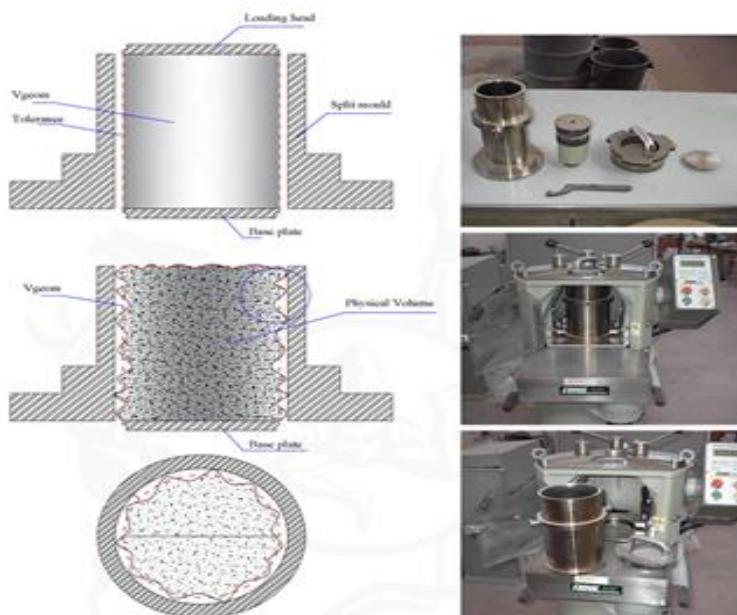


Fig. 6 (a) Compaction mold design in CAD; (b) Actual model of SGC

Thus, the procedure used for the mix-design of the mixtures was in accord with the Superpave but adopting the Italian standard, which is based on the results of the Marshall and water sensitivity tests. Reference [13] provides at least a void content of 3-4 %, a Marshall stability of 10 kN, and a higher indirect tensile strength at 15 °C of 0.6 N/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 after a Superpave mix-design process.

TABLE I Granulometric distribution of aggregates

Sieves (mm)	Target	HMA	DRY1.5	DRY2.0	DRY3.0
	% passing				
31.5	100.00	100.0	100.0	100.0	100.0
22.4	92.86	92.39	92.26	92.22	92.11
16	76.75	77.18	76.82	76.70	76.45
11.2	63.97	63.28	62.77	62.60	62.32
8	54.41	54.96	54.23	53.98	53.38
5.6	46.36	47.20	46.32	46.02	45.32
4	41.00	38.40	37.72	37.49	37.41
2	27.25	27.75	27.45	27.35	27.62

1	18.23	20.69	20.61	20.59	20.79
0.40	12.69	15.72	15.80	15.82	15.98
0.177	9.28	10.41	10.51	10.54	10.65
0.063	6.75	6.75	6.85	6.88	6.95

(*) *Granulometric grading curve based on target values from Sub-ballast mixtures (RFI, Capitolato costruzione opera civili, Ital ferr, Sezione XV, rev. 2004)*

B. Aggregate gradation and properties

The mixtures studied in this paper were made of limestone filler and, fine-coarse gravel, whose mineral skeleton is composed of limestone aggregates (which allows for enough contact with the bitumen to achieve a bond between binder and aggregates) [34] for the different fractions (see Table I) with nominal maximum aggregate size (NMAS) of 22.4mm and a maximum particle size (MPS) of 31.5mm.

During the sieving process of the aggregates, an average of six until twelve (e.g., sand fraction) grading curves was made for each current portion. The materials obtained from the quarry established the following fractions: *Filler (<0.063mm); Sand (0.177-4mm); Gravel (5-10mm); Fine gravel (10-15mm); Thick gravel (20-25mm); Very thick gravel (25-31.5mm)*. In the following Table II and Table III, the dosage formula according to each mixture (HMA or DRY) is finally provided

Table II. Sieve analysis of fine and coarse aggregates

Sieve Size(mm)	Lower passing limit (%)	Upper passing limit (%)	Target curve (%)	FILLER	SAND	Ø5-10mm	Ø10-15mm	Ø20-25mm	Ø25-30mm
31.5	100.00	100.00	100.00	100.000	100.000	100.000	100.000	100.000	100.000
22.4	90.48	100.00	92.86	100.000	100.000	100.000	100.000	100.000	64.043
16	71.59	92.23	76.75	100.000	100.000	100.000	100.000	77.439	11.875
11.2	58.56	80.21	63.97	100.000	100.000	100.000	96.425	18.859	0.467
8	49.04	70.49	54.41	100.000	100.000	100.000	67.015	3.152	0.334
5.6	41.22	61.80	46.36	100.000	100.000	83.031	32.223	0.350	0.334
4	36.00	56.00	41.00	100.000	93.393	30.641	7.959	0.350	0.334
2	23.00	40.00	27.25	100.000	62.062	0.660	0.398	0.350	0.334
1	14.77	28.61	18.23	98.038	34.334	0.660	0.398	0.350	0.334
0.40	9.76	21.51	12.69	96.077	15.115	0.660	0.398	0.350	0.334
0.177	7.02	16.05	9.28	70.615	6.206	0.660	0.398	0.350	0.334
0.063	5.89	9.35	6.75	50.038	1.802	0.329	0.199	0.350	0.334

TABLE III. DISTRIBUTION OF AGGREGATES FOR AN HMA – DRY MIXTURES (ADJUSTMENT OF SIEVE FRACTIONS).

Passing	[%]	[%]	Filler	Sand	fØ5-10mm	fØ10-15mm	fØ20-25mm	fØ25-30mm	Σ component s
			<0.063	0.063/4	0.063/8	0.063/11.2	5.6/22.4	5.6/31.5	
RFI_HM	12.24	24.60	5.21		18.29		18.49		21.16
A									100.00
Γmix=	2.740g/cm ³								Γaggr= 2.809g/cm ³
DRY 1.5%	12.45	23.79	4.62		18.98		18.65		21.52
Γmix=	2.716g/cm ³								Γaggr= 2.808g/cm ³
DRY 2%	12.52	23.51	4.42		19.21		18.70		21.65
Γmix=	2.700g/cm ³								Γaggr= 2.808g/cm ³
DRY 3%	12.66	22.94	4.01		19.69		18.80		21.90
Γmix=	2.687g/cm ³								Γaggr= 2.808g/cm ³

Because in conventional HMA blends the sieving is performed by adjusting the material, in this case, the dense type granulometric curve has been improved by varying the content of filler, sand and coarser grades to the lower limits of said curve. The *maximum density gradation* (or sometimes the *Fuller maximum density curve*), is

calculated using (2):

$$\% PMD = 100 \cdot \left(\frac{d}{D} \right)^{0.45} \quad (2)$$

Where:

- % PMD = % passing, maximum density gradation;
- d = sieve size in question, mm;
- D = maximum sieve size, mm;
- m_1 is the mass of the dry specimen, in grams (g);

In this research, the grading curve has been optimized to lower levels within the limits established by the sub-ballast standard, RFI [13]. The aggregate gradation is shown on the 0.45 power chart (Fig. 7).

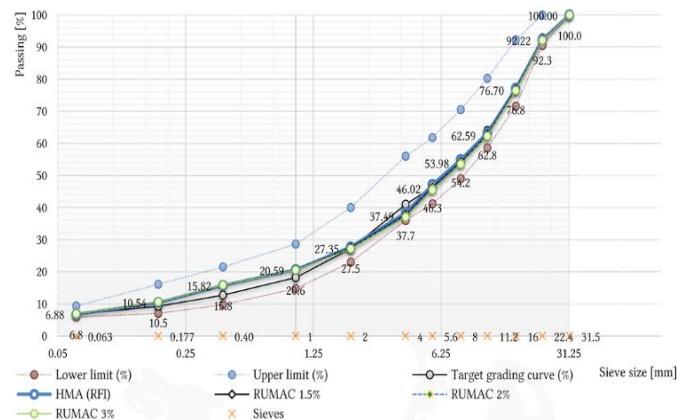


Fig. 5 Grain-size curves

C. Asphalt binder

The asphalt binder used was a B50/70-penetration grade having a performance grade of PG70-16 [35] after traditional and Superpave asphalt binder specifications that include specific gravity, penetration, ductility, softening point, rotational viscosity (RV), Dynamic Shear Rheometer (DSR) and, Bending Beam Rheometer (BBR) tests.

According to the specifications [36]-[37], that both covers asphalt binders graded by viscosity at 60°C, in this study the asphalt binder used is identified with a viscosity grade reference AC-20. A Viscosity value, 60 °C [140 °F] of 102 Pa·s, a Flash point min. 230 °C, a Solubility percentage in trichloroethylene of 99 % and, a Penetration value, °C, 100 g, 5 s, minimum of 53.

D. Rubber particles from scrap tires.

The rubber fractions come from the trituration of heavy-truck tires (natural rubber) supplied gently by "Baucina Recycling Tyres Srl" located in Baucina (PA). At this establishment, the process begins with a selection of tires, differentiating them from light vehicles, mostly from cars, motorcycles, and bicycles, heavy (trucks and self-articulated), and massively sized, constituting the volume above the previous one, including the abandoned wheels of aircraft.

CRM used in this case by dry process had two particle sizes of 0.4-2mm and 2-4mm (Fig. 8). The rubber aggregate with gap-gradation is a two-component system in which the fine gradation interacts with the asphalt cement while the coarse rubber performs as an elastic aggregate in HMA mixtures.

The characteristics of the materials used for the fabrication of the bituminous sub-ballast are summarized in Table III

TABLE III. CHARACTERISTICS OF THE MATERIALS UTILIZED 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 150°C [Pa·s]	ASTM D2493M-09	0.195
Equiviscosity values by Brookfield viscosim. [°C]	0.28P as 0.17P as	143.1 156.2
Aggregates (<i>limestone</i>)		
Properties	Standard	Value
Los Angeles abrasion loss [%]	EN 1097-2:2010	20.8
Bulk gravity coarse aggregates [g/cm ³]	EN 1097-3:1998	2.82
Bulk gravity sand [g/cm ³]	EN1097-6:2013	2.84
Bulk gravity filler [g/cm ³]	EN1097-7:2009	2.70
Resistance to fragmentation	EN 1097-2 (%)	20.8
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	
Moisture content (%)	<0.75	
Textile content (%)	<0.65	
Metal content (%)	<0.10	
Maximum density according proportion (% Ø0.4-2mm ; % Ø2-4mm)		
Standards: C.N.R. UNI-1 ; ASTM C128 ; UNE 12597-5:2009		
T° water: 27°C (ρ. 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 with water, m4 (gr)	3039	
Maximum Specific Gravity of rubber (g/cm ³)	1.154	



Fig. 6 Sieve analysis of the rubber from discarded truck-tires

IV. MIXTURES

The mixtures analyzed and the process followed in the laboratory to study the Beta-factor to enhance the Superpave methodology with the new parameters of energy applied to the study case of the rail sub-ballast are described in a graphic diagram (Fig. 9).

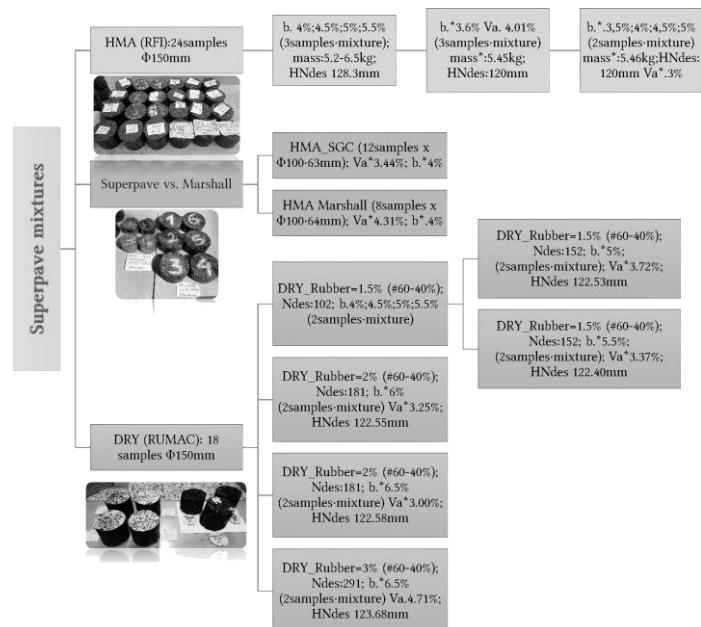


Fig. 7 Flowchart of all elaborate mixtures

For mixtures with rubber, the percentage of voids varies 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, because enhances the interaction between binder-rubber modifying the mechanical blend properties.

The number of gyrations used for compaction was, according to as the problems explained (swelling, rebound, and non-uniform expansion), 102 cycles [1]-[2].

So, for this procedure it was compared the densification curves for the next mixtures:

- HMA_(RFI), optimal binder contents 3.5%, 3.6%, 4%, 4.5%, and 5%, N_{des} 102 cycles, and Va*3% (Fig. 10 a);
- DRY RUBBER 1.5% #60_40 N_{des}.102, b.4%, 4.5%, 5%, and 5.5%, with an optimal air voids content of Va*3% (Fig. 10 b).

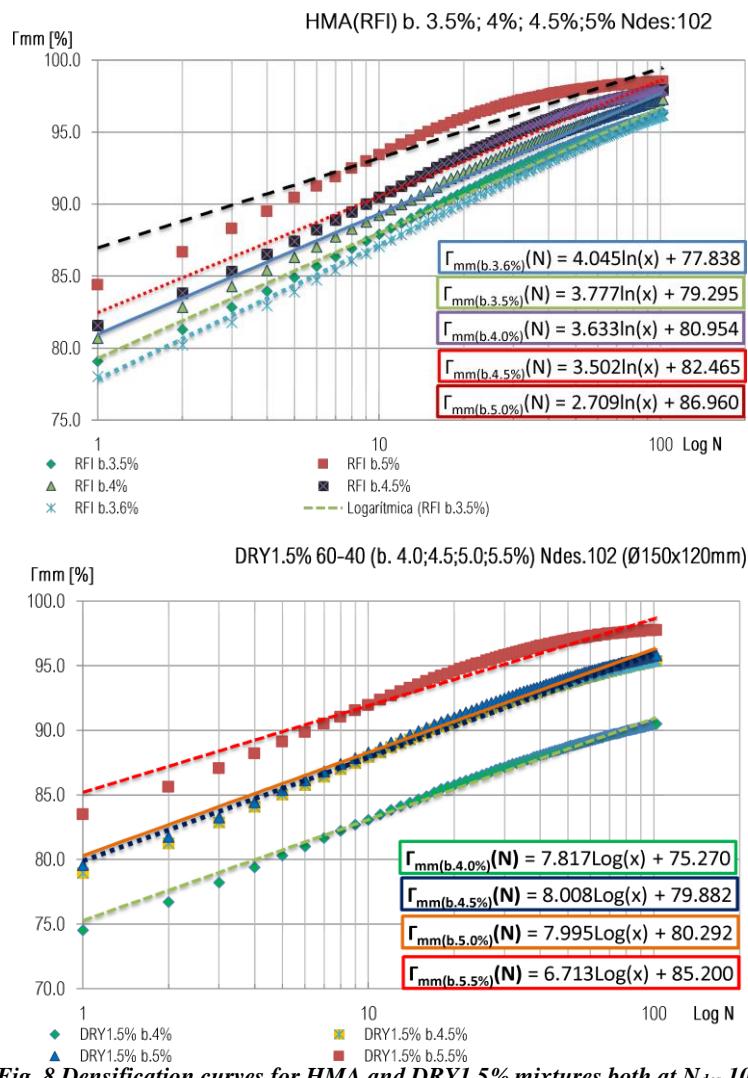


Fig. 8 Densification curves for HMA and DRY1.5% mixtures both at $N_{des} = 102$

In conclusion, the average regression equations are:

$$\text{HMARFI (b.3.5\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 8.697\ln(x) + 79.295$$

$$\text{HMARFI (b.3.6\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 8.314\ln(x) + 77.838$$

$$\text{HMARFI (b.4.0\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 8.365\ln(x) + 80.954$$

$$\text{HMARFI (b.4.5\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 8.065\ln(x) + 82.465$$

$$\text{HMARFI (b.5.0\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 6.238\ln(x) + 86.960$$

and

$$\text{DRY1.5 (b.4.0\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 7.817\ln(x) + 75.270$$

$$\text{DRY1.5 (b.4.5\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 8.008\ln(x) + 79.882$$

$$\text{DRY1.5 (b.5.0\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 7.995\ln(x) + 80.292$$

$$\text{DRY1.5 (b.5.5\%)} \rightarrow \Gamma_{mm} (N_{des} = 102) = 6.713\ln(x) + 85.200$$

Densification curves were plotted for each mixture that represents the measured relative density at N_{des} or N_{max} cycles (% Γ_{mm}) versus the logarithm of the number of gyrations. Each trend line is reported using (3):

Densification curves were plotted for each mixture that represents the measured relative density at N_{des} or N_{max} cycles (% Γ_{mm}) versus the logarithm of the number of gyrations. Each trend line is reported using (3):

$$\Gamma_{mm} = \frac{\Gamma_{N_{des}}^*}{\Gamma_{max}} \quad [\%] \Leftrightarrow \Gamma_{mm}(N) = \Gamma_1 + k \cdot \ln(N) \quad [\%] \quad (3)$$

Where:

- Γ_{mm} is the averaged specimen relative density at N_{des} (%);

- Γ_1 is the relatively specific density of energy accumulated during the compaction (%);
- k is the workability of the mixture (-)

V. EMPIRICAL APPROACH: RESULTS AND DISCUSSION

A. Superpave asphalt mixtures: Mix-Design

To develop the *empirical beta factor* method, we summarize only the procedure with conventional mixtures and the mixture with recycled rubber at 1.5%. Then, the same process was repeated by comparing the HMA mixture with the respective DRY2% and DRY3% to obtain the corresponding factor to be shown in the conclusive results.

It is seen that to reach the same degree of compaction, therefore, a percentage of internal voids of 3%, the bitumen content must be increased by around two decimals of binder with respect to the conventional bitumen, as well as the number of gyrations is increased, N_{des} , applying the beta factor of 1.2 to 1.48 for each 0.5% of rubber added. So, in the next section is explained this methodology to reach successful results of compaction as HMA as DRY blends.

B. “Beta factor.”

Thus, the method that responds to an approximation based on laboratory (empirical) results is summarized in Fig. 11 as an average example of both mixtures where the following process is observed.

At the critical level in this article, I will limit myself to showing the iterations made with a case study (“*beta 5*”, *see Fig. 12*) since with the other combinations proceed in the same way, thus avoiding successive figures of excessive development. In addition, it is the most representative case since it corresponds with the optimal recipe of bitumen content developed.

For example, for the upper case, for a densification value of 97% (i.e., an air voids content of 3%), the beta factor has been determined by developing the respective *regression equation* from the compaction curves (3)-(4), as is shown in Fig. 10, by clearing the unknown “*x*” corresponding to the number of gyrations so that each mixture reaches 3% of air voids (e.g.):

$$HMA_{b.4\%} : 97\% = 8.365 \log(x) + 80.954 \rightarrow \quad (4)$$

$$\Rightarrow \text{antiLog}(x) = \left(\frac{97 - 80.954}{8.365} \right) = 82.838$$

$$DRY_{b.5\%} : 97\% = 7.995 \log(x) + 80.292 \rightarrow \quad (5)$$

$$\Rightarrow \text{antiLog}(x) = \left(\frac{97 - 80.292}{7.995} \right) = 122.97$$

M	M	M	M	M	M
M	M	M	M	M	M

I continue sequentially with each combination mentioned above, and making the respective table of values “*beta*” for each two samples by mixing (two averaged specimens by mixture), a cloud of points (one per cycle in the densification curve) is obtained that graphically shows the mean value that must be adopted to establish a final beta between a conventional mixture HMA and a blend with DRY1.5% rubber (Fig. 14).

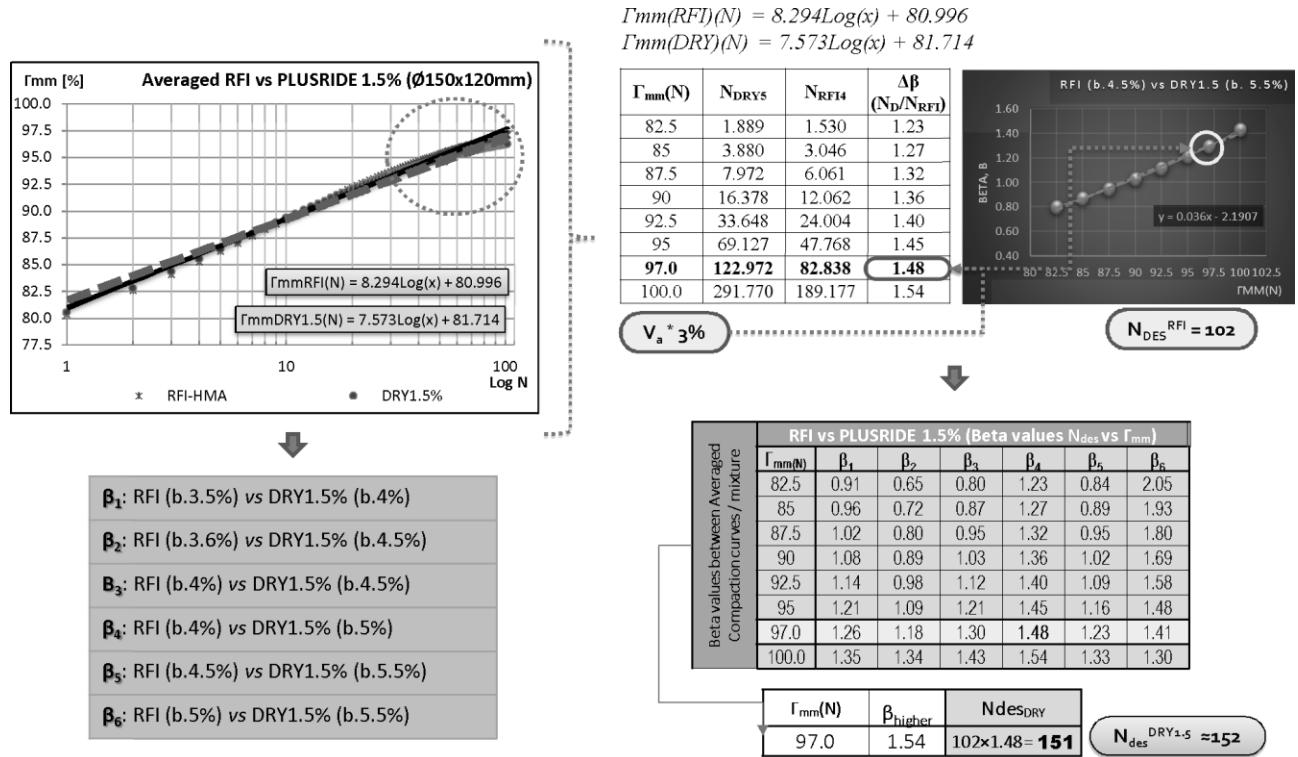


Fig. 9 Example of the "beta factor" approach method (HMA-DRY1.5% blends)

- $\beta_5: HMA \text{ b.4,5\% vs. DRY1.5\% (b.5,5\%)}$.

In this example, the regression curves of the two specimens per sample developed by SGC are shown (Table IV).

TABLE IV. REGRESSION CURVES HMA B.4.5% VS. DRY1.5 B.5.5%

Sample 01 HMA	$\Gamma_{mm}(HMA1 \text{ b.4.5\%})(N) = 7.596\log(x) + 83.409$
Sample 02 HMA	$\Gamma_{mm}(HMA2 \text{ b.4.5\%})(N) = 8.529\log(x) + 81.521$
Sample 01 DRY	$\Gamma_{mm}(DRY1 \text{ b.5.5\%})(N) = 6.394\log(x) + 84.763$
Sample 02 DRY	$\Gamma_{mm}(DRY2 \text{ b.5.5\%})(N) = 7.032\log(x) + 85.638$
Avg. HMA	$\Gamma_{mm}(HMA \text{ b.4.5\%})(N) = 8.064\log(x) + 82.465$
Avg. DRY	$\Gamma_{mm}(DRY \text{ b.5.5\%})(N) = 6.713\log(x) + 85.200$

As can be seen, a first conclusion is that to obtain the same degree of compaction at the same number of turns by Superpave we must consider between 0.5% and 1% more bitumen content in the mixtures with the recycled rubber of 1.5% to 2%.

Later, it will be shown how the beta factor grows as the rubber volume increases in the mixture, and therefore also increases the number of cycles (N_{des}) to an acceptable limit of the Superpave methodology [28].

Recall that conventional blends are made to N_{des} 102 cycles, so the result we are looking for is the "beta" factor that must multiply to that N_{des} in the case of a mixture of 1.5% rubber.

The beta factors obtained from the regression curves applying the target value of 97% of compaction are presented in Table V and Fig. 13.

In this example, to achieve the same grade of compaction and air voids content, the rubberized mixture will have a N_{des} equal to 102 cycles multiplied by 1.33, resulting 136 cycles to SGC.

TABLE V. "BETA" FACTORS (SAMPLE 1 HMA B.4.5% VS. DRY1.5 B.5.5%)

$\Gamma_{mm}(N)$	$N_{DRY5.5}$	$N_{HMA4.5}$	$\Delta\beta$
82.5	0.443	0.759	0.58
85	1.089	1.619	0.67

87.5	2.680	3.456	0.78
90	6.592	7.374	0.89
92.5	16.219	15.733	1.03
95	39.905	33.568	1.19
97.0	82.002	61.550	1.33
100.0	241.550	152.820	1.58

From the results obtained, with a binder content of 4%, the air voids are 2.74% in HMA mixture while in DRY 1.5% it is 4.13%, for that reason is not a valid value (higher than 3%¹).

The densification curves respectively are (Fig. 12a-b):

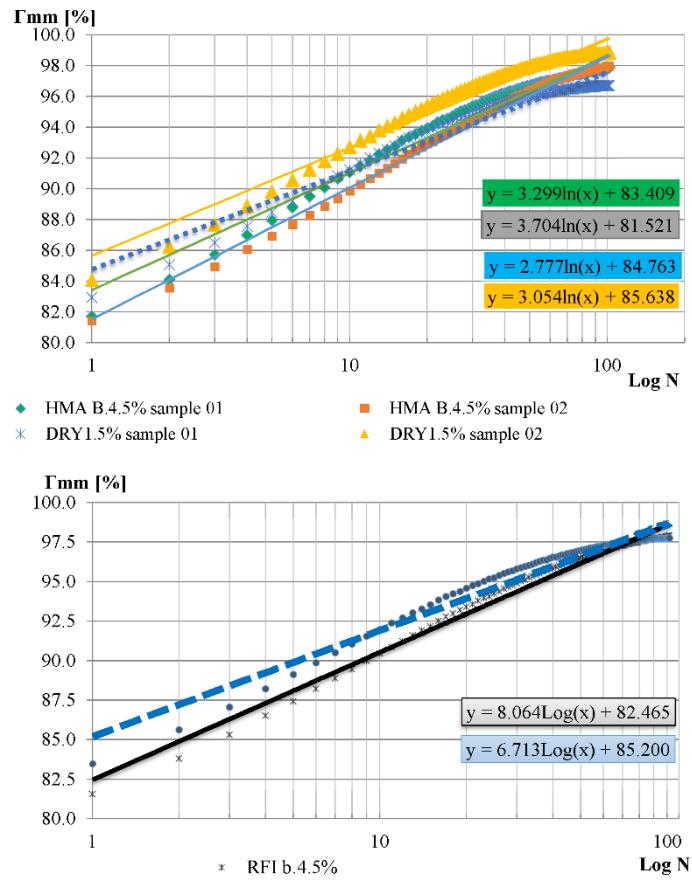


Fig. 10 Densification curves (HMA B.4.5% VS. DRY1.5 B.5.5%); (a) Each sample; (b) Averaged as Log(N_{des})

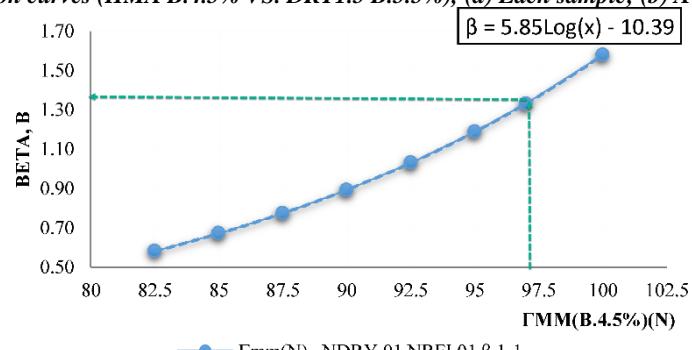


Fig. 11 Example of "beta factor" (HMA B.4.5% VS. DRY1.5 B.5.5%)

C. “Beta factors” averaged results

The present work has proposed an empirical approach for the optimization of the mix-design of bituminous asphalt mixtures HMA or DRY made with the Superpave gyratory compactor of bituminous mixtures having crumb rubber between 1.5% to 3%. The method considers the elastic behavior of the rubber and calculates its release of deformation after compaction. Therefore, it is possible to estimate and control the final void content by applying a correction factor which adjusts the N_{des} depending on the target voids to be reached.

Based on the results, the empirical approach is considered helpful in adjusting the required number of gyrations set by the Superpave mix-design to compact rubber-aggregate asphalt blends.

Finally, for all the combinations of “beta factors” is selected an average value in each case of the mixture. Considering the earlier example of an HMA mixture and another DRY 1.5%, the results are represented in Fig. 14 and Fig. 15.

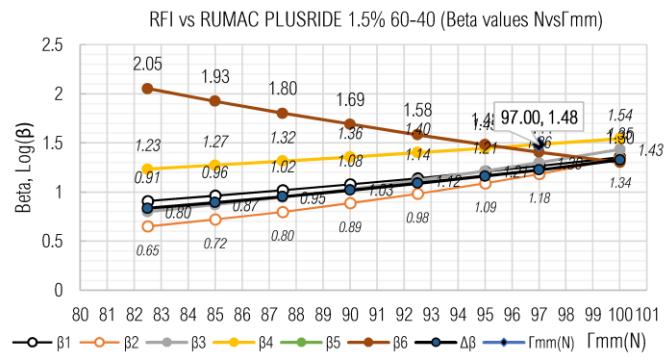


Fig. 12 Results of “beta” values for each combination of averaged HMA vs. DRY1.5%

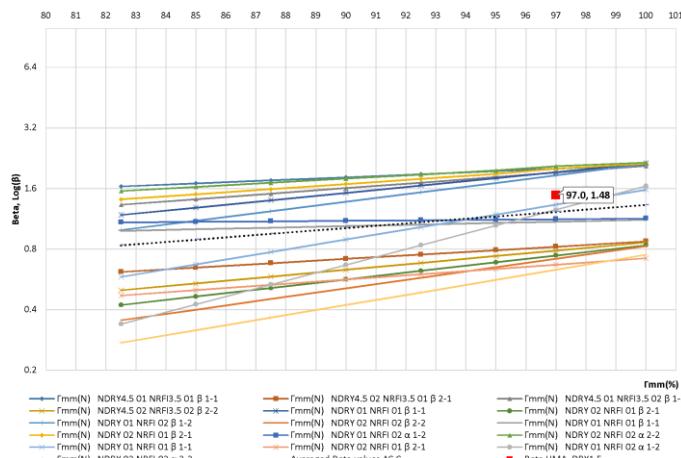


Fig. 13 Results of all “beta” values for each combination of 2 samples per mixture HMA vs. DRY1.5%

As can be seen, to obtain an optimum mixture by gyratory compactor at the level of a conventional HMA bituminous mixture, a beta factor of 1.48 should be added as a multiple of the N_{des} applied.

In this example, the number of turns is $102 \cdot 1.48$ equal to 152 turns of SGC for a mixture DRY 1.5%. Subsequently, the same procedure was performed in the remaining mixtures developed with 2% and 3% recycled rubber. The conclusive results are shown in Fig. 16

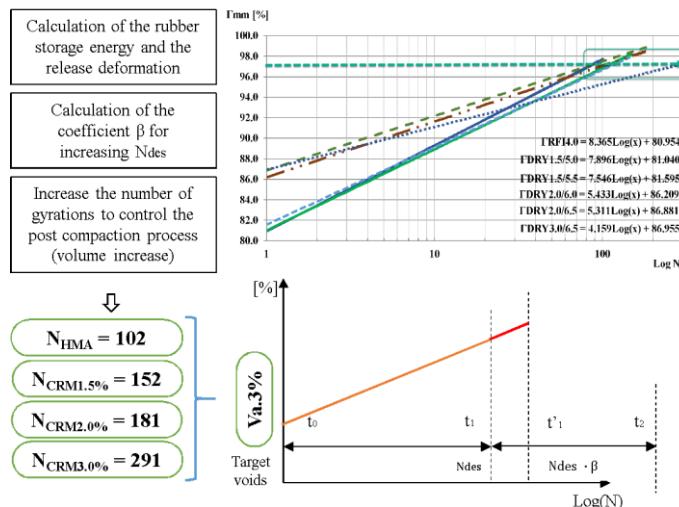


Fig. 14 (a) Optimization of rubber-aggregate mixtures with “beta” factors; (b) Scheme of regression curves

It is observed that in order to reach the same degree of compaction, therefore, a percentage of internal voids of 3%, the bitumen content must be increased by around two decimals of binder with respect to the conventional bitumen, as well as the number of gyrations is increased, N_{des} , applying a factor of 1.2 to 1.48 for each 0.5% of rubber added.

Considering the HMA the reference mixture, we have found the last “beta” results for each blend (Table VI).

TABLE VI. RESULTS FOR ALL MIXTURES

Mixture	“Beta factor”	N_{des}^*
HMA	1	102
DRY 1.5%	1.48	152
DRY 2%	1.77	181
DRY 3%	2.85	291

VI. MIX-DESIGN OF DRY RUBBERIZED MIXTURES

These are basically dense, and gap-graded asphalt concrete mixes to which scrap tire rubber is added as a part of the aggregate part. 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 by an intimate mixing of asphalt cement, are referred as “asphalt concrete rubber filled” or “rubber modified asphalt concrete mixes (RUMAC)” [41].

Crumb rubber is made by shredding scrap tires that it is a particulate material free of fiber and steel. The size of the rubber particles is graded and can be found in many shapes and sizes. The finest one can be as small as about 0.2 mm and below. The gradation used in this research is 0.4-2.0 mm to 2-4 mm. Crumb rubber is light in weight and also durable. It can last for a lengthy period in a natural environment. From a safety aspect, crumb rubber can be categorized as a nontoxic and inert material (Figure 17).



Fig. 15 Difference sizes of crumb rubber used

For mixtures with rubber, the percentage of voids varies between 3.01% and 3.37%. Therefore, it is never possible to exceed the largest value of an established 4% of voids for a suitable bituminous mixture in sub-ballast. As was done in the case of non-rubber bituminous mixtures, in this case, the granulometric curves and the laboratory recipes for the manufacture of recycled rubber are adjusted (Table VII).

TABLE VII CONSTITUTION OF THE THEORETICAL RECIPES

Rubber substitution (% of total mix by)			
Mixture	Asphalt (%)	Weight (%)	Volume (%)
DRY 1.5	5.5	1.5	3.02
	6.0	1.5	2.98
DRY 2.0	6.0	2.0	3.95
	6.5	2.0	3.90
DRY 3.0	7.0	3.0	5.71

The next step is to check in real mixes the new number of turns assigned to each mix based on the corresponding factor "beta" determined. Three different mixtures of four specimens were each made with percentages of recycled gum of 1.5%, 2%, and 3%.

A. DRY RUBBER 1.5%#60_40 Ndes.152 b*.5-5.5%

In this new experience in laboratory, mixtures respond to the following characteristics (Fig. 18; Table IX):

1. The proportions of rubber are #60-40% for mixtures with 1.5 to 2% of rubber and, #20-80% for mixture with 3% of rubber (i.e., 60% of Ø0.4-2 mm and 40% of Ø2-4 mm). The temperature of the asphalt cement is between 160 and 220 °C for mixing and 145 °C and 160 °C for compaction, according to the optimal values for viscosity using Brookfield viscometer and "Ring and Ball" penetration tests. Ambient ground rubber with a specific gravity of 1.154 g/cm³ is used.
2. Asphalt containing 0.2 and 0.4 mm size rubber indicated the best laboratory results. The particles size disruption of crumb rubber influenced the physical properties of bitumen rubber blend.

Also, after compaction, a dead load of 5kg was applied for a further 24 hours to provide enough time for the sample to reach room temperature. The samples were removed from the split molds after 24 hours curing and stored at 20 °C for future testing

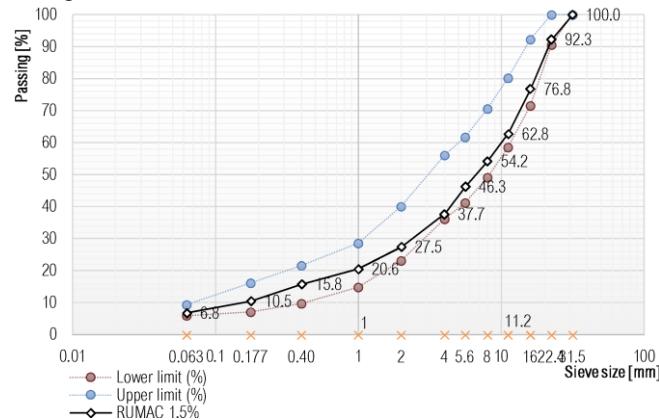


Fig. 16 (a) Grading curve DRY 1.5% Ndes.152; (b) Specimens compacted and extruded after 24h

TABLE IX. DRY1.5% #60-40 AIR Voids VS. BINDER CONTENT (0H;24H;168H), (N_{DES}.152)

Specime n	H. N _{des} [mm]	H. 24h [mm]	H. 7d [mm]	Va(Va(Va(% 7 days
Ø15x12c m				N _{des}	24h	
DRY ⁰¹ _{5.0/} 1.5	121.30	121.9	121.9	2.43	2.76	2.78
		8	9	%	%	%
DRY ⁰² _{5.0/} 1.5	122.20	123.0	123.0	2.48	2.81	4.66
		6	8	%	%	%
DRY ⁰³ _{5.5/} 1.5	121.70	122.6	122.7	2.39	2.79	3.21
		2	0	%	%	%
DRY ⁰⁴ _{5.5/} 1.5	121.70	121.7	121.7	3.01	3.40	3.54
		2	4	%	%	%
%b	VMA (%)	VFA (%)	Γ_{max} g/cm ³	Γ_{ssd} g/cm ³	Γ_{mm} (%)	
5.0	14.95	75.38	2.596	2.508	96.6 1	
5.5	15.60	78.37	2.577	2.500	97.0 2	

TABLE X. ENERGETIC PARAMETERS (DRY1.5% #60-40 ϕ 150-120MM)

Design ESAL	%b.	N _{init}	N _{des}	N _{max}	% Γ_{mm} N _{init}	% Γ_{mm} N _{des}	% Γ_{mm} N _{max}	%Va	Dust ratio (DP) ²
>3·10 ⁷	5.0	10	152	251	88.67	97.55	99.98	3.37	0.716
	5.5	10	152	251	88.87	97.30	99.65	3.01	0.709

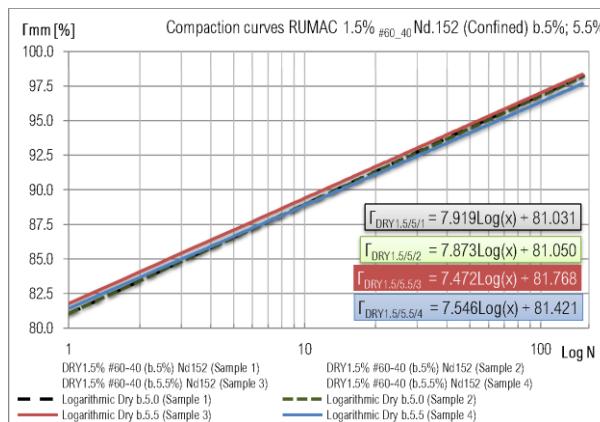


Fig. 17 (a) Densification curves DRY 1.5 b. 5%;5.5%; (b) Trend line and regression equations

Through the results of these mixtures, it can be stated that the rubber mixtures allow a lower workability of the mixture to compaction than the conventional bituminous mixture. However, due to the elasticity of the recycled rubber, the densification is greater with the rubber content and the higher the bitumen introduced into the mix.

That is, despite the increased number of gyrations (N_{des} 152 > 102), the blends at the same number of N_{des} had already reached the empty content target of 3% (Tables X-XI).

TABLE XI COMPARATIVE ENERGETIC PARAMETERS (HMA VS. DRY1.5% ϕ 150-120MM)

Design ESALs	%binder	N _{des}	% Γ_{mm} N _{des}	%Va (N _{des})
	4.0	102	97.26	2.74
>3·10 ⁷	5.0	152	97.55	2.45
	5.5	152	97.30	2.70

For control mixtures, and dry process modified mixtures, the mixing and compaction temperatures were specified as 170±5 °C and 150±5 °C, respectively.

B. DRY RUBBER 2% #60-40 Ndes.181 b*.6-6.5%

Lastly, the results for a rubber-aggregate blend at 2% in a gap-graded mixture is demonstrated the successful “beta factor” mixing at N_{des}. 181 gyrations (Fig. 20; Table XII).

TABLE XII DRY2.0% #60-40 AIR Voids VS. BINDER CONTENT (N_{des}.181)

Specimen Ø15x12cm	H. N _{des} [mm]	H. 24h [mm]	H. 7d [mm]	Va(%) N _{des}	Va(%) 24h	Va(%) 7 _{days}
DRY ⁰¹ _{6.0/2.0}	122.40	122.50	122.60	2.21%	2.67%	2.77%
DRY ⁰² _{6.0/2.0}	120.40	121.00	122.91	2.51%	2.97%	3.25%
DRY ⁰³ _{6.5/2.0}	120.90	122.00	122.07	1.94%	2.48%	2.96%
DRY ⁰⁴ _{6.5/2.0}	120.70	121.00	123.10	2.18%	2.72%	3.04%
Dust-to-asphalt ratio	%b	VMA (%)	VFA (%)	Γ_{max} g/cm ³	Γ_{ssd} g/cm ³	Γ_{mm} (%) 7 _{days}
0.670	6.0	16.21	81.44	2.559	2.494	96.67
0.620	6.5	17.11	82.48	2.541	2.479	96.25

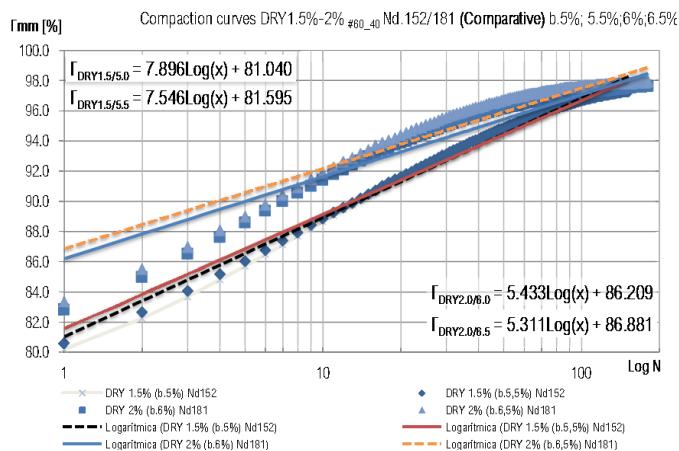


Fig. 18 Comparison Avg. Densification curves DRY 1.5-2%

TABLE XIII COMPARATIVE ENERGETIC PARAMETERS (HMA vs. DRY2.0% ϕ 150-120MM)

Design ESALS	%binder	N _{des}	% Γ_{mm} at N _{des}	% Va (N _{des})
	4.0	102	97.26	2.74
$>3 \cdot 10^7$	6.0	181	97.64	2.36
	6.5	181	97.94	2.06

In conclusion, the regression equations are (Fig. 21):

$$\begin{aligned}
 \text{HMA (b.4%)} &\rightarrow \Gamma_{mm} (N_{des.} 102) = 8.365\log(x) + 80.954 \\
 \text{DRY1.5 (b.5%)} &\rightarrow \Gamma_{mm} (N_{des.} 152) = 7.896\log(x) + 81.040 \\
 \text{DRY1.5 (b.5.5%)} &\rightarrow \Gamma_{mm} (N_{des.} 152) = 7.546 \log(x) + 81.595 \\
 \text{DRY2.0 (b.6.0%)} &\rightarrow \Gamma_{mm} (N_{des.} 181) = 5.433\log(x) + 86.209 \\
 \text{DRY2.0 (b.6.5%)} &\rightarrow \Gamma_{mm} (N_{des.} 181) = 5.311\log(x) + 86.881 \\
 \text{DRY3.0 (b.6.5%)} &\rightarrow \Gamma_{mm} (N_{des.} 291) = 4.161\log(x) + 86.955 \\
 \text{DRY3.0 (b.7.0%)} &\rightarrow \Gamma_{mm} (N_{des.} 291) = 3.848\log(x) + 89.432
 \end{aligned}$$

VII. CONCLUSIONS

A literature review revealed that field performance of dry rubber-modified asphalt mixtures is not consistent if the proposed protocol is not followed in this article. The swelling effect was confirmed and observed, in mixtures DRY 1,5%, 2% and, 3% of rubber at high temperatures. Rubber absorbs the lighter fractions of bitumen during 7 days from its manufacture, so problems are observed due to swelling and non-uniform expansion of the mixture due to the residual energy accumulated inside the asphalt matrix. An excessive compaction, so that if it falls below 3% of voids can contribute to this problem.

Thus, a fundamental investigation on the mechanical properties of rubber-bitumen was carried out to understand the interaction effect, to solve the rebounding and non-uniform distress in laboratory specimens during the manufacturing process of mixtures with SGC.

For each specimen prepared, best results were obtained with a digestion time of 90min and, considering the asphalt binder (135-150°C), aggregates (160-190°C) and compaction molds (150°C) heated to the proper mixing temperature according to the mixture type. Then, before being removed, each sample must be stored at room temperature (20°C) after 24h of post-compaction and thermal stabilization.

The advantage of applying the “beta” factor approach is that considering the experimental results with HMA and DRY mixtures, the method provides a basis for estimating an increase in the level of compaction when rubber is added to the blends. The method can be used for all types of asphalt mixtures that vary the bitumen content and type of aggregates, such as data entry. Also, the percentages of gaps required by the standards can be set at the beginning of the process.

However, additional work is needed to verify the robustness of the methodology using other materials and different sizes of recycled rubber, other ratios. In addition, the procedure based on experimental approximations still lacks strong aspects of turning it into a widely accepted methodology. In fact, this research has considered a simplified system of a bituminous matrix (aggregates, bitumen, air voids and rubber) and the compression as a determining factor in compaction.

It is proposed as a future work to determine the effect of temperature on the behavior of rubber and the mutual interactions between rubber and bitumen, also to establish 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 blend design approach, it provides promising results in estimating the final void content after thermal stabilization and curing in mixtures of asphalt with rubber as we have seen during the development of this study.

The protocol to produce test specimens in the laboratory already presented has been justified by the behavior of the rubber, that requires care in the post-compaction phase that does not occur in conventional HMA mixtures.

Compliance With Ethical Standards

The author(s) declare(s) that there is no potential conflict of interest. We further confirm that the order of authors listed in the manuscript has been approved and, it was followed the regulation of our institution concerning intellectual property.

VIII. REFERENCES

- [1] AASHTO (American Association of State Highway and Transportation Officials). (2001). "Superpave Volumetric Design for Asphalt Mixtures."
- [2] AASHTO R 35-151, "Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt," HMA444 North Capitol Street N.W., Suite 249 Washington, D.C.
- [3] NCHRP (National Cooperative Highway Research Program). (2007). "Superpave Mix Design: Verifying Gyration Levels in the Ndesign Table." Report 573.
- [4] Epps J.A., (1994). "Uses of recycled rubber tires in highways." Washington, DC: Synthesis of Highway Practice No.198, TRB National Research Council. NCHRP Report.
- [5] Heitzman, M. A., "State of the Practice - Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier," Federal Highway Administration, Report No. FHW A-SA-92-022, May 1992.
- [6] Emery, J. (1995), "Evaluation of Rubber Modified Asphalt Demonstration Projects," Transportation Research Record 1515, TRB, Washington, D.C, pp 37-46.
- [7] Fager, G.A. (2001), "Asphalt Rubber: A Summary of the Use of Crumb Rubber in the Hot Mixes: Kansas Experience 1990-2000", Kansas Department of Transportation, Kansas.
- [8] Gowda, G.V., Hall, K.D. and Elliott, R.P. (1996), "Arkansas Experience with Crumb Rubber Modified Mixes Using Marshall and Strategic Highway Research Program Level I Design Methods," Transportation Research Record 1530, TRB, Washington, D.C., pp. 25-33.
- [9] Heitzman, M.A. (1992), "State of the Practice for the Design and Construction of Asphalt Paving Materials with Crumb Rubber Additive," Report No. FHWA-SA-92-022, Office of Engineering, Pavement Division, Federal Highways Administration.
- [10] F. Martínez-Soto, G. Di Mino, et al. "The resistance to fatigue of dry asphalt rubber concrete for sub-ballast layer," 15th International Conference on Railway Engineering. 2015.
- [11] Rose, J. G., & Konduri, K. C. (2006, June). "KENTRACK—A railway trackbed structural design program." In AREMA 2006 Annual Conference (pp. 17-20).
- [12] Rose, J. G., Agarwal, N. K., Brown, J. D., & Ilavala, N. (2010, January). "KENTRACK, A Performance-Based Layered Elastic Railway Trackbed Structural Design and Analysis Procedure—A Tutorial." In Proceedings of the 2010 Joint Rail Conference (pp. 73-110).
- [13] RFI (Rete Ferroviaria Italiana, 2016). Gruppo Ferrovie dello Stato Italiane. "Capitolato costruzioni opere civili. sezione XV sub-ballast - pavimentazioni stradali".
- [14] EN 933-1 (2012) Tests for geometrical properties of aggregates. Determination of particle size distribution. Sieving method.
- [15] EN 933-10 (2009) Tests for geometrical properties of aggregates. Assessment of fines. Grading of filler aggregates.
- [16] ISO 3310-1 (2000) Test sieves Technical requirements and testing -- Part 1: Test sieves of metal wire cloth.
- [17] Farouk, Abdulwarith Ibrahim Bibi, et al. "Effects of mixture design variables on rubber-bitumen interaction: properties of dry mixed rubberized asphalt mixture" Materials and Structures 50.1 (2017).
- [18] Ma, T., Ye, Q., Wu, C., & Huang, X. (2016). "Characterization of stable crumb rubber asphalt and mixture." In Functional Pavement Design: Proceedings of the 4th Chinese-European Workshop on Functional Pavement Design (4th CEW 2016, Delft, The Netherlands, 29 June-1 July 2016) (p. 277). CRC Press.

- [19] F. Martínez-Soto, G. Di Mino. "Increased Stability of Rubber-Modified Asphalt Mixtures to Swelling, Expansion and Rebound Effect during Post-Compaction," WASET, International Journal of Transport and Vehicle Engineering Vol: 4, Nº7.
- [20] Abdul Hassan (2006). "Performance of Hot Mix Asphalt Using Fine Crumb Rubber," Ph.D. Civil Engineering Malaysia, 2006/2007.
- [21] Soon-Jae Lee, Chandra K. Akisetty, Serji N. Amirkhanian, "The effect of crumb rubber modifier (CRM) on the performance properties of rubberized binders in HMA pavements," Construction and Building Materials, Volume 22, Issue 7, 2008, pp 1368-1376, ISSN 0950-0618.
- [22] Singleton, T. M., Airey, G. D., & Collop, A. C. (2000). "Effect of rubber-bitumen interaction on the mechanical durability of impact absorbing asphalt." In Proceedings submitted for review at 2nd Eurasphalt and Eurobitume congress, 2000, Barcelona, Spain.
- [23] Mashaan, N. S., Ali, A. H., Karim, M. R., & Abdelaziz, M. (2012). "An overview of crumb rubber modified asphalt." International Journal of Physical Sciences, 7(2), 166-170.
- [24] Cao, W. (2007). "Study on properties of recycled tire rubber modified asphalt mixtures using dry process." Construction and Building Materials, 21(5), 1011-1015.
- [25] Ayad Subhy, Gordon Airey, D. Lo Presti (2007). "An investigation of the mechanical properties of rubber modified asphalt mixtures using a modified dry process." Conference proceedings BCRRRA 2017 Greece.
- [26] Xie, H., & Watson, D. (2004). "Determining air voids content of compacted stone matrix asphalt mixtures." Transportation Research Record: Journal of the Transportation Research Board, (1891), 203-211.
- [27] AASHTO, T. (2007). 166-07.(2007)."Bulk Specific Gravity of Compacted Hot Mix Asphalt using Saturated Surface-Dry Specimens." Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 27th Edition, American Association of State Highway and Transportation Officials, Washington, DC.
- [28] NCHRP (National Cooperative Highway Research Program). (2007). "Superpave Mix Design: Verifying Gyration Levels in the Ndesign Table." Report 573.
- [29] F. Martinez-Soto, G. Di Mino & F. Acuto (2017). "Effect of Temperature and traffic on mix-design of bituminous asphalt for railway sub-ballast layer." BCRRRA2017 Conference Proceedings CRC Press Taylor & Francis Group.
- [30] F. Martinez-Soto, G. Di Mino (2017). "Procedure for a temperature-traffic model on rubberized asphalt layer for roads and railways," (JTTE-E 20170721-1) Journal of Traffic and Transportation Engineering, ISSN: 2328-2142, DOI: 10.17265/2328-2142/2017.05.002, David Publishing Company, Valley Cottage, NY, USA.
- [31] BS EN 13108-1:2016 "Bituminous mixtures. Material specifications. Asphalt Concrete", doi:10.3403/30278709.
- [32] BS EN 12591, "Bitumen and bituminous binders - Specifications for paving grade bitumen."
- [33] BS EN 12697-35, "Bituminous mixtures — Test methods — Part 35: Laboratory mixing."
- [34] Zhang, J.; Apeagyei, A.; Airey, G.D.; Grenfell, J.R.A. (2015). "Influence of aggregate mineralogical composition on water resistance of aggregate-bitumen adhesion." International Journal of Adhesion and Adhesives, 62, 45-54.
- [35] AASHTO, M. 320 (2002) Standard Specification for Performance-graded Asphalt Binder. Washington, DC: American Association of State Highway and Transportation Officials.
- [36] Cement, B. A. Comply with AASHTO M-226/ASTM D 3381. AC-20, AR-80, viscosity grade.
- [37] ASTM D3381 / D3381M-13, Standard Specification for Viscosity-Graded Asphalt Cement for Use in Pavement Construction, ASTM International, West Conshohocken, PA, 2013.
- [38] Rose, J.G.; Teixeira, P.F. (2010) Ridgway NE. "Utilization of asphalt/bituminous layers and coatings in railway trackbeds – a compendium of international applications." ASME Conf; 1:239–56.
- [39] Shuler, T. S., Pavlovich, R. D., Epps, J. A., & Adams, C. K. (1985). "Investigation of materials and structural properties of asphalt-rubber paving mixtures". Technical Rep. Prepared for Federal Highway Administration, Washington, DC