Increased Stability of Rubber-Modified Asphalt Mixtures to Swelling, Expansion and Rebound Effect during Post-Compaction

Fernando M. Soto, Gaetano Di Mino

Abstract**—** The application of bituminous mixtures modified with rubber from scrap-tires require attention and care during mixing and compaction. Rubber modifies the properties because it reacts in the internal structure of bitumen at high temperatures changing the performance of the mixture (interaction process of solvents with binder-rubber aggregate). The main change is the increasing of the viscosity and elasticity of the binder due to the larger sizes of the rubber particles by dry process but, this positive effect is counteracted by short mixing times, compared to wet technology, and due to the transport processes, curing time and post-compaction of the mixtures. Therefore, negative effects as swelling of rubber particles, rebounding effect of the specimens and thermal changes by different expansion of the structure inside the mixtures, can change the mechanical properties of the rubberized blends. Based on the dry technology, different asphalt-rubber binders using devulcanized or natural rubber (truck and bus tread rubber), have been used to show how these defects occur and, at the same time, to solve the problems generated in dense-gap graded rubber modified asphalt concrete mixes (RUMAC) to enhance the stability, workability and durability of the compacted samples by Superpave gyratory compactor method. This paper specifies the procedures developed in the Department of Civil Engineering of the University of Palermo during September 2016 to March 2017, for characterizing the post-compaction and mix-stability of the one conventional mixture (hot mix asphalt without rubber) and two gap-graded rubberized asphalt mixtures, adopting the granulometric characteristic grading curve for rail sub-ballast layer, with nominal size of Ø22.4 mm of aggregates according European standard. Thus, the main purpose of this laboratory research is the application of ambient ground rubber from scrap tires processed at conventional temperature (20 ºC) inside hot bituminous mixtures (160-220 ºC) as a substitute for 1.5%, 2% and 3% by weight of the total aggregates (3.2%, 4.2% and, 6.2% respectively by volumetric part of the limestone aggregates of bulk density equal to 2.81 g/cm^3) considered, not as a part of the asphalt binder. The reference bituminous mixture was designed with 4% of binder and ±3% of air voids, manufactured for a conventional bitumen B50/70 at 160 ºC-145 ºC mix-compaction temperatures to guarantee the workability of the mixes. The proportions of rubber proposed are #60-40% for mixtures with 1.5 to 2% of rubber and, #20-80% for mixture with 3% of rubber (as example, a 60% of Ø0.4-2 mm and 40% of Ø2-4 mm). The temperature of the asphalt cement is between 160 and 180 ºC for mixing and 145 and 160 ºC for compaction, according the optimal values for viscosity using Brookfield viscometer and "ring and ball" - penetration tests. These crumb rubber particles act as a rubber-aggregate into the mixture, varying sizes between 0.4 mm and 2 mm in a first fraction, and 2 and 4 mm as second proportion. Ambient ground rubber with a specific gravity of 1.154 g/cm^3 is used. The rubber is free of loose fabric, wire and other contaminants. It was found optimal results in real beams and cylindrical specimens with each HMA mixture reducing the swelling effect. Different factors as temperature, particle sizes of rubber, number of cycles and pressures of compaction that affect the interaction process are explained.

Keywords**—**Crumb-rubber, Gyratory Compactor, Rebounding Effect, Superpave Mix-Design, Swelling, Sub-ballast Railway.

I. INTRODUCTION

SCRAP tire rubber (STR) can be incorporated into asphalt mixtures in two different methods or techniques, which are referred to as the wet-dry process. The blending of recycled rubber with asphalt cement has been used for years and several manufacturing processes have been developed in Europe as well as in the United States [1]. However, all these processes have a major drawback: the rubber aggregate or rubber modified asphalt concrete must be used within a few hours after being manufactured.

The environmental objectives are the disposal of discarded tires and the reduction of landfill use. In the field of railways, the dry technological process involved the use of crumb rubber followed by the mechanical characterization of the asphalt concrete in terms of the fatigue resistance and the stiffness modulus, both are necessary to use an exclusively mix-design method for the sub-ballast railway material, even more if the asphalt concrete investigated is an innovative material such as a dry asphalt rubber concrete [2].

The dry process is normally used as a fraction of the coarse-fine aggregate [3]. Recent studies have been carried out with the aim of finding an alternative material that is used as a modifier improving mechanical properties inside the asphalt mixtures. 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 [4].

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 [5].

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A. State of the Art: Rail Bituminous Sub-Ballasted Track

The sub-ballast layer acts as a foundation to the superstructure (i.e. rails, sleepers and ballast) and carries the loads caused by the vehicles to the ground underneath. Therefore, it is a key element within the track, and its performance dramatically affects the reliability and durability of the whole infrastructure. The materials available and commonly used in the railway sub-ballast correspond to the same aggregates ordinarily specified and used in the construction of road bases and sub-bases. These include crushed stone, natural or crushed gravels, natural or manufactured sands, crushes slag or a homogeneous mixture of these materials. Fig. 1 shows the importance of sub-ballast layer. The thicker the sub-ballast is, the larger the area that can be used to withhold the force because the stress is distributed horizontally with depth.

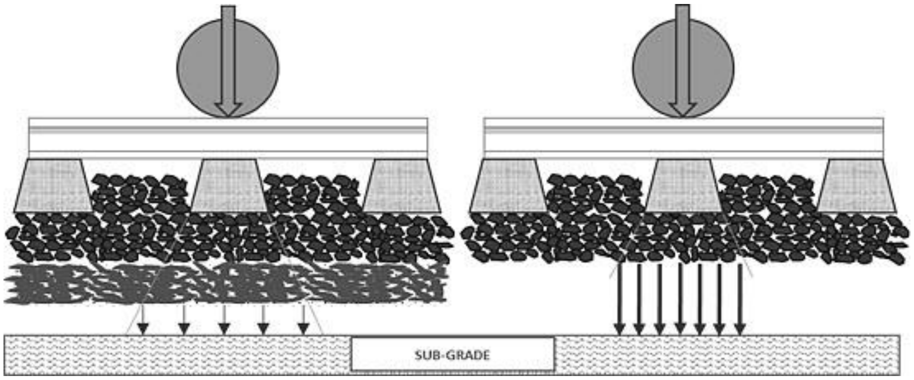


Fig. 1 Sub-ballast as a stress reducer (Adapted from [11])

Bituminous mixtures consist primarily of mineral aggregates, asphalt binder, and eventually additives. The mechanical properties of a bituminous mixture are dependent on the nature and the amount of the components. It is important to have suitable proportions of asphalt binder and aggregates to develop mixtures that have desirable properties associated with superior performance such as resistance to permanent deformation, fatigue cracking, and low temperature cracking [6].

The use of bituminous mixtures in sub-ballast undoubtedly provides several advantages, such as:

- Low production costs;
- High quality physical and mechanical characteristics (resistance and modulus), which tend to increase in time due to the fact that the calcium carbonate in natural aggregates dissolves thereby ensuring that the layer becomes homogenous and stress can be apportioned;
- Waterproof;
- Environmental problems involved in finding the necessary natural aggregates;
- Sensitivity to freezing and the fact that work cannot be carried out below certain temperatures;
- The optimum durability of the layer is ensured, since vehicle traffic is not allowed until the end of the compaction process, and;
- The surface of the layer allows to add extra protection thanks to the application of bituminous emulsions to the atmospheric agents.

B. Problem Statement

Tires out of use have proven to be one of the most problematic environmental issues in recent years. With landfills reducing their acceptance of whole tires and the health risks, new markets have been created for scrap tires. Significant progress has been made regarding its reuse to improve the performance of binders and bituminous mixtures. In fact, the same characteristics that make waste tires problematic, their availability, bulk, and resilience, also make them attractive targets for recycling.

Thus, crumb-ground rubber by a mechanical trituration process until reaches a 0.6-4 mm particle size, is being used in tire-derived fuel, in modified binders and polymer products, in agricultural uses, recreational and sports applications. In this research, the field of application has been the sub-ballasted track structured (see Fig. 2).

In this regard, STR application has achieved significant use in diverse applications in civil engineering [7], [8], particularly in the road and rail sector. For example, they constitute one of the most successful elastic wastes in railway pad manufacturing [9], and are suitable in bituminous mixes, as a modifier of their mechanical properties.

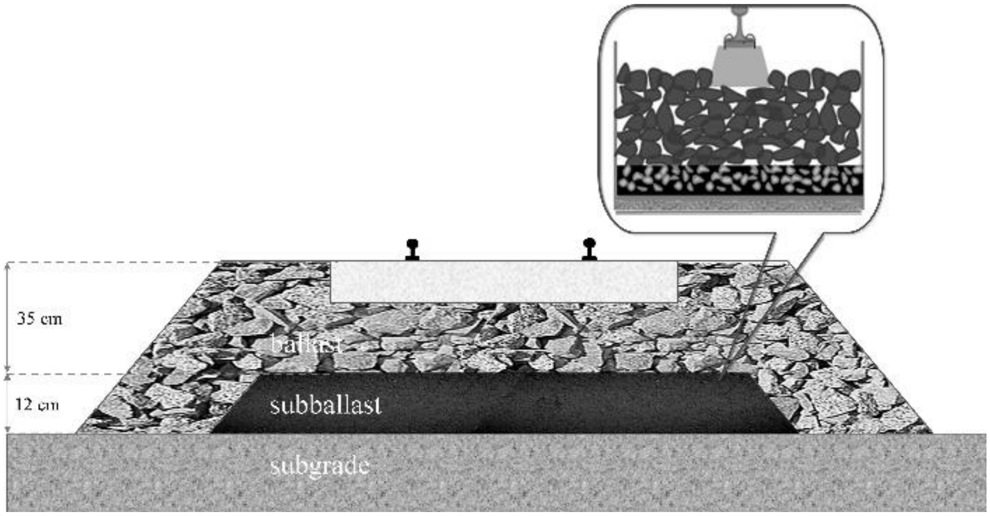


Fig. 2 Sub-ballasted track rail section with asphalt layer

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 mixture, the compaction temperature, the time of digestion and, the way in which the recycled rubber reacts with the bitumen at high temperatures [10].

In this case, one of the main purposes in this research is the development of tests of bituminous hot mix asphalt mixtures and, its subsequent curing, minimizing the effects derived from the rubber-bitumen interaction. To validate these results, different rubber-bitumen ratios have been used to evaluate the amount of bitumen absorbed by the rubber during the digestion process. Therefore, it is important to understand the interaction process or reaction between asphalt cement and crumb rubber modifier (Ø0.4-2 mm) when blended together. The reaction, defined as polymer swell, is not a chemical reaction. It is the absorption of aromatic soils from the asphalt binder into the polymer chains of the crumb rubber [12].

The thermal susceptibility of the binder is very important because it indicates the proper mix and compaction temperatures. Also, the optimal content of dust filler is doubtful to be a master contributor to fatigue failure where its content has a significance effect on the stiffness, and thereby affect the HMA sub-ballast performance [13].

In this study, the combined effect of test and mix-design temperatures, traffic loadings due to the rail traffic spectrum, and following a reviewed-stablished protocol for an optimal mix-design according gyratory compactor [14] procedure (Superpave asphalt mixtures, SGC [15]) were investigated on different mixtures; a common hot-mix asphalt for sub-ballast layer and, two different rubberized asphalt concrete mixtures (RUMAC).

Each of the blends has been designed and optimized during the manufacturing phase to improve the performance of the rail sub-ballast layer, against heavy traffic and against maximum loads on high speed lines. The final purpose is to withstand constant fatigue and permanent deformation efforts during the life of the railway line.

The volumetric properties, for the HMA mixture mix design method, are evaluated using Marshall Test and the Superpave Gyratory Compactor as an additional measure of control.

C. Contextualization

The use of rubber-modified bituminous mixtures of recycled tires is a special consideration both during mixing and during compaction. The rubber, in its different forms (vulcanized natural, synthetic rubber ...), and independently of the size of the particles, it interacts with bitumen, partly dissolved by means of the process of imbibition or rather, by diffusion process.

The diffusion's theory says that after the maturation process of the mixture, the recycled rubber has increased its size due to the swelling process, product of the absorption of the molecular liquids released by bitumen during digestion.

Based on the methodology applied in this study, the consequence of increased viscosity and higher elasticity of the final blends were study. A greater effect is appreciated when the size of the rubber particles is greater, by the dry process.

The rubber particles in dry mixes absorb the stresses due to the thermal changes, thereby increasing the resistance to cracking and avoiding the structural expansion. In addition, laboratory studies developed have indicated changes on the mechanical properties of the rubberized mixtures.

The rubber granules exposed in surface slightly compress when subjected to traffic loads. This produces a small area of flexibility which makes the appearance of micro-cracks due to the expansion and rebound effect inside the mixtures.

Considering, therefore, the dry technology, the use of different percentages of binder - content of recycled rubber and, analyzing that the origin of the rubber is of heavy vehicles, the consequences of the swelling, rebound and, expansion effects after the mixture are explained through Superpave.

D. Objectives

One of the main objectives has been to study the viability of using bituminous mixtures manufactured with recycled materials such as crumb rubber from truck-bus tires (natural rubber) as sub-ballast in railways track to obtain sustainable and environmentally alternatives to asphalt products [16].

The aim of the first step pf this study was to define the procedures developed in laboratory to avoid problems with the lab preparation of RUMAC mixtures (rubber modified asphalt concrete mixes). For this purpose and for characterizing the post-compaction and mix-stability, one dense graded hot-mix asphalt without rubber (HMA) mixture, two dense-gap graded rubberized mixtures with 1.5% to 2% of rubber by total weight and, one generic dry (dense-graded aggregate) by adding up to 3% by mass of fine-course rubber particles were tested.

For preparing the RUMAC mixes, the rubber at ambient temperature (20ºC) was mixed with the hot aggregates (160-220ºC). The design of these mixtures was in accordance with the Italian standard for sub-ballast layer, which determines a granulometry with nominal size of Ø22.4 mm. These mixes were mixed by adopting the Superpave (Superior Performing Asphalt Pavements program) at level III, depending upon the traffic loads (ESALs) and environment (max/min air temperatures).

There are two technologies in the dry method depending on the STR and aggregate gradations: *Plusride* and *Generic dry* technologies. To analyze the effect of rubber on the cohesion of the bituminous mixes, two gradations of rubber were used, one with a diameter of 0.4-2mm (f1) and, another one with a dimeter of 2-4mm (f2). Also, a different particle size distribution was proposed. The *Plusride* dense graded mixtures used a distribution called "60-40" (i.e. 60% of Ø0.4-2mm and 40% of Ø2-4mm rubber size), on the other hand, *Generic* mixtures used a "20-80" distribution (i.e. 20% of Ø0.4-2mm and 80% of Ø2-4mm rubber size).

In the study carried out in this work, the effects due to swelling, rebounding and non-uniform deformation in the post-compaction stage are analyzed from a practical point of view.

Several dense-gap graded asphalt mixtures modified with rubber (maximum aggregate size of 22-25 mm) and, all with the same type of bitumen, were designed for the realization of an optimum dry method, which in the experimental phase, is validated through the compaction curves by Superpave gyratory compactor, adopting as air voids target value 3%. Then, other mechanical characterization tests, such as indirect tensile strength, water sensitivity and Marshall stability, were performed in the laboratory to comply with European regulations.

The parameters for volumetric compaction using Superpave are established by prior calculations of internal stresses and stresses using Kentrack software of a rail model with 12cm thick sub-ballasted bituminous layer for a 50-year life cycle, intense traffic in high-speed lines and a temperature range of 0 to 35ºC, with a traffic increase rate of 1%.

Attention is paid to the structural stability of the mixtures from the compaction phase to 7 days, during which deformation effects are observed due to the accumulated internal energy of the recycled rubber. Finally, a valid protocol of execution for mix-design of asphalt rubber mixtures following the dry process is proposed. Design considerations and performance are discussed.

II. PROBLEM STATEMENT

A. Interaction of bitumen with rubber

The utilization of crumb rubber in asphalt mixture has significantly evolved in the past few decades. The increasing usage of crumb rubber in hot mix asphalt (HMA) requires a better understanding of its effect on the physical, chemical, and rheological properties of rubberized binders.

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. The aim of this study is to demonstrate a different thought by controlling the reaction rubber-bitumen. 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].

The basis of the dry technique is to replace a volumetric proportion of rubber modifying the aggregate content, in particular sieve fractions of the grading curve. Depending on the gradation, proportion and density of the rubber, a different reaction between bitumen-rubber will occur. The interaction of rubber-bitumen makes the bonder stiffer and elastic and, consequently, changes the properties of the asphalt mixture.

It is common not to achieve uniform distribution of the rubber particles throughout the mix when adding it as a dry-filler inside a HMA mixture (120-190ºC). Distresses as early cracking, raveling or potholes will be found in the case of the rail with sub-ballast will cause defects in the regular level of the track as is shown in Fig. 3.

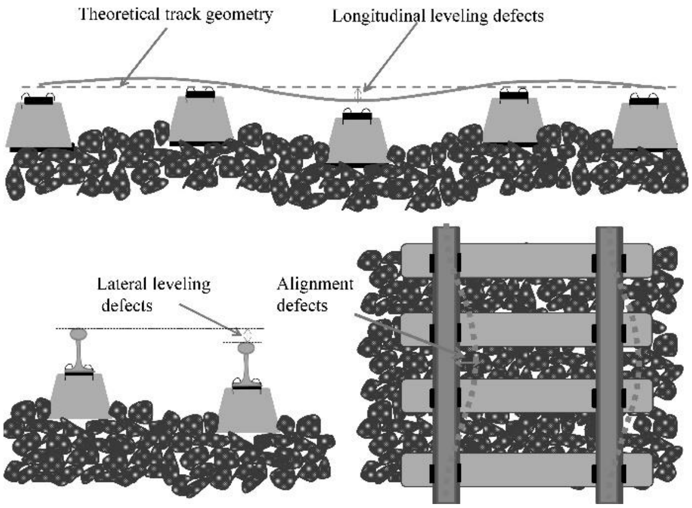


Fig. 3 Distresses caused by lateral defects, fatigue cracking and potholes of the rail track

The dry process has been used by many agencies but disregarding the manufacturing methodology in all stages, and performing the mixtures in industrial mode, problems are always the same, inconsistency of the mixtures [18], low durability and high void content.

It is difficult to achieve uniform distribution of the crumb rubber 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, in other words, diffusion or the process of imbibition of the solvent into the polymer is not happening [19].

This effect causes a concentration of clusters of rubber inside the mixture after compaction, because of heterogeneous densities, not enough energetic gyrations during Superpave mix-design and/or due to a decrease of temperature during mixing. In Fig. 4 is shown this effect on some sections of cut specimens during the rubberized mixtures with 1.5 to 2% of rubber and binder content 5.5 to 6% developed.

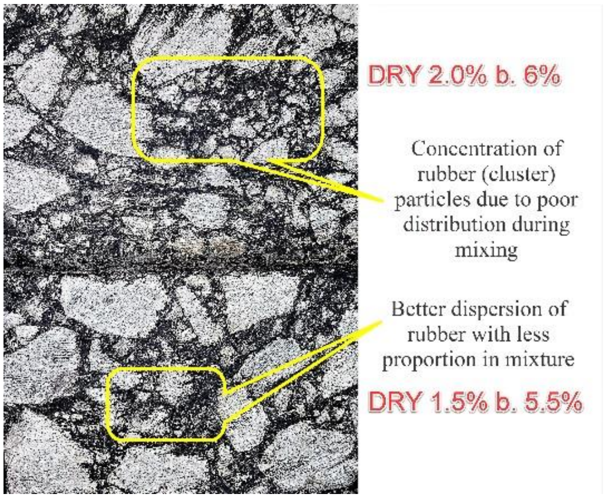


Fig. 4 Concentration of rubber without mixing properly in different sections of the mixtures studied

B. Swelling of crumb rubber in bitumen

In the wet process, smaller sizes of rubber acts as a bitumen modifier where the reaction time is longer. However, viscosity and elasticity of the binder increased [20].

The dry process, on the other hand, uses rubber particles in several ways (ambient or wet; grinding or granulating) in terms of economics and particle size distribution inside the mixtures. Reaction time is usually shorter, therefore, the effect of swelling of rubber particles is different from the wet mixtures as the binder modified and rubber swelling changes the mechanical properties.

The swelling tests results developed in this research, confirmed that a higher temperature, lighter portions of bitumen are absorbed by the rubber through the diffusion process. The consequence is a residual bitumen becomes stiffer and rubber is more elastic but, the performance of the final mixture is affected due to the changes in the mixture resulting from the mechanical variations of each integral material.

The effect is considered in the Fig. 5 as an example produced in laboratory with preliminary mixtures with rubber.

Fig. 5 Swelling effect on rubber-modified HMA samples of Ø150x120mm manufactured according Superpave SGC

A partial replacement in volumetric proportion of aggregates is always the most important step inside the mixture, if you are mixing different sizes and sieves for aggregate-rubber, independently if the rubber available is vulcanized (no treatment by heat, pressure or softening agents to alter the chemical composition) or devulcanized (treatment by heat) providing differences in mixing ratio, reduction in viscosity, mixing time and mixing temperature-compaction, according to the equi-viscosities values of the bitumen.

Swelling depends mainly on test temperature, rubber particle size, loading frequency, bitumen type, liquid-viscosity and, the amount of bitumen concentrated:

- Temperature has different reactions on swelling if rubber constitution does not change. If the temperature increases during mixing, the subsequent swelling effect increases because the rubber-bitumen composition has already occurred, because of solvent input into the network. A higher mixing energy would be required to maintain the molecular structure.
- If the constitution of rubber is changed at high temperature during reaction, the maximum amount of

swelling will be increased too and, the specimen will be weakened as the effect will cause an increase in height during post-compaction, increasing the percentage of internal voids [21].

- *Thin or small particles of rubber will swell quickly than thicker particles. The rate of swelling is faster for smaller particles and the maximum amount of swelling is lower for bigger particles.*
- *The dust proportion (dust/asphalt ratio) and the filler content, are parameters that also influence on swelling with the effect of rubber-liquid interaction. Excessive dust or filler reduces durability and asphalt thickness film, which result in unstable mixes.*
- *The penetration rate of solvent in rubber increases with decreasing viscosity of the bitumen and, this fact also depends on the degree of concentration present in the mixture.*

In Fig. 6 is explained that rubberized mixture needs a curing period to complete the swelling and to stabilize.

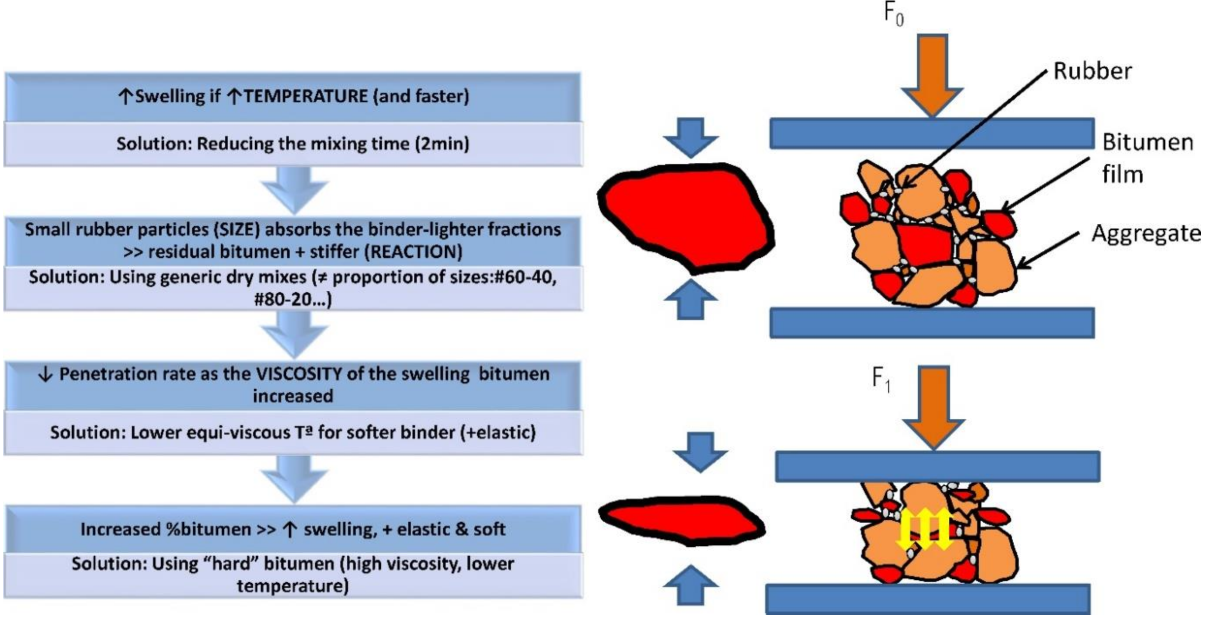


Fig. 6 Schematic representation of the swelling effect and effects

C. Rebounding effect after compaction

Swelling is a physical process, in which crumb rubber particles absorb some of the light fractions of asphalt and swell [22]. But the interaction process between rubber and asphalt can generally occur simultaneously with degradation of the mixture due to the rebounding effect, whose devastating effect can be seen in Fig. 7.

Fig. 7 Post-compaction deformation by rebound effect with rubber mixtures compacted with gyratory compactor

After compaction, prepared specimens undergo a dilation (a bounce-back effect) during the curing period (first 24h 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.

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 mixture (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).

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 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 of volume and additional voids (Fig. 8).

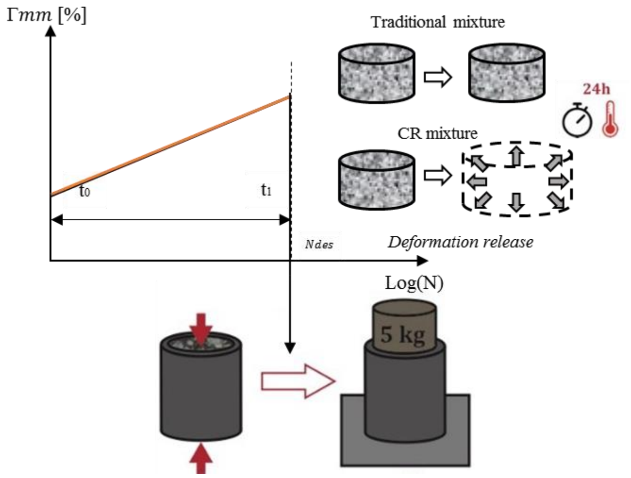


Fig. 8 Superpave densification curve. Rebounding effect after compaction. Schematic proposed solution (see ref. [21])

D. Non-uniform expansion (Confinement)

During the experimental development, it was observed that coring from slabs or cylindrical samples with excessive height (remember that the use of HMA to replace the granular sub-ballast is a solution that has the potential to ensure the required bearing capacity and impermeability, whilst simultaneously reducing the thickness of the layer to 12 - 15 cm, compared with the 22-25 cm used in the conventional granular design [23]), the surface of the specimens was damaged due to the difficulty in cutting uniform because of coarse aggregates and rubber not-uniform expansion. Therefore, different geometrical specimens instead of being mould confined for 24h were found, as is shown in Fig. 9.

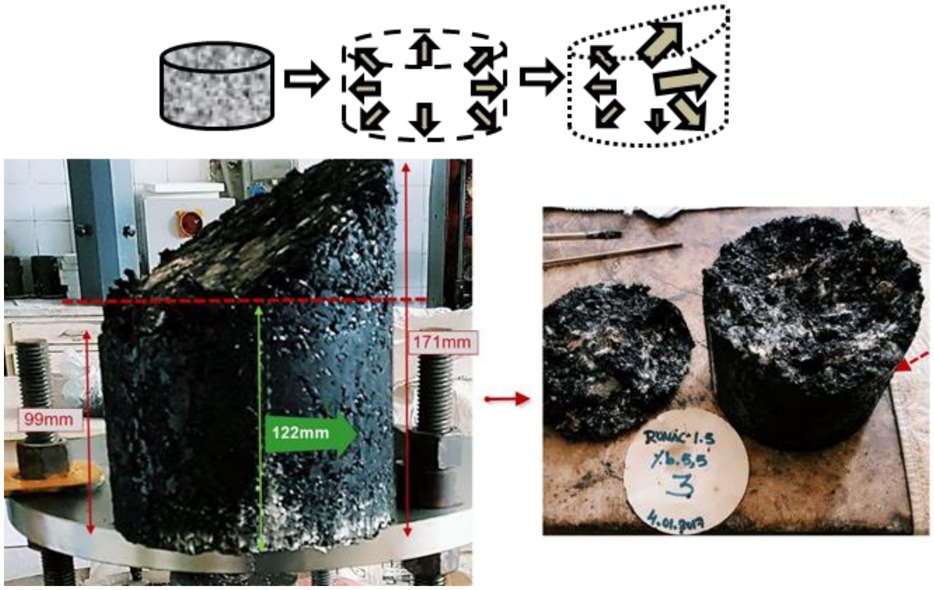


Fig. 9 Example of non-uniform expansion and damage due to the uncontrolled rubber recovery

To avoid it, cylindrical split moulds of Ø150mm and height achieved around 120±2mm were used to compact the specimens and after 24h it was easier to remove with a manual hydraulic extractor (ASTM D698) without disturbing the matrix. The possible distress that could appear was the extra expansion due to the energy accumulated after compaction in the mixture.

The rubber-bitumen reaction process does not occur homogeneously, there is no uniform distribution of the mixture, therefore, the expansion does not occur equally on the surface of the specimen. To ensure homogeneity, the theoretical maximum density (EN 12697-5) and the bulk specific gravity of bituminous mixtures (EN 12697-6), should be compared with the procedures of dry saturated-surface dry density, waterproofing test specimens and by geometric method.

III. METHODOLOGY

A. Designing asphalt mixtures for high-speed rail lines.

The type of mixture more commonly used within the track is a dense-graded bituminous mixture with a maximum aggregate size of 22–25 mm manufactured with characteristics that are suitable for the construction of road pavements [24].

For its application as sub-ballast, however, some authors recommend increasing the content of bitumen by 0.5% in comparison with that considered as optimum for highway applications in mixtures with air-voids content of 1–3% [25]. In addition, it is important to consider the aspects of traffic and temperature with the aim of representing the real conditions of a sub-ballast layer in high-speed rail lines.

1) Temperature and traffic factors

Considering several previous studies to predict the temperature profile within the railway section [26], [27], these results were validated, which motivated the measurement of thermal changes in the sub-ballast layer [6].

From the results of this previous research, we can consider that the temperature range most representative of the thermal behavior, for a warm climate, corresponds with a minimum temperature of 0ºC and maximum of 35ºC.

Temperature variations cause changes in the performance of asphalt mixtures (more elastic at low temperatures, critical factor governing fatigue cracking and, more viscous at higher temperatures, that characterizes the permanent deformation or rutting) [6].

A predicting temperature model based on Barber [27] was validated for road infrastructures and showed to be applicable to railway infrastructures too. In this paper, Barber´s theory was used to determine the temperature in the road base course and, the modifications purposed by Crispino [26] were applied in the sub-ballast layer.

The traffic information to be used for the thickness design includes the magnitude of wheel loads and the number of repetitions per year. The high-speed train considered for the case study operates on Italian rail-lines (Fig. 10).

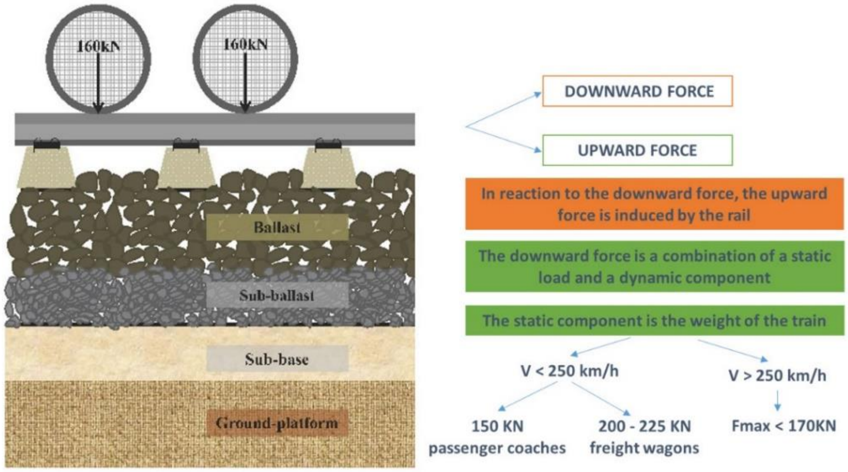


Fig. 10 Long distance intercity train (250km/h) in rail track

The load for the conventional Italian passenger train consists of two (160kN) wheels in a group on each side, spaced at 60cm on rail. The loading system was implemented in Kentrack software [28], and it was designed considering the Long-distance intercity (Italian) train configuration, composed of 1 locomotive followed by 4 bogies (16 axles) with a static load of 16 tons per axle and a distance between axles (wave-length of vibration) of 14,65m. The maximum speed is 250km/h (56-70m/s), diesel-electric respectively power and, 1,435mm standard gauge. It is considered a frequency f, equal to the ratio between average train speed v, and wavelength λ, equivalent to 5Hz (ratio between the maximum speed of a long-distance train 250km/h or 69.45m/s, and the wavelength characterized by the axle distance-tandem wheel, in this case, 14.65m, where f=v/λ).

2) Railway traffic design life

The design life depends on the railway type and the traffic level, generally, it is longer for the railroads with major traffic to cause the least interference to the exercise due to rehabilitation maintenance works. Generally, the design life is 50 years for the high-speed lines and 30 years for the ordinary lines. The traffic level expected over a 50-year period for a common high-speed line considered, and the rest of parameters of input inside the Kentrack$^{@}$ software, are summarized in Table I, adopting different simulations with some traffic growth rates equal to 0, 0.2, 0.4, 0.6, 0.8 and 1%.

TABLE I (A)
MAIN PARAMETERS FOR RAILWAY LINE

Layer	Thickness	Poisson's ratio	Young's modulus
mm	ν	kN/m^2	
Concrete Tie	210	0.30	2.757×10^7
Ballast	350	0.20	1.274×10^5
Sub-ballast	120	0.45	8.997×10^6
Subgrade	300	0.30	1.472×10^5
Bedrock	---	0.50	6.890×10^{10}

TABLE I (B)
MATERIALS PROPERTIES FOR KENTRACK INPUT

		Layer Tª [°C]	η 10^6poise]	log |E*|	|E*| [MPa]	ν
Air temperature 0°C						
Rail	SB	1.94	59.5026	1.434	18929.8	0.4
Air temperature 35°C						
Rail	SB	36.9	0.0074	-0.235	1185.7	0.4

Type of rail: 60E1 (UIC) 3141			Pandrol Fastclip system		
Young's modulus [MPa]	Limit of proportionality [MPa]	Limit of elasticity [MPa]	Static stiffness [MN/m]	Clamping force [kN]	Creep [kN]
192000	500	600	>150	>16	>9
Sleepers in PSC wires					
Sleeper thickness [cm]	Sleeper width [cm]	Sleeper u.weight [g/cm^3]	Sleepers spacing [cm]	Length of sleeper [cm]	Rail distance [cm]
21	16.9	5.18	60	259	143.5
Type of axle considered for the simulations			Single		

Note: (*) SB: sub-ballast layer.
UIC = Union Internationale des Chemins de fer

3) *Superpave mix-design for railways*

The Superpave volumetric mix design (SGC) is the key step in developing a well-performing asphalt mixture NCHRP (2007). It was developed as the optimal laboratory tool that more closely simulates field compaction of asphalt mixtures. The SGC is a 1.25º fixed angle, 600kPa pressure and rate of gyration (30rev/min) compactor that creates samples of Ø150x120mm. For asphalt contained trackbeds, asphalt grading system and their properties were considered inside KENTRACK$^{@}$ software [28]. For the bituminous mechanical behavior, although its response is better described by elastic-viscoplastic constitutive laws accounting for temperature effects, for this analysis a linear elastic model is assumed for numerical reasons [29]. For the past several years trackbed construction has used the Superpave Performance Graded (PG) system based asphalt binders. Therefore, the program maintains the previous asphalt grading system and incorporates information of the new one for comparison purposes (NCHRP 2007).

The SGC establishes three different gyration numbers corresponding to three different compaction levels: $N_{initial}$, N_{design} and N_{max}. N_{des} represents the number of gyrations required to match the density of the material expected in the field and it is the parameter considered in this study. The values established in the original regulations of Superpave contemplated different levels of gyration, that represent seven traffic levels for each of four climates. In the years following the improved N_{design} value, the climatic region factors were eliminated and incorporated in the bitumen selection process depending on the performance grade.

Thus, based on the table for Superpave ESALs for a medium-high traffic (3 to 30 $\times 10^6$ ESALs) corresponds a vaue of $N_{initial}$ of 8 cycles, 100 cycles for N_{des} and, N_{max} of 160cycles, in the case of conventional asphalt for base roads or sub-ballast layer. Based on these values recorded, the simulations results are summarized on Table II, where traffic levels and optimal values for N_{des} are shown for each rail category.

TABLE II
SUMMARY OF TRAFFIC SPECTRUM BY RAIL LINES

RESALs at the end of the service life (30 years)			
Traffic growth [%]	*High-speed line*	Conventional lines	Wagonload freight lines
0	3.171E+07	1.796E+07	3.131E+06
0.2	3.265E+07	1.849E+07	3.223E+06
0.4	3.362E+07	1.904E+07	3.319E+06
0.6	3.463E+07	1.961E+07	3.419E+06
0.8	3.568E+07	2.020E+07	3.523E+06
1	*3.677E+07*	2.082E+07	3.630E+06

Using the values as shown in Table II, for the temperatures selected, the N_{des} for the bituminous sub-ballast and, considering a traffic growth rate equal to 1%, the energetic parameter for compaction is equal to 100 cycles (AASHTO R35, 2001). The Superpave Gyratory Compactor (SGC) is used to determine the optimum mixture. Once the overall procedure for the Superpave mix design calculation was defined, a laboratory verification with different mixtures was conducted.

B. *Procedure to dry process. Basic rules.*

There are different types of dry process technology used in the industry (*Plusride* and *Generic dry*, both patented). The process used rubber as a flexible substitute of aggregates and, binder modification occurs from finer crumb rubber particles, reaction which has already been described above and that we can ensure a maximum rubber content of 3% by total weight of the mix, for dense-gap graded mixtures.

The mixes are not considered to be asphalt-rubber (wet process) since rubber particles are not blended with bitumen before to the mixing with the mineral aggregates.

The dry process is depending upon the type of rubber (natural or synthetic rubber) and, the processing method (vulcanized rubber is more elastic, better resistant to weather and heat but more likely to swelling when compared to the non-vulcanized rubber). In the same way, the rubber particles affect the reaction process, since the gradation of the recycled rubber must be chosen by ensuring that it does not react completely with the bitumen but rather filling the voids of the matrix. The unreacted rubber becomes spongier, giving greater elasticity to the final blend, and will affect the final void content of the blend after the compacting process. In Fig. 11 the work plan of this article is developed showing the steps that must be followed for a correct execution of the mixtures with dry rubber.

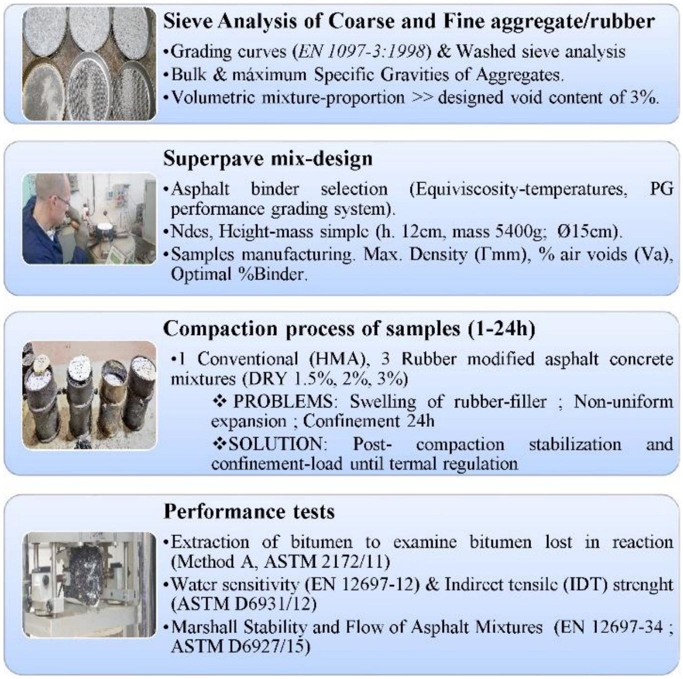
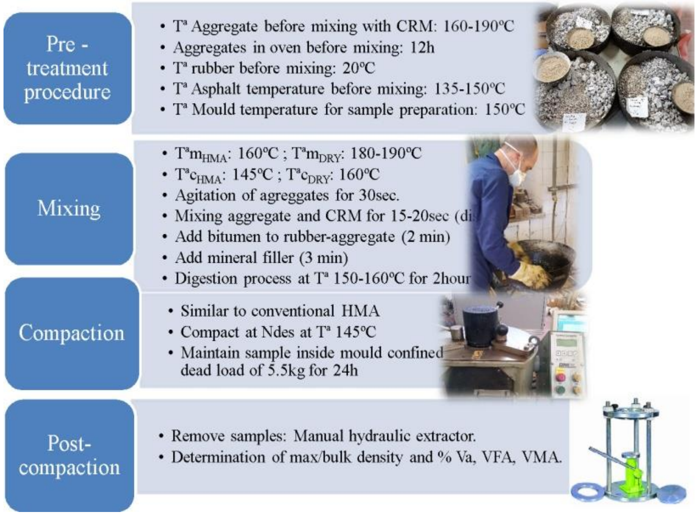


Fig. 11 Construction procedures of dry mixtures

In Fig. 12, based on experience observed in laboratory, an operational framework is proposed as a new protocol for optimal procedure with rubber-aggregate modified asphalt mixtures.



- Tª Aggregate before mixing with CRM: 160-190ºC
- Aggregates in oven before mixing: 12h
- Tª rubber before mixing: 20ºC
- Tª Asphalt temperature before mixing: 135-150ºC
- Tª Mould temperature for sample preparation: 150ºC

- Tªm$_{HMA}$: 160ºC ; Tªm$_{DRY}$: 180-190ºC
- Tªc$_{HMA}$: 145ºC ; Tªc$_{DRY}$: 160ºC
- Agitation of agreggates for 30sec.
- Mixing aggregate and CRM for 15-20sec (di
- Add bitumen to rubber-aggregate (2 min)
- Add mineral filler (3 min)
- Digestion process at Tª 150-160ºC for 2hour

- Similar to conventional HMA
- Compact at Ndes at Tª 145ºC
- Maintain sample inside mould confined dead load of 5.5kg for 24h

- Remove samples: Manual hydraulic extractor.
- Determination of max/bulk density and % Va, VFA, VMA.

Fig. 12 Operational framework. Basic rules

IV. MATERIALS

During these study, different mixes were analyzed by volumetric mix-design, obtaining optimal mixes with diverse amounts of asphalt binders (*):

- A dense-graded mix type (onwards HMA or reference mixture, with bitumen B50/70 and a content of 4% according standard EN 13108-1);
- A dense-graded *Plusride* mixture with 1.5% of rubber and binder 5 to 5.5% (hereinafter DRY 1.5);
- A dense-graded *Plusride* mixture (DRY 2.0) with binder content of 6 to 6.5% and;
- A *Generic* dry gap-graded (SMA) mixture (DRY 3.0) with a 3% of rubber and 7% of optimal binder.

(*) 1.5%, 2% and 3% of the total weight of the aggregates (3.2%, 4.2% and, 6.2% by volumetric substitution). Limestone aggregates with density value of 2.81g/cm^3 were 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) and;

As a function of the aggregate gradation used in the mix, mixtures are divided into three categories: dense-graded, open-graded and, gap-graded or SMA, Stone matrix asphalt [31] as is shown in Fig. 13. All these mixtures were developed and performed at the Laboratory of Civil Engineering of the University of Palermo (Italy).

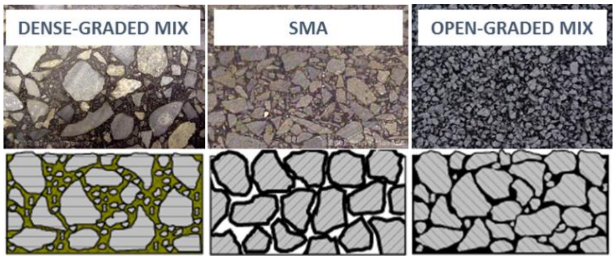


Fig. 13 Classification by aggregate gradation

A. Aggregate gradation and properties

The mixtures studied in this paper were made of two main inert part materials: filler and, fine-coarse aggregate, whose mineral skeleton is composed of limestone aggregates (which allows for sufficient contact with the bitumen to achieve a bond between binder and aggregates) [30] for the different fractions (see Table III) with nominal maximum aggregate size (NMAS) of 22.4mm and a maximum particle size (MPS) of 31.5mm.

In this study, the aggregate gradation was selected based on the Superpave specifications and, the specifications for the bituminous sub-ballast are defined by the Italian standard (RFI). This standard is based on the results of the Marshall and water sensitivity tests, and it specifies a minimum void content between 3-5%.

Individual aggregate components, were combined in precise percentages to produce asphalt mixtures which exhibit controlled levels of coarse-interlock.

TABLE III. 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)

These mixtures were optimized in laboratory after testing different binder's content to relate the compaction and volumetric characteristics with changes in the coarse-fine gradations and the corresponding ratios of filler-aggregates.

TABLE IV. PERCENTAGE OF EACH FRACTION CRUDE FOR CONSTITUTION OF THE THEORETICAL RECIPES.

Type of fraction (Ø)	Filler	Sand	Ø5-10	Ø10-15	Ø20-25	Ø30	Σ
Sieve size (mm)	<0.063	1 - 4	5 - 8	8 - 11.2	11 - 22.4	< 31.5	
Mixtures	[%]	[%]	[%]	[%]	[%]	[%]	[%]
HMA	12.24	24.60	5.21	18.29	18.49	21.16	100
ρ_{mix}, g/cm^3	2.748					ρ_{aggr}	2.809
DRY 1.5%	12.45	23.79	4.62	18.98	18.65	21.52	100
ρ_{mix}, g/cm^3	2.716					ρ_{aggr}	2.808
DRY 2%	12.52	23.51	4.42	19.21	18.70	21.65	100
ρ_{mix}, g/cm^3	2.700					ρ_{aggr}	2.808

DRY 3%	12.66	22.94	4.01	19.69	18.80	21.90	100
ρ_{mix}, g/cm^3	2.687					ρ_{aggr}	2.808

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 fact that testing mixtures for the characterization of voids in sand size fine part, the study of aggregate voids, VFA and VMA percentages was performed until satisfactory results (Table IV). In this research, the grading curve has been optimized to lower levels within the limits established by the Italian sub-ballast standard, RFI [31]. The aggregate gradation is shown on the 0.45 power chart (Fig. 14).

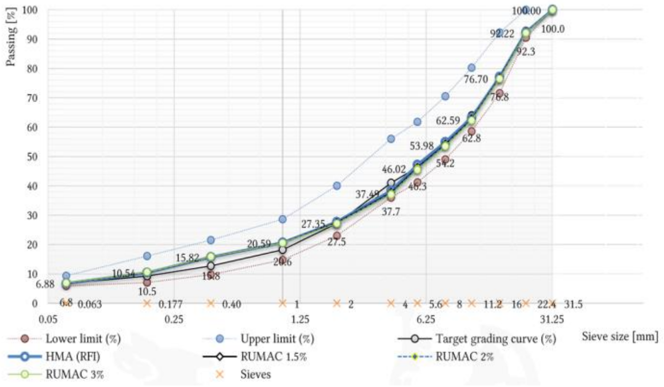


Fig. 14 Grain-size curves

B. Asphalt binder

The asphalt binder used was a B50/70-penetration grade having a Superpave performance grade of PG70-16 (AASHTO M-320) after traditional and Superpave asphalt binder specifications (see Fig. 15) that include specific gravity, penetration, ductility, softening point, rotational viscosity (RV), Dynamic Shear Rheometer (DSR) and, Bending Beam Rheometer (BBR) tests.

According the specifications AASHTO M226-80 (2012) and ASTM D3381M-13, that both covers asphalt binders graded by viscosity at 60ºC, in this study the asphalt binder used is identified with a viscosity grade reference AC-20. A Viscosity value, 60°C [140°F], Pa·s of 102 Pa·s, a Flash point min 230ºC, a Solubility percentage in trichloroethylene of 99% and, a Penetration value, 25°C, 100g, 5 s, min of 53.

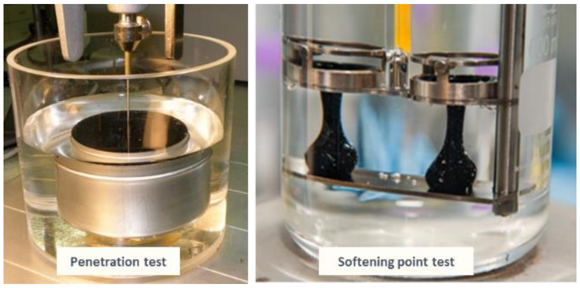


Fig. 15 Penetration and Ring-&-Ball softening point tests *(EN1426-27)*

C. Rubber particles from scrap tires.

The crumb rubber used in this case by dry process had two particle sizes of 0.2-4mm and 2-4mm (Fig. 16). 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 [32].

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

TABLE V. 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
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^a 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 of water, m4 (gr)			3039
Maximum Specific Gravity of rubber (g/cm3)			1.154

Fig. 16 Sieve analysis of the rubber from discarded truck-tires

V. RESULTS AND DISCUSSION

A. Superpave asphalt mixtures: Mix-Design

The reference mixture was a bituminous dense graded for sub-ballast layers with a maximum size of 31.5mm coarse aggregate, a 6.75% amount of filler passing sieve 63µmm and, a 72% had a particle size smaller than 0.177mm to guarantee good adhesion and chemical bonding were designed with a fine fraction less than 2mm.

The manufacturing temperature for a conventional B50/70 bitumen was 160ºC and the compaction temperature was set at 145℃, were carried out with the Brookfield viscometer (ASTM D2493). In rubber-aggregate mixes these values are increased 10ºC.

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 enhance the interaction between binder and rubber modifying the mechanical properties of the mixes.

The number of gyrations used for compaction were, according as the problems explained (swelling, rebound and non-uniform expansion), 102 cycles for the HMA reference mixture, 151 cycles for the DRY 1.5% mixture, 181 cycles for the DRY 2% mixture and, 291 cycles for the DRY 3% mixture, based on previous tests on specimens compacted at 100 gyrations (standard N_{des} according to ESAL for sub-ballast, see Table II).

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 [14]-[21].

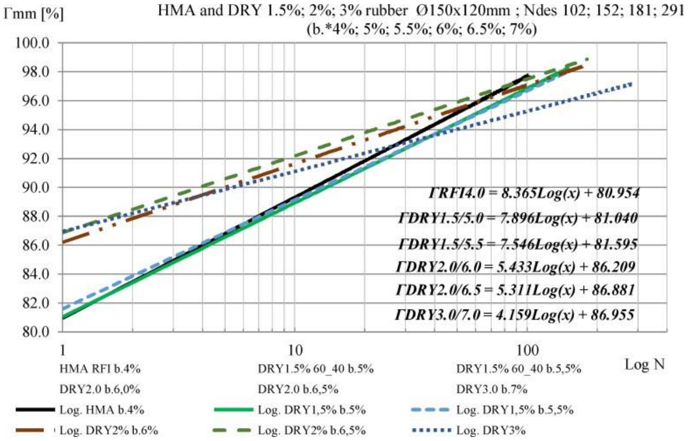


Fig. 17 Trend lines of final compaction curves using Superpave

This increase in the number of gyrations (N_{design} number of gyrations required to produce a sample with the same density as that expected in the field after the indicated amount of traffic) is the main factor in these mixtures, despite proving a post-relaxation and consequent expansion that weakens its structure and favors the increase of the percentage of voids, manages to control this swelling effect and obtain rubberized specimens after 24 hours of mold extrusion.

After compacting the specimens to N_{des} gyrations, it has been determined the bulk specific gravity (Γ_{mb}) and the theoretical maximum specific gravity (Γ_{mm}) of each of the mixtures (EN 12697-6). Comparing the results, the densification curves are plotted (Fig. 17).

Each sample were 24h cooled to room temperature without being removed from the mould with the purpose to avoid the bounce back effect due to the swelling of rubber. Because it was observed a dilatation (expansion) of the specimens after 7 days, final air voids are considered to precise the optimal binder content (Table VI, Fig. 18).

TABLE VI. OPTIMAL BINDER CONTENT FOR MIXTURES TO ACHIEVE A TARGET VALUE OF 3% OF AIR VOIDS

Mixture	%Va*	%b*$_{(Ndes)}$	%b*$_{(24h)}$	%b*$_{(7d)}$
HMA	3.0%	3.96%	4.00%	4.00%
Dry 1.5%	3.0%	4.95%	5.34%	6.05%
Dry 2%	3.0%	4.91%	5.61%	6.38%
Dry 3%	3.0%	6.70%	7.13%	7.27%

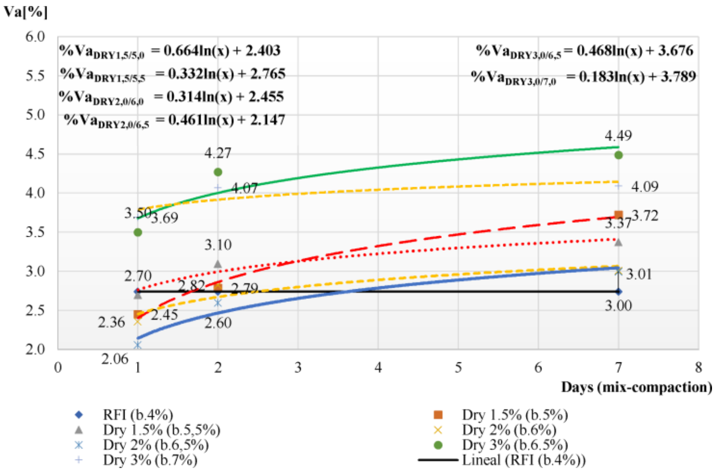


Fig. 18 Optimal binder content after one week due to the swelling effect of rubberized compacted specimens

B. Design air voids content. Optimization.

From the tests conducted it emerged that the sub-ballast mixture at N_{design} achieved the target voids content with 4% of bitumen in relation to the weight of aggregates, for a conventional mixture without rubber. In the rubberized cases, the optimal binder content is showed in the Table VII.

For example, for a mixture with 2% of rubber, the optimal design asphalt content is 6%, the minimum voids in mineral aggregate (VMA) requirement for the design aggregate structure is 16.5% and, the voids filled of asphalt value (VFA) is 81.5%.

TABLE VII
VOLUMETRIC COMPACTION RESULTS FOR EACH MIXTURE

Mix	Specimen Ø15x12cm	H. N_{des} [mm]	H. 24h [mm]	H. 7d [mm]	Va(%) N_{des}	Va(%) 24h	Va(%) 7_{days}
HMA	$RFI^{01}_{4\%}$	114.30	113.33	113.33	2.78%	2.78%	2.78%
	$RFI^{02}_{4\%}$	115.90	115.50	115.50	2.70%	2.70%	2.70%
Dry 1.5	$DRY^{01}_{5.0/1.5}$	121.30	121.99	121.99	2.43%	2.76%	2.78%
	$DRY^{02}_{5.0/1.5}$	122.20	123.08	123.08	2.48%	2.81%	4.66%
	$DRY^{03}_{5.5/1.5}$	121.70	122.62	122.70	2.39%	2.79%	3.21%
	$DRY^{04}_{5.5/1.5}$	121.70	121.74	121.74	3.01%	3.40%	3.54%
Dry 2	$DRY^{01}_{6.0/2.0}$	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%
Dry 3	$DRY^{02}_{7.0/3.0}$	121.90	123.58	123.68	3.50%	4.27%	4.42%
Mixture	Dust-to-asphalt ratio	%*b*	VMA (%)	VFA (%)	Γmax g/cm^3	Γssd g/cm^3	Γmm (%)
RFI	0.892	4.0	12.36	77.86	2.636	2.565	97.26
Dry 1.5%	0.716	5.0	14.95	75.38	2.596	2.508	96.61
	0.709	5.5	15.60	78.37	2.577	2.500	97.02
Dry 2%	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
Dry 3%	0.590	7.0	18.9	78.38	2.524	2.431	95.68

Entering the plots of percent air voids versus asphalt content, we observed the optimal binder content in each case according the obtained results (Fig. 19).

The compatibility of these mixes is quite different even though 3% of air voids is the target value, being more sensitive to the gyration levels than the other.

Another relevant aspect that can be observed in the results is that as the rubber content in the mixture increases, the workability (slope of the trend line) decreases (higher densification), due to several reasons:

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

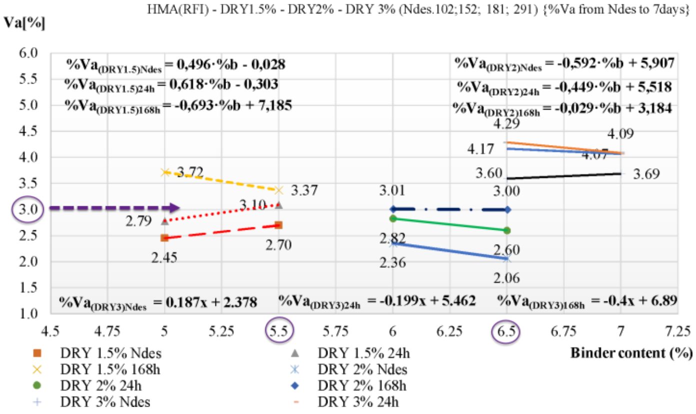


Fig. 19 Mean values of air voids of each mixture. Trend equations to determine the optimal percentage of bitumen

Due to the increase in compaction energy, the compactability is greater initially by having mixtures which, within the initial 24 hours, experience a strong swelling effect in the case of not following the proposed protocol of execution in this article, as we can see in Fig. 20.

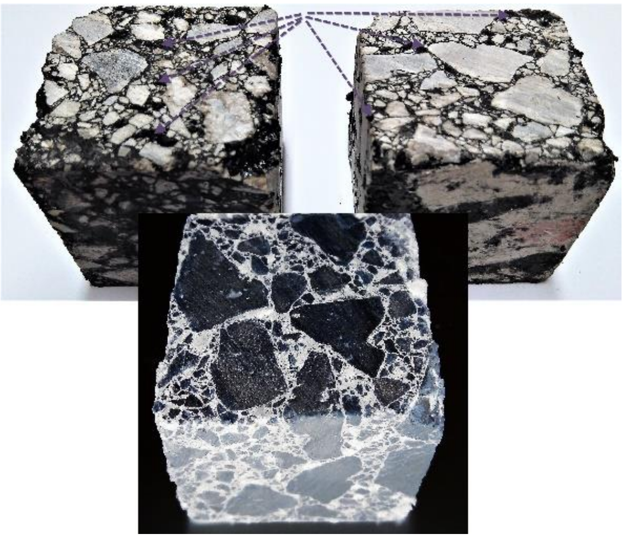


Fig. 20 Swelling and bounce-back effects of particles of rubber observed in cut specimens (black points raised)

C. Volumetric results

An important step inside the volumetric compaction by Superpave is the optimal finding of the relationship between mass inert part and height of the final specimen, in that case, for cylindrical specimens of Ø150x120mm (gyratory compaction), a mass value around 5460gr was founded and, specimens for ITS tests and water sensitivity of dimensions Ø100x65mm by Marshall compaction, a value of 2850gr was selected after different studies in the laboratory (Table VIII).

TABLE VIII. VOLUMETRIC MIX DESIGN CHARACTERISTICS.

	Ndes.102	Ndes.152	Ndes.181	Ndes.291
	RFI b.4%	DRY1.5%	DRY2%	DRY3%
Mixture weight $^{(*)}$	5460	5460	5460	5460
Aggregrate mass	5250	5176	5127	5103
SG Aggregates	2.809	2.808	2.808	2.808
%Inert part	96.15%	94.79%	93.89%	93.45%
Bitumen mass	210.0	284.5	333.4	331.9
S. Gravity binder	1.033	1.033	1.033	2.033
% binder	3.85%	5.21%	6.11%	6.08%
γ_{max} [g/cm^3]	2.634	2.577	2.541	2.553

(*) Optimal inert part for a specimen of Ø150x120mm

Equation 1 defines the basic form for a trend line inside a Superpave graph for compaction curves. Γ_{mm} represents the measured relative density or relative specific weight at each number of gyrations, Γ_1 is a experimental value that indicates the densification, N is the number of gyrations selected and, k is the slope of the curve or workability of the mixture. For each mixture is shown the optimal equations studied.

$$\Gamma_{mm}(N) = \Gamma_1 + \kappa \cdot LogN \qquad (1)$$

By graphic interpolation, the optimal results are:

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

In addition, for the different specimens (4 for each mix) obtained from the workability study, its indirect tensile strength, IDT (EN 12697-23) was evaluated because it directly measures the tensile strength in the mixing and cohesion steps. For the reference mix, six test cylinders of diameter 101,6mm and heights ranging from 35 to 75mm were subjected to compressive loads between two loading strips at a constant velocity of 50m/min. These tests were run at 15ºC in dry/wet groups conditioned to measure the water sensitivity. The ratio of the IDT (%) of the water conditioned subset compared to that of the dry subset is shown in Table IX and Fig. 21.

Figure 21. (a) IDT device, and (b) Marshall specimens for IDT and water sensitivity tests

TABLE IX. SUMMARY OF IDT AND ITSR FOR HMA REFERENCE MIXTURE

Properties (SG specimens)	WET	DRY	Standard
Indirect tensile strength at 15ºC (N/mm^2)	1.19	1.40	≥0.6
Water sensitivity (ITSR %)	85.2		>80
Coefficient indirect tensile strength (CTI) at 25ºC [EN 12697-23] (N/mm^2)	123.75	91.84	30-110
Properties (Marshall specimens)	WET	DRY	Standard
Indirect tensile strength at 15ºC (N/mm2)	1.32	1.53	≥0.6
Water sensitivity (ITSR %)	86.3		>80
Coefficient indirect tensile strength (CTI) at 25ºC [EN 12697-23] (N/mm^2)	66.09	77.88	30-110

Water sensitivity test (EN 12697-12), was also conducted for the different mixes to evaluate the impact of the rubber on the behaviour of the mixes under the water susceptibility properties for their application in sub-ballast layer.

VI. CONCLUSIONS

The use of asphalt rubberized mixtures in place of granular sub-ballast is a solution that must ensure the conditions required of bearing capacity, impermeability and, environmental benefits. As we can see, literature review revealed that field performance of dry rubber-modified asphalt mixtures is not consistent in case you do not carry out the proposed protocol in this article. The swelling effect confirmed and observed, in mixtures DRY 1,5%, 2% and, 3% of rubber by total weight of the mixture, that at high temperatures, rubber absorbs the lighter fractions of bitumen during a period of time of 7 days from its manufacture, problems are observed due to swelling and non-uniform expansion of the mixture due to the residual energy accumulated inside the asphalt matrix, product of excessive compaction, in order to achieve the target void ratio of 3%, typical in sub-ballast railway layer for high-speed lines.

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 distresses in laboratory specimens.

In order to determine the N_{des} required, previous simulations with the Kentrack software have been carried out, analyzing the stresses in the sub-ballast layer, obtaining the corresponding value of ESAL. For this, the traffic spectrum for a high-speed line and with a train applying 16t per axle has been considered. The other key factor, temperature, after analyzing the theory of Barber and Crispino, the mean values adopted oscillate between 0 and 35ºC, as a predictive model of temperatures.

The sub-ballast has a structural function absorbing the loads coming from the train passages providing higher stability to the track-bed and resisting fatigue solicitations. To ensure capabilities the target voids content was lowered from 4% to 3% with the consequent increase of bitumen content. An experiment was conducted through SGC to determine N_{des} varying according the type of mix specimens. As a valid criterion of orientation, samples were developed with 120mm of height after compaction in analogy of the real thickness of the sub-ballast layer, and a diameter of 150mm according the Superpave gyratory compactor technique in each case, conventional and rubberized asphalt mixtures.

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 moulds (150ºC) heated to the proper mixing temperature according the mixture type. Then, before being removed, each sample must be stored at room temperature (20ºC) after 24h of post-compaction and thermal stabilization.

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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.

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