Innovative Approaches to Eco-Sustainable Mix-Design in Modified Bituminous Mixtures with Recycled Tire Rubber

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ABSTRACT

The design of 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 rubber-aggregate mixtures containing ground rubber-aggregate by a dry process (RUMAC to 1,5 to 3% of rubber by total weight and 5-7% of binder) was evaluated. Using an eco-sustainable original approach based on experimental findings obtained in the laboratory with the Volumetric mix-design by gyratory compaction for a level 3 (high-traffic) design rail lines.

This work proves that rubberized blends having ground rubber in bituminous asphalt mixtures behave better than conventional asphalt materials.

By using the same method of volumetric compaction, the densification curves resulting from each mixture have been studied with the purpose to obtain a best empirical parameter multiplier of the number of gyrations necessary to reach the same compaction energy as in conventional mixes.

It has provided experimental parameters evaluating the results obtained from the gyratory-compaction of bituminous mixtures with an HMA and rubber-aggregate blends as a sub-ballast layer in railway underlayment trackbed. By adopting this increase-parameters of compaction, called “beta” factor, uniform densification and higher workability are found in modified mixtures with rubber considering the usual bearing capacity requirements in rail track.

INTRODUCTION

The entire mix design system, including field control, is based on the use of the Volumetric mix-design, which estimates the binder demand needed for the selected aggregate structure. Superpave Volumetric Design for Hot-Mix Asphalt proceeds with preparing a maximum specific gravity sample and a set of 15 cm specimens for compaction in the gyratory compactor device (SGC) [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 Volumetric mix design 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.

Superpave Gyratory Compactor (SGC) estimates the binder demand needed for the selected aggregate structure and proceeds with preparing a maximum specific gravity sample and a set of 150 mm specimens for compaction in the gyratory compactor.

The gyratory simulates the mix densities achieved under the actual climate and loading conditions. This device is capable of accommodating large aggregate, recognizing potential tender mix behavior and similar compaction problems, and is well suited for mixing plant quality control operations.
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 more significant quantities of scrap tires and is also logistically more natural 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 central 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 mixtures were designed as dense-graded HMA (conventional for the base course in roads, and also as a sub-ballast underlayment in railways [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.

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 for bitumen, and this could hurt 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 (120-190ºC). 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. In addition, through experimentation, a coefficient is developed that adjusts the number of turns required by the SGC technique to compact mixtures with recycled rubber and avoid the problems of swelling and density increase during the post-compaction phase.

METHOD

Optimization of the manufacturing process

The dry process is usually used as a fraction of the coarse-fine aggregate. 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 asphalt. 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 and the design of the mix. Also, other factors are 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 primary purposes of this research was the development of an optimal Superpave volumetric 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 methodology is applied to CRM mixtures.

The biggest problem is that the rubber is an element involved in the mixture that has 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 specific 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 essential to understand the interaction process or reaction between asphalt cement and crumb rubber modifier (Ø0.2-4 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.

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).

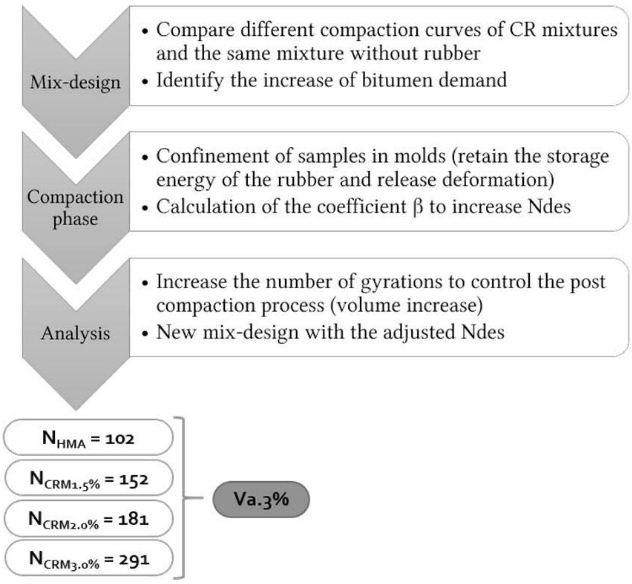


Fig. 2 Schematic representation of research stages

The presence of STR (Scrap Tire Rubber) 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.

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 asphalt. 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.

Empirical-Analytical 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], causing an increase of voids in the post-compaction phase, and 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.

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 content (HMA) and three with rubber (DRY or RUMAC) 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).

In this graph, the compaction difference is shown at the same number of rotations in specimens of identical dimensions but with/without the addition of granular rubber of the recycled tire. To achieve the appropriate densification levels, the compaction must be increased in the modified mixtures. This phenomenon is due to the subsequent effect of recovery of internal accumulated energy inside the specimen when being confined in the mold during 24h.

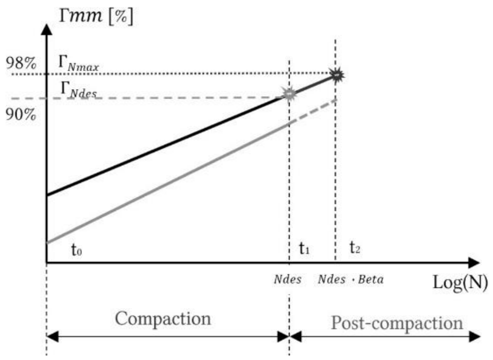


Fig. 3 Preliminary stage of comparison densification curves

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 ($\beta \cdot N_{design}$) necessary to compact a sample of traditional asphalt mixture to obtain the design number of gyrations required to compact a sample of CRM mixture (NCR):

$$N^{i}_{CRM} = \beta \cdot N^{i}_{des} \quad i = 1, 2 \ldots samples$$
$$\beta = \frac{\%V_a^{CRM}}{\%V_a^{HMA}} \; if \; Va = 3\% \rightarrow \beta = \frac{\Gamma_{mm97\%}^{CRM}}{\Gamma_{mm97\%}^{HMA}} \quad (1)$$

Where:

- N_{CRM} = design number of gyrations optimized for rubber-aggregate mixtures;
- $\Gamma_{mm97\%}^{mix}$ = 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. NCRM must have an upper bound (N_{limit}) defined to perform compaction with a reasonable number of turns.

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

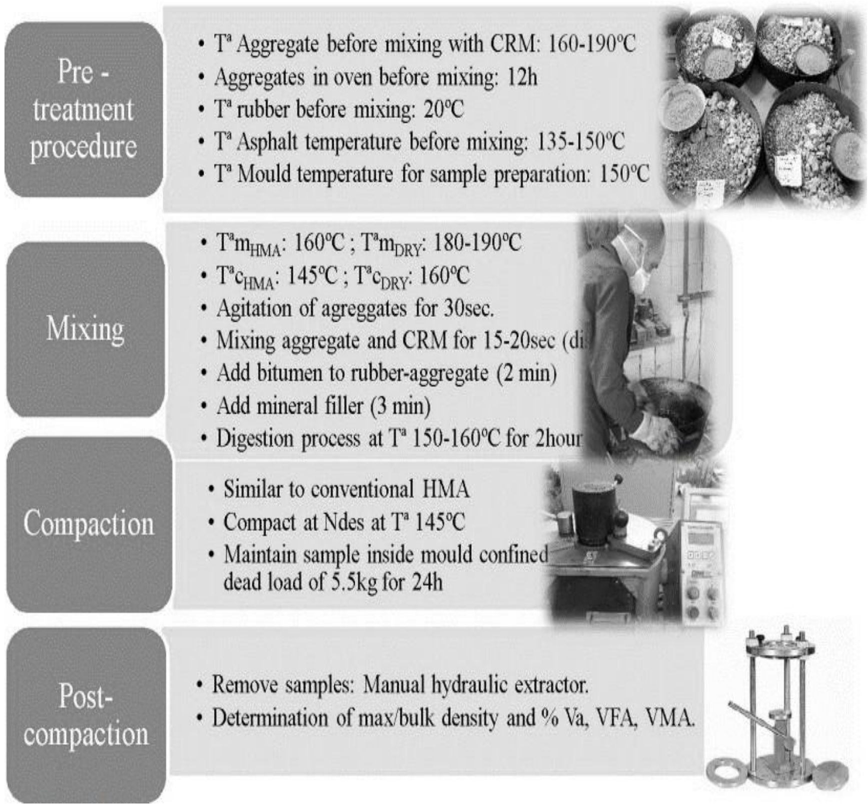
Post-compaction phase

After compaction, prepared specimens undergo a dilation (a bounce-back effect) during the curing period (first 24 h at temperature 145 ºC to ambient 20 ºC). 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 higher compaction energy to reach the percentage of target voids, a minimum period of stabilization of the mix (post-compaction) is necessary to maintain 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).



Operational framework. Basic rules for mix-design

Immediately after compaction, a dead load equivalent to the sample weight (±5.5kg thus limiting a possible post-compaction that reduces the final void percentage) must be applied for a further 24 hours, which allows the mixture to cool down to ambient temperature. Bitumen will 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 percentage.

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

As an example of the consequences of not following the post-compaction process suggested before, 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 Figure 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.

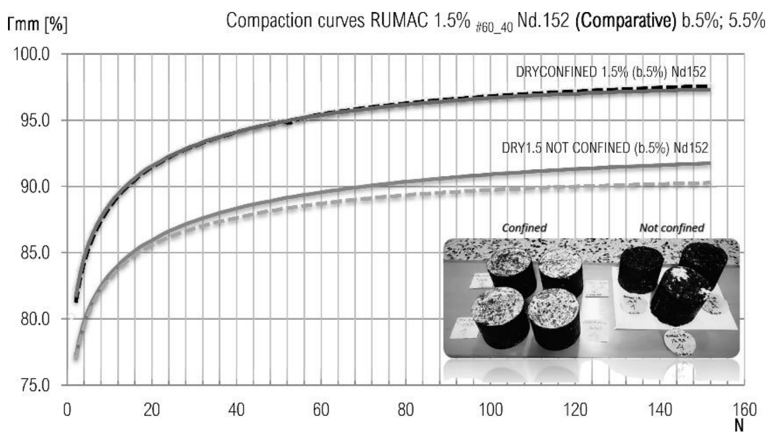


Fig. 5 Maximum specific gravity vs. Number of gyrations under DRY 1.5% mixtures confined/unconfined in molds during 24h

The final aim is to provide the beta parameters that we must apply to Ndes 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.

MATERIALS

Techniques

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 φ150mm, 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 ±3%.

In previous publications [29]-[30], N_{design} for the bituminous sub-ballast was calculated with an equivalent standard axle load higher than 30 RESAL (Railway equivalent standard axle load). 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%.
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.

1.5%, 2% and 3% of the total weight of the aggregates (3.02%, 3.95% and, 5.71% by volumetric substitution). Limestone aggregates with density value of 2.81g/cm^3 was considered.
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).).

Mix-design of conventional Hot mix asphalt (HMA) and DRY mixtures

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.

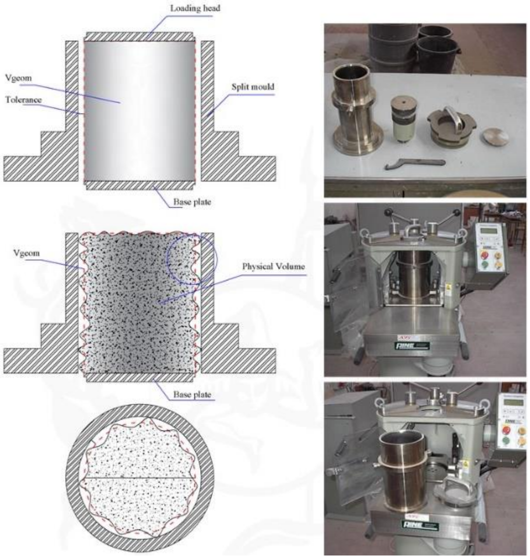


Fig. 6 (a) Compaction mold design in CAD; (b) Actual model of SGC

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 an air void content of 3-4 %, a Marshall stability of 10 kN, and a higher indirect tensile strength at 15 ºC of 0.6 N/mm^2. 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.

Aggregate gradation and properties

The mixtures studied 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 showed 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 Tables 1-2 and Table 3, the grading curve by sieves and the final dosage formula according to each mixture (HMA or DRY) are finally provided.

Table 1. Granulometric distribution of aggregates

	Target	HMA	DRY1.5	DRY2.0	DRY3.0
Sieves (mm)	% 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, Italferr, Sezione XV, rev. 2004)

Table 2. 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 3. Distribution of aggregates for HMA-DRY mixes

Passing	Filler <0.063 [%]	Sand 0.063/4 [%]	fØ5-10mm 0.063/8 [%]	fØ10-15mm 0.063/11.2 [%]	fØ20-25mm 5.6/22.4 [%]	fØ25-30mm 5.6/31.5 [%]	∑components [%]
RFI_HMA	12.24	24.60	5.21	18.29	18.49	21.16	100.00
Γ_{mix}=	2.740g/cm^3					Γ_{aggr}=	2.809g/cm^3
DRY 1.5%	12.45	23.79	4.62	18.98	18.65	21.52	100.00
Γ_{mix}=	2.716g/cm^3					Γ_{aggr}=	2.808g/cm^3
DRY 2%	12.52	23.51	4.42	19.21	18.70	21.65	100.00
Γ_{mix}=	2.700g/cm^3					Γ_{aggr}=	2.808g/cm^3
DRY 3%	12.66	22.94	4.01	19.69	18.80	21.90	100.00
Γ_{mix}=	2.687g/cm^3					Γ_{aggr}=	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 the Fuller maximum density curve), is calculated using (2):

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

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 limits established by the sub-ballast standard, RFI [13]. The aggregate gradation is shown on the 0.45 power chart (Fig. 7).

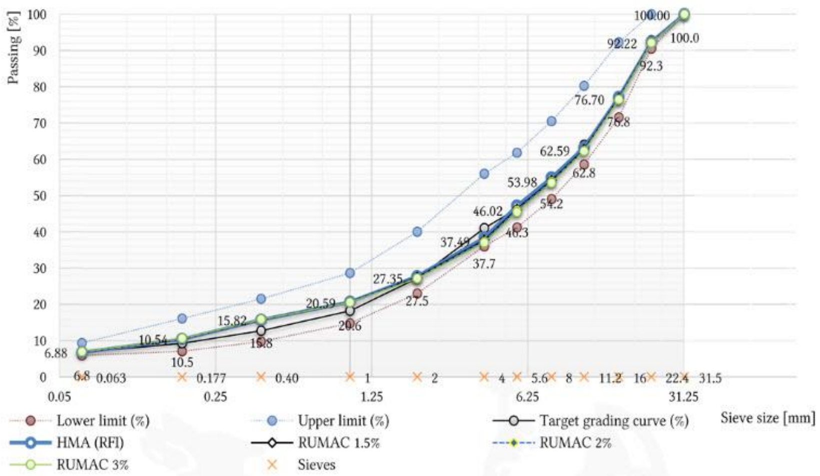


Fig.7 Grain-size curves (Target limits)

Asphalt binder properties

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 ºC, in this study the asphalt binder used is identified with a viscosity grade reference AC-20. Other properties were the 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.

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, Palermo (Italy). 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 Ø0.4-2mm and Ø2-4mm (Fig. 8).

- 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 ºC for mixing and 145 ºC and 160 ºC 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/cm^3 is used.
- 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 ºC for future testing.

Fig.8 Sieve analysis of the rubber from discarded truck-tires

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 4.

Table 4. Characteristics of the materials used for the bituminous sub-ballast production

Bitumen			
Properties		Standard	Value
Penetration at 25°C		EN1426:2007	53
Penetration index [-]		EN12591 Annex A	-0.575
Softening point [°C]		EN1427:2007	50
Bulk gravity [g/cm^3]		EN 15326:2007	1.033
Viscosity at 150ºC [Pa·s]		ASTM D2493M-09	0.195
Equiviscosity values by Brookfield viscosim. [°C]	0.28Pas	EN 12695:2000	143.1
	0.17Pas	AASHTO T316-04	156.2
Aggregates *(limestone)*			
Properties		Standard	Value
Los Angeles abrasion loss [%]		EN 1097-2:2010	20.8
Density coarse aggregates [g/cm^3]		EN 1097-3:1998	2.82
Density sand [g/cm^3]		EN1097-6:2013	2.84
Density 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		
Tª water: 27ºC (ρ. 1.00025 gr/cm3)	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/cm3)		1.154

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). 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 [40].

These are mainly dense, and gap-graded asphalt concrete mixes to which scrap tire rubber are 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 intimate mixing of asphalt cement, are referred as “asphalt concrete rubber filled” or “rubber modified asphalt concrete mixes (RUMAC).”

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 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 10).

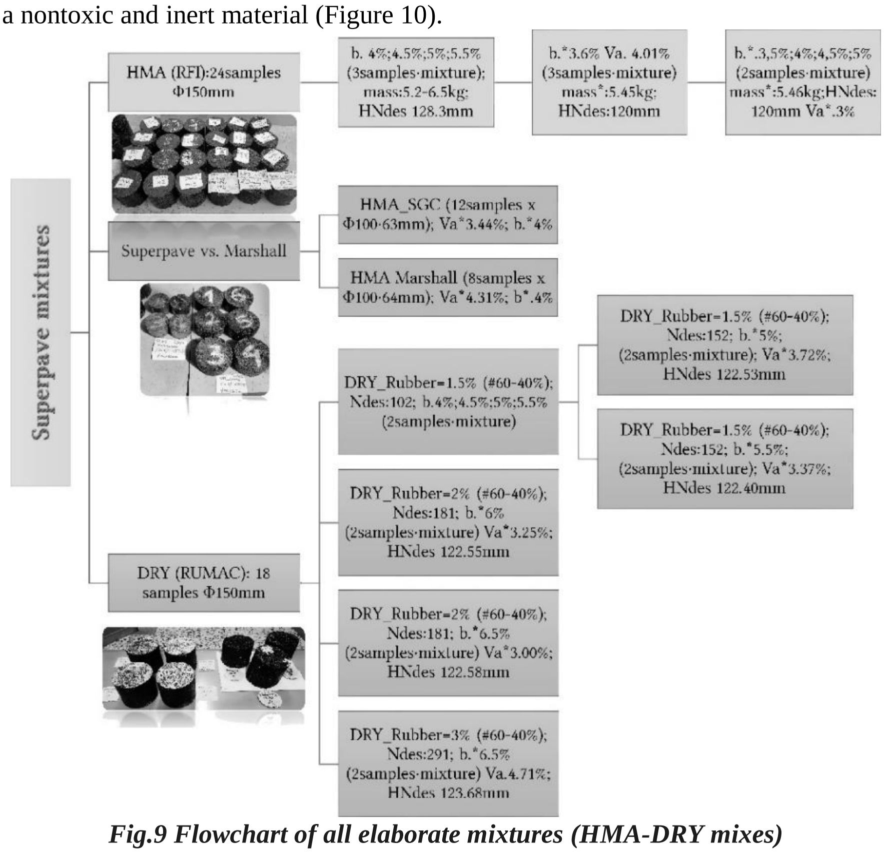


Fig.9 Flowchart of all elaborate mixtures (HMA-DRY mixes)

Fig. 1 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 5). 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 rubber of 1.5%, 2%, and 3%.

Table 5. Constitution of the theoretical recipes for rubber modified mixes

	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

So, for summary, in 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. 11a);
- DRY RUBBER 1.5% #60_40 N_{des}.102, b.4%, 4.5%, 5%, and 5.5%, with a best air voids content of $Va^{*}3\%$ (Fig. 11b).

Each curve corresponds to the mean of two samples manufactured in the laboratory of the same mixture.

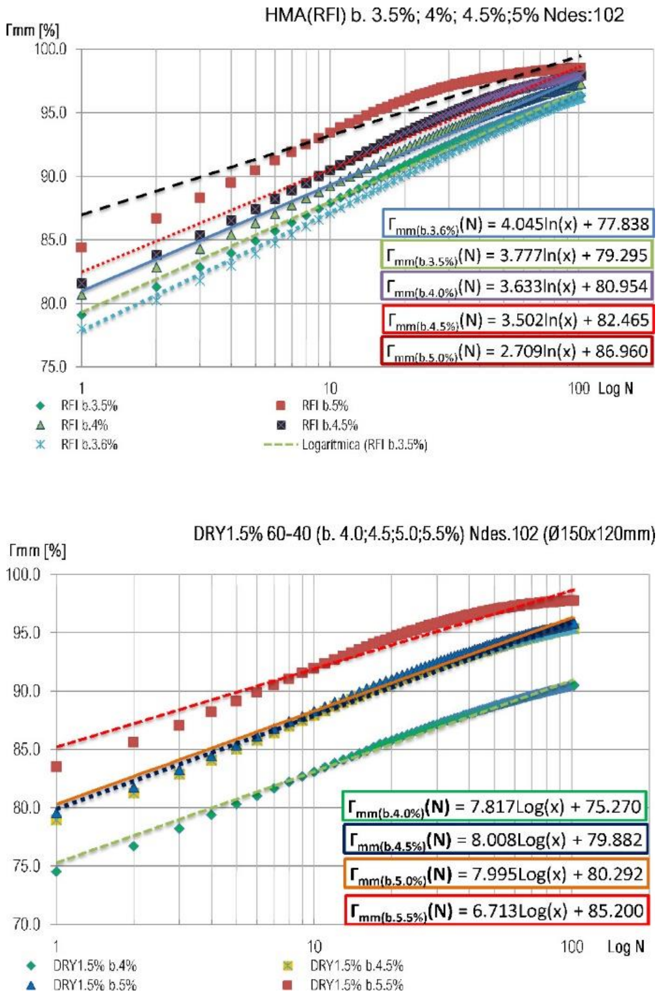


Fig. 11 Densification curves for HMA and DRY1.5% mixtures both at Ndes.102

From the graphs, the average regression equations were:

$HMA_{RFI\ (b.3.5\%)} \rightarrow \Gamma_{mm}\ (N_{des.}\ 102) = 8.697Log(x) + 79.295$

$HMA_{RFI\ (b.3.6\%)} \rightarrow \Gamma_{mm}\ (N_{des.}\ 102) = 8.314Log(x) + 77.838$

$HMA_{RFI\ (b.4.0\%)} \rightarrow \Gamma_{mm}\ (N_{des.}\ 102) = 8.365Log(x) + 80.954$

$HMA_{RFI\ (b.4.5\%)} \rightarrow \Gamma_{mm}\ (N_{des.}\ 102) = 8.065Log(x) + 82.465$

$HMA_{RFI\ (b.5.0\%)} \rightarrow \Gamma_{mm}\ (N_{des.}\ 102) = 6.238Log(x) + 86.960$

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

DRY1.5 $_{(b.4.5\%)}$ $\rightarrow \Gamma_{mm}$ ($N_{des.}$ 102) = 8.008Log(x) + 79.882
DRY1.5 $_{(b.5.0\%)}$ $\rightarrow \Gamma_{mm}$ ($N_{des.}$ 102) = 7.995Log(x) + 80.292
DRY1.5 $_{(b.5.5\%)}$ $\rightarrow \Gamma_{mm}$ ($N_{des.}$ 102) = 6.713Log(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 the equation (3):

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

Where:

- Γ_{mm} is the averaged specimen relative density of N_{des} (%);
- Γ_1 is the relatively specific density of energy accumulated during the compaction (%);
- k is the workability of the mixture (-).

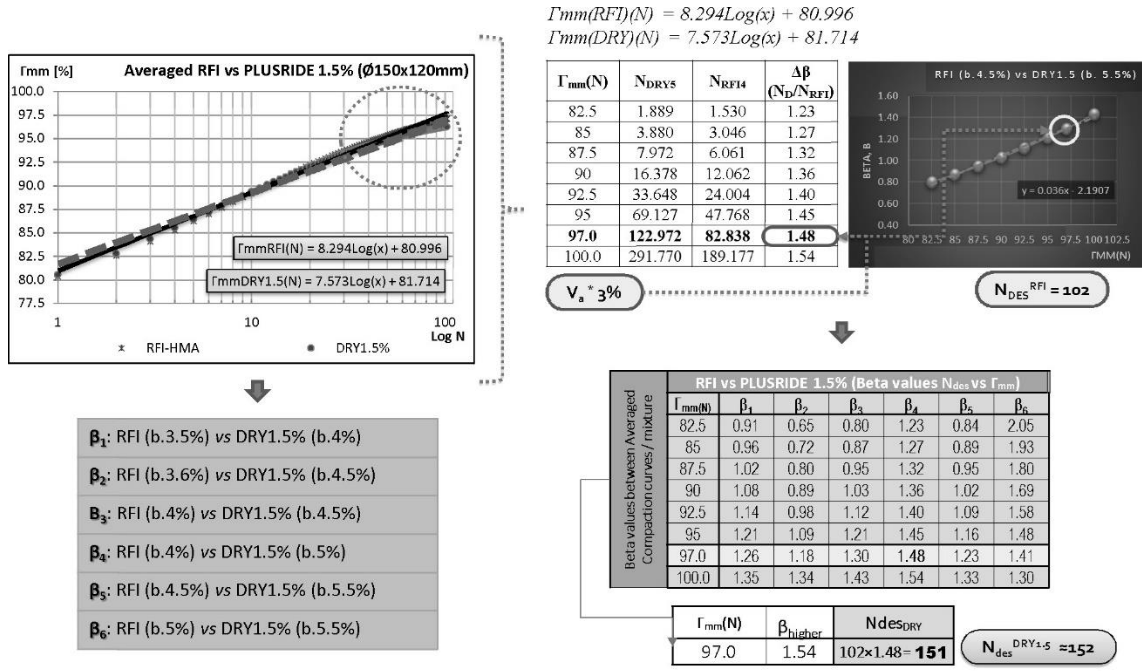
EMPIRICAL APPROACH: RESULTS AND DISCUSSION

Volumetric mix-design asphalt mixtures

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. In the next section is explained this methodology to reach successful results of compaction as HMA as DRY blends.

Beta factor

Thus, the method that responds to an approximation based on laboratory (empirical) results is summarized in Fig. 12 as an average example of both mixtures where the following process is observed.



$\Gamma_{mm}(N)$	N_{DRY5}	N_{RFI4}	$\Delta\beta$ (N_D/N_{RFI})
82.5	1.889	1.530	1.23
85	3.880	3.046	1.27
87.5	7.972	6.061	1.32
90	16.378	12.062	1.36
92.5	33.648	24.004	1.40
95	69.127	47.768	1.45
97.0	**122.972**	**82.838**	**1.48**
100.0	291.770	189.177	1.54

RFI vs PLUSRIDE 1.5% (Beta values N_{des} vs Γ_{mm})						
$\Gamma_{mm(N)}$	β_1	β_2	β_3	β_4	β_5	β_6
82.5	0.91	0.65	0.80	1.23	0.84	2.05
85	0.96	0.72	0.87	1.27	0.89	1.93
87.5	1.02	0.80	0.95	1.32	0.95	1.80
90	1.08	0.89	1.03	1.36	1.02	1.69
92.5	1.14	0.98	1.12	1.40	1.09	1.58
95	1.21	1.09	1.21	1.45	1.16	1.48
97.0	1.26	1.18	1.30	**1.48**	1.23	1.41
100.0	1.35	1.34	1.43	1.54	1.33	1.30

$\Gamma_{mm}(N)$	β_{higher}	$Ndes_{DRY}$
97.0	1.54	102×1.48= **151**

Fig. 12 Example of the "beta factor" approach method (HMA-DRY1.5% blends)

At the critical level in this article, it has been limited to develop two of the six interactions made to summarize the method thus shows two cases study ("beta 4 and 5") since with the other combinations proceed in the same way, thus avoiding successive figures of excessive development. Also, these are the most representative cases since that corresponds to the best recipes of bitumen content developed (b. 4-4.5%). 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. 11, by clearing the unknown "x" corresponding to the number of gyrations so that each mixture reaches 3% of air voids (e.g.):

$$HMA_{b.4\%} : 97\% = 8.365 Log(x) + 80.954 \rightarrow antiLog(x) = \left(\frac{97-80.954}{8.365}\right) = 82.838 \quad (4)$$

$$DRY_{b.5\%} : 97\% = 7.995 Log(x) + 80.292 \rightarrow antiLog(x) = \left(\frac{97-80.292}{7.995}\right) = 122.97 \quad (5)$$

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.

Beta 4 (HMA b.4% vs. DRY1.5% b.5%)

Above, the actual values of each mixture of %Va (percentage of air voids) with a binder at 4% to mix at 102 cycles are shown, as well as the compaction curves (Fig. 14) of each two samples of each mixture and its corresponding average regression curve (Fig. 13).

Averaged compaction curves

$\Gamma_{mm}(N)$	N_{DRY5}	N_{RFI4}	Δβ
82.5	1.889	1.530	1.23
85	3.880	3.046	1.27
87.5	7.972	6.061	1.32
90	16.378	12.062	1.36
92.5	33.648	24.004	1.40
95	69.127	47.768	1.45
97.0	122.972	82.838	1.48
100.0	291.770	189.177	1.54

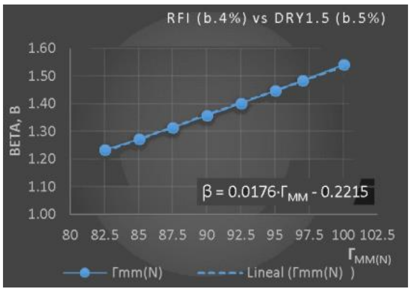


Fig. 13 Beta values and regression curve(case study β4)

As can be seen, a first conclusion is that to obtain the same degree of compaction at the same number of gyrations with SGC, we must consider between 0.5% and 1% more bitumen content in the mixtures with the recycled rubber of 1.5% to 2%. Also, 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 Volumetric mixing methodology [28].

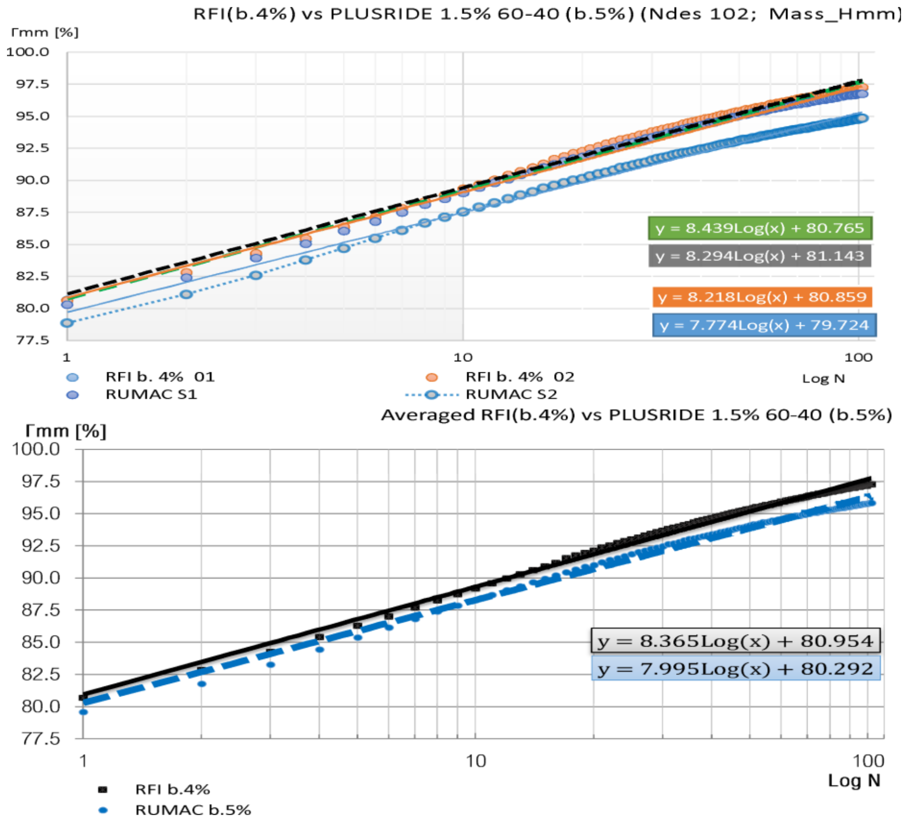


Fig. 14 Example of comparison between the compaction curves of CRM-1.5 with 5% of bitumen and the traditional HMA mixture with 4% of bitumen

Beta 5 (HMA 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 6).

Table 6. Summary of regression curves for each specimen and mixtures (HMA b.4.5% vs. DRY1.5 b.5.5%)

Sample 01 HMA	$\Gamma_{mm}(HMA_{sample1}$ b.4.5%)(N)	= 7.596Log(x) + 83.409
Sample 02 HMA	$\Gamma_{mm}(HMA_{sample2}$ b.4.5%)(N)	= 8.529Log(x) + 81.521
Sample 01 DRY	$\Gamma_{mm}(DRY_{sample1}$ b.5.5%)(N)	= 6.394Log(x) + 84.763
Sample 02 DRY	$\Gamma_{mm}(DRY_{sample2}$ b.5.5%)(N)	= 7.032Log(x) + 85.638
Avg. HMA	$\Gamma_{mm}(HMA_{avg.}$ b.4.5%)(N)	= 8.064Log(x) + 82.465
Avg. DRY	$\Gamma_{mm}(DRY1.5_{avg.}$ b.5.5%)(N)	= 6.713Log(x) + 85.200

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 7 and Figure 15. 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 7. Summary of beta factors for case study "Beta 5"

$\Gamma_{mm}(N)$	$N_{DRY5.5}$	$N_{HMA4.5}$	Δβ
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 a valid value (air voids between 3-4%).

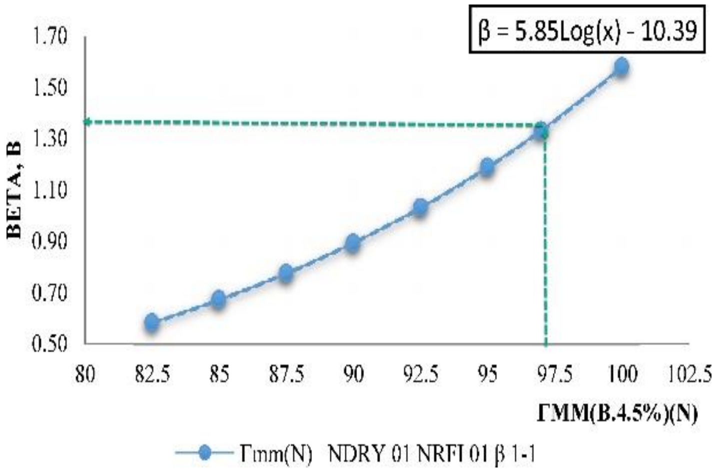


Fig. 15 Example of "beta factor 5" (HMA B.4.5% VS. DRY1.5 B.5.5%)

The densification curves respectively are represented in figure 16:

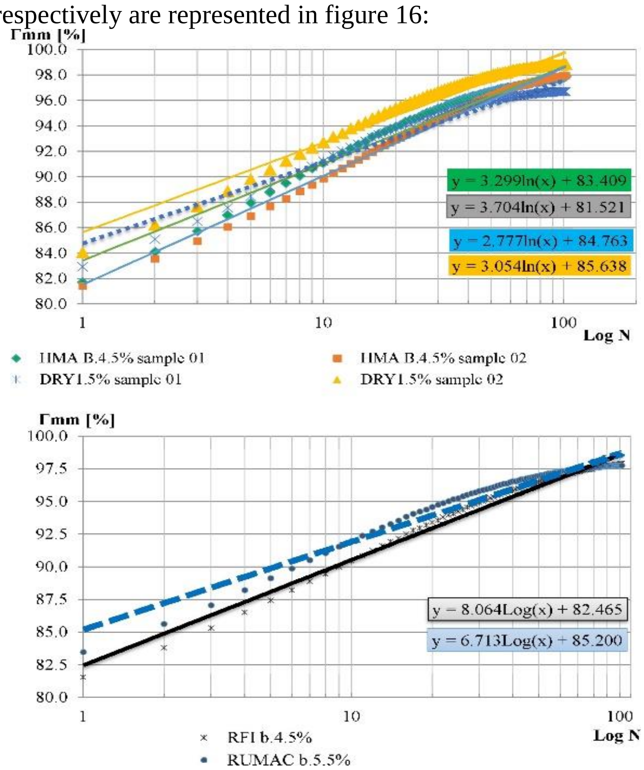


Fig. 16 Densification curves (HMA B.4.5% VS. DRY1.5 B.5.5%); (a) Each sample; (b) Averaged as Log(N_{des})

"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.

By proceeding sequentially with each combination mentioned above and making the respective table of values "beta" for each two samples by mixing, a cloud of points is obtained. Graphically shows the average value that must be adopted to establish a final beta between a conventional mixture HMA and a mixture with DRY1.5% rubber (Fig. 17).

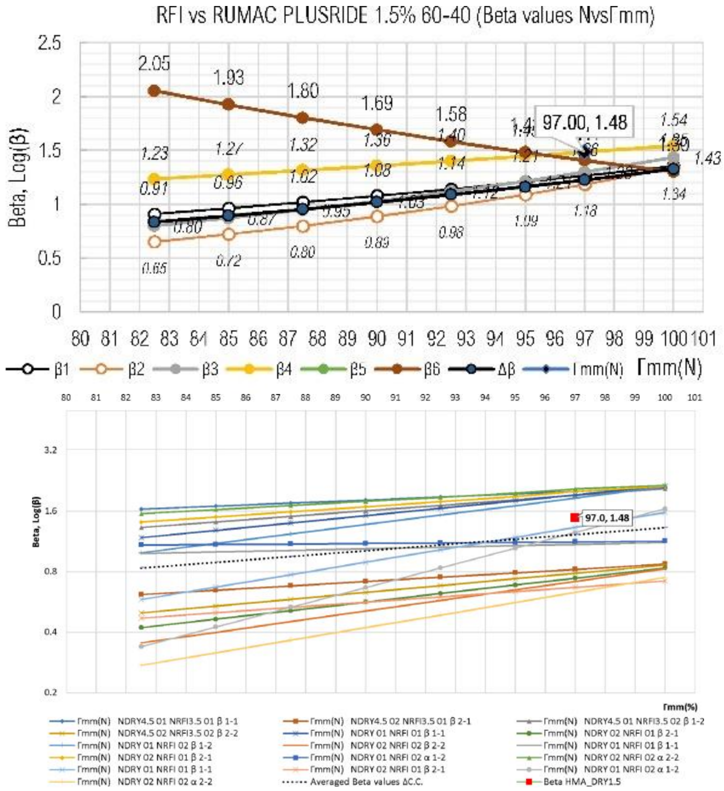


Fig. 17 (a)Curves of "beta" values for each combination of avg. HMA vs. DRY1.5%; (b) Regression curves for "beta" values for each combination of 2 samples per mixture HMA vs. DRY1.5%

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 · 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 and procedure are shown in Fig. 18.

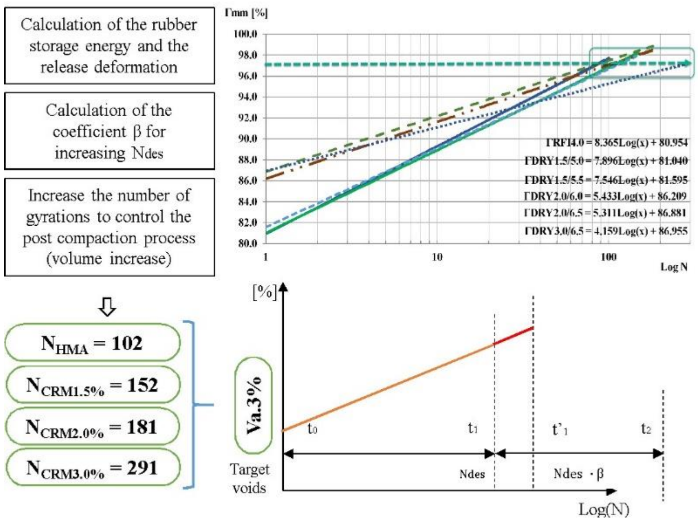


Fig. 18 Optimization of rubber-aggregate mixtures with "beta" factors and scheme of regression curves

It is observed that in order to reach the same degree of compaction, therefore, a percentage of internal voids of 3-4%, the bitumen content must be increased by around two decimals of binder with respect to the conventional bitumen. In addition to this the number of gyrations was increased, N_{des}, applying a factor of 1.21 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 8).

Table 8. 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

CONCLUSION

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 seven 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. 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 (135-150ºC), aggregates (160-190ºC) and compaction molds (150ºC) heated to the proper mixing temperature according to the mixture type. Then, before being removed, each sample must be stored at room temperature (20ºC) 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.

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