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Article *in* Materials and Structures · January 2018

DOI: 10.1617/s11527-018-1152-9

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Analytical approach for the mix design optimisation of bituminous mixtures with crumb rubber

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ABSTRACT

The present paper provides a basis for defining a mix design method specifically tailored to rubberised asphalt that takes into account the behaviour of crumb rubber. An analytical approach to quantifying the recovered deformation of crumb rubber in the post-compaction phase has been developed in order to adjust the number of gyrations proposed by the Superpave method for compacting specimens of hot mix asphalt using a Superpave gyratory compactor (SGC). The maximum allowable amount of rubber has been calculated. Finally, a step-by-step protocol has been proposed in order to fabricate and compact Crumb Rubber Modified (CRM) mixtures with the gyratory compactor.

Keywords: crumb rubber, Superpave gyratory compactor, mix design, rubberised asphalt

1. INTRODUCTION

1.1. From scrap tires to engineering material in bituminous mixtures

The quantity of End-of-Life tires (ELTs) is progressively increasing due to the growing traffic volume and number of vehicles produced worldwide. The problem is well known in US where Environmental Protection Agency (EPA) reported the presence of 290 million of scrap tires in 2003, but also in Europe where every year 355 million tyres are produced according to European Tyre and Rubber Manufacturers Association (ETRMA) [1]. ETRMA is a group of experts created in Europe in 1989 with the goal of managing the collection of scrap tires and seeking for sustainable solution for implementing their reuse. Indeed, ELTs are among the largest and most problematic sources of waste, due to the large volume produced and their durability [2]. On one hand, these characteristics are negative if ELTs are considered waste material, but being very resistant and durable became an advantage when crumb rubber (CR) made by reprocessing (ELTs) is recycled and used for other products. Therefore, this material started finding different types of application in available expanding markets that have shown the potential of using large number of scrap tires such as fuel combustion and crumb rubber modifier (CRM) for production of asphalt mixtures [3-7].

The re-use of CR in asphalt mixtures can produce environmental benefits in terms of reduction of natural resources employed in the construction and maintenance/rehabilitation (M&R) and traffic noise from light-duty vehicles [8-9].

However, the production and installation of CR mixtures may lead to other issues such as hazardous emissions. Several studies performed by the Federal Highway Administration [10] and recently in Italy [11] demonstrated that using wet or dry mixtures do not increase health risks to personnel. In particular, the values gathered from monitoring Polycyclic Aromatic Hydrocarbon (PAH) did not exceed the recommended value of 3 mg/mc defined by the American Conference of Governmental Industrial Hygienists (ACGIH). At present, however, it cannot be concluded that the observed differences between traditional and modified asphalt are caused only by intrinsic factors of the mixtures, rather than by other external factors such as variability in the meteorological conditions, differences in lay down operations, and different fabrication and compaction temperatures [11]. Indeed, decreasing the fabrication temperature and consequently the compaction temperature by using Warm mix technology leads to a relevant reduction of emissions during the field installation [12-13]. According to Italian legislation, from an environmental point of view, there are no limitations in the maximum allowable content of rubber. On the contrary, the reuse of scrap tires is encouraged by policies that aim to strengthen the environmental, economic and social benefits deriving from the recycling chain where a waste product enters in a new production process for infrastructure construction.

Two main different methods allow the addition of the rubber to asphalt mixtures: the wet and dry process. The *wet process* involves the dissolution of the crumb rubber in the bitumen as a modifying agent [14]. The *dry process* involves the replacement of a small portion of aggregates with the same fraction of rubber grains before adding the bitumen [15]. The dry process became recently a very attractive technology because of its production simplicity compared to the wet process [16], because the crumb rubber is added directly to the aggregates during the fabrication as another ingredient in the mix. The bitumen is slightly modified when it is exposed to the rubber [17]. Indeed, an interaction is observed between bitumen and rubber: the volatile components of bitumen are transferred to the rubber [18]. The absorption of lighter components (paraffin and maltenes) is part of the maturation process known as ‘maceration’ [19, 20]; it causes swelling of the crumb rubber particles and leads to a more viscous bitumen. The swelling as well as the performance of rubberised asphalt depend largely on the dimensions of the rubber grains [21, 22].

1.2. Mix design of bituminous mixtures

Compaction of bituminous mixtures is intended to reduce the voids content, optimizing the granular skeleton orientation to increase the material density [23].

Among the various types of laboratory compactors (Marshall compaction, roller compactor etc.), Partl et al. [24] proved, that gyratory compaction allows obtaining heterogeneous samples in terms of air void content distribution and aggregate particle orientation. Furthermore, results performed on the correlation of different compaction methods showed that the gyratory compactor most often generated samples similar to pavement cores [25].

Therefore, to obtain heterogeneous samples and voids distribution as similar as possible to the materials in the field, the Superpave mix design procedure featured by the Superpave gyratory compactor (SGC) has been selected.

The Superpave mix design system enables definition of the optimal blend of different elements that may yield hot mix asphalt (HMA) with certain characteristics: for instance, sufficient voids in the mineral aggregate (VMA) and air voids, and satisfactory workability and performance over the entire service life of the pavement [26]. The Superpave gyratory compactor establishes three different gyration numbers corresponding to three different compaction levels: $N_{initial}$, N_{design} and N_{max}. $N_{initial}$ is the number of gyrations that represents the asphalt mixture compaction during the construction and used to analyse the early densification characteristics. N_{max} is the number of gyrations to reach a density that should never be exceeded in the field based on the design traffic volume. The asphalt mixture should never contain less than 2% air voids at N_{max} to avoid bitumen bleeding potentially caused by a further densification under the traffic action [27]. N_{design} represents the number of gyrations required to match the density of the material expected in the field and this is the parameter considered in this study. The original Superpave table envisaged seven traffic levels for each of four climates and for each case the number of gyrations was identified [26]. Traffic levels are defined by intervals counting the number of passages of equivalent single-axle loads (ESALs) accumulated during a 20-year design life. Different climates were expressed by the average 7-day high air temperature recorded at the project site. N_{design} increased as either design ESALs or high air temperature increased. In the following years, the table was modified, eliminating the climatic regions, because the differences in the temperatures were incorporated in the selection of the bitumen through the performance grade (PG) [27].

When crumb rubber is added to asphalt mixtures, the compactability of the material is affected, because the rubber is an additional element involved in the mixture that has a different behaviour from the other components (bitumen, filler and aggregates). Recent studies [28-29-30] observed that the spring-back effect of the rubber causes an increase in the specimen volume after compaction and this variation depends on the quantity and size of the rubber grains. The spring-back effect of the rubber raises the need to adjust the compaction method originally tailored to the traditional mixture. Indeed, when rubber is used, the mixing and compacting temperature may vary [31, 32]. Despite the numerous efforts employed in improving the mix design system for bituminous mixtures, still certain limitations emerge when the traditional Superpave is applied to CR mixtures. First, the rubber absorbs part of the bitumen, increasing its need in the mixture for a satisfactory workability [33]. Moreover, the CR mixture needs a certain curing time to complete the swelling and stabilise [28]. This curing time is mainly influenced by temperature and the size of the rubber particles [34]. The swelling is partly due to the chemical interaction between rubber and bitumen [20] that leads to an increase in bitumen demand. Moreover, especially in the case of the dry process, the swelling after compaction is mostly due to the mechanical behaviour of the rubber (spring back effect) [28, 29, 30].

1.3. Problem statement and objective

Crumb rubber could be approximately considered an elastic material, but it is significantly less stiff than aggregates. Therefore, when a stress is applied it is subjected to a deformation, but once the stress is removed, it returns to its original configuration. Thus, crumb rubber releases the deformation accumulated during the compaction process. This may turn out in a non-negligible swelling of the asphalt mixture sample and can cause an increase in the amount of voids in the post-compaction phase, leading to 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 adequately the compaction process.

The objective of this paper is to develop a mix design approach for rubberised asphalt (dry process) that takes into account the behaviour of crumb rubber during the compaction and post-compaction processes. An analytical approach to quantifying the recovered deformation of crumb rubber in the post-compaction phase has been developed in order to adjust the number of gyrations proposed by

Superpave, with the final aim of meeting the requirements for voids content. Moreover, a mathematical relationship has been defined for computing the maximum allowable content of rubber in the mixture once the void content has been established. Finally, based on the results obtained, a full step-by-step protocol has been proposed in order to fabricate and compact CR mixtures.

2. METHODOLOGY

2.1. Research steps: preliminary, compaction and post-compaction phases

The behaviour of the CR mixtures is analysed in three main phases:

1) Preliminary phase – quantification of the increase in bitumen demand when CR mixtures are fabricated.
2) Compaction phase – definition of a *correction factor* for increasing N_{design} taking into account the elastic recovery of the rubber.
3) Post-compaction phase – thermal stabilisation, confinement and curing phase. The curing phase in the framework of this work is defined as the time necessary for the rubber to recover its initial volume after compaction.

In the first step of the research it is necessary to understand how the demand for 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 rubber and three with rubber were fabricated with different percentages of bitumen and they were compacted at the same N_{design} used for the traditional mixture. The compaction curves obtained have been compared. The aim of this preliminary phase is to identify the bitumen content in a CR mixture that allows its compaction curve to be similar to the one characterising the conventional mixture. This bitumen content was considered for further analysis. Having, at the end of the compaction phase, the same voids content for the traditional and CR mixtures allows the same starting point to be used for both mixtures when the post-compaction phase starts. This allows the contribution of the deformation release of the crumb rubber in increasing the voids content during the post-compaction phase to be isolated and highlighted.

This analysis led to the definition of a coefficient (α) for multiplying the standard number of gyrations in order to achieve, at the end of the curing time, the same voids content as that obtained for the traditional mixture. In other words, starting with the same voids content after compaction (traditional and CR mixtures), an analytical method has been defined to calculate how the compaction (N_{design}) should be increased for the CR mixtures given that after compaction, during the thermal stabilisation and curing phase, the rubber deformation release causes an increase in volume and additional voids. Figure 1 shows a schematic representation of the research steps.

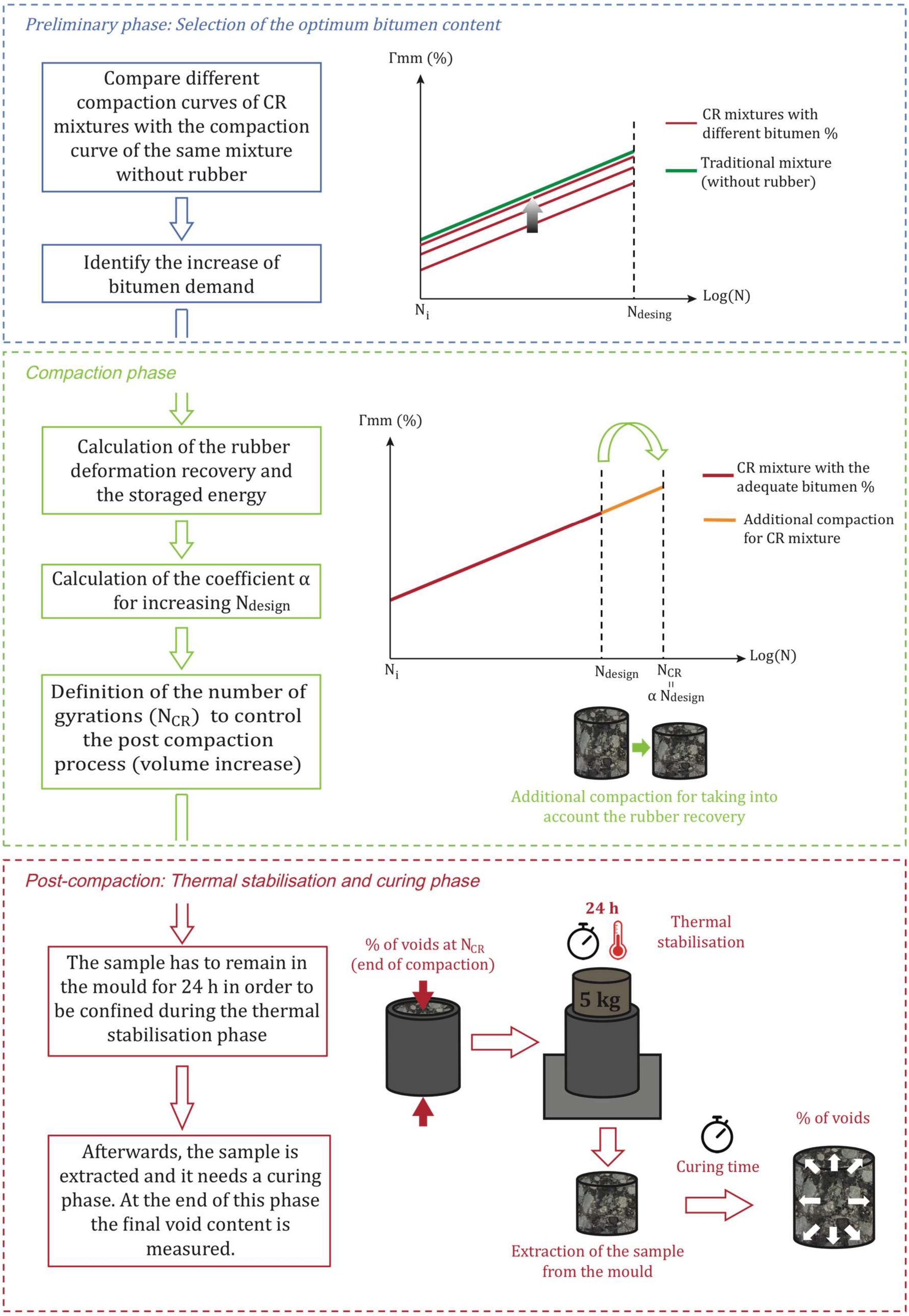

Figure 1. Schematic representation of research stages.

2.2. Determining *Correction factor* α

In order to calculate a *correction factor* that adjusts the number of gyrations for CR asphalt mixtures, it is necessary to present a few considerations and hypotheses regarding the compaction process and the recovery of the rubber in the post-compaction phase. Compaction is achieved by applying vertical stress (600 KPa) via end plates. A known mass of asphalt mixture is placed into a mould between the two plates and completely confined. The plates are kept parallel, but the longitudinal axis of the mould is rotated to a fixed angle equal to 1.25°. The mould rotates at 30 revolutions per minute and the load is continuously applied. This configuration increases the presence of shear stress applied to the sample. Nevertheless, the shear stress is considered negligible for the rubber deformation recovery, therefore in the framework of this work, only compression is taken into account in the calculation process.

Three main elements within the sample are considered in terms of volume: air voids (V_V), aggregates + bitumen (V_{A+B}) and rubber (V_R) (Figure 2).

The aggregates and bitumen are considered unique elements in the system. The bitumen is also subjected to a recovery after compaction, but this will be the same recovery as occurs in the traditional mixture. The volume of the bitumen after the digestion of the crumb rubber does not change significantly if compared with the variation in volume caused by the rubber, especially for hard bitumen. Indeed, the tests performed by Peralta et al. 2010 [35], show that the variation of the density for the bitumen 60/70 is approximately 0.03 g/cm^3 while the variation of the rubber density is approximately 0.70 g/cm3. These results refer to the wet process, thus crumb rubber (21% of the weight of bitumen) is blended with bitumen at high temperatures to produce a modified binder. In the case of dry process, this interaction between rubber and bitumen is lower, because the rubber is not directly used to modify the binder. Consequently, it is reasonable to assume that the density of the bitumen does not change significantly and the recovery of bitumen after compaction will be the same recovery as occurs in the traditional mixture. Thus, the difference between the recovery of traditional and CR mixtures and the expansion of CR mixture can be attributable only to the presence of the rubber. Therefore, the calculations below focus only on the rubber recovery. The size of rubber grains may have an influence in the recovery of the deformation after compaction [21, 22, 34]. However, this effect is limited to the domain of fine particles. Indeed, scrap tires are employed in bituminous mixtures in the form of crumb rubber with sizes ranging from 0.075 mm to 4.75 mm [36]. This range of dimensions of the grains allows using the definition of fine aggregates, i.e. any aggregate that passes the 4.75-mm sieve [37]. According to this definition, only fine particles of crumb rubber continuously graded are used in asphalt mixtures, facilitating the densification process and mitigating the influence of the size of the rubber grains.

After having defined the compaction condition, let the index *i* and N_{CR} denote, respectively, the initial and the final configuration (before and just after compaction) of the CR asphalt sample at $t = t_i$ and at $t = t_{CR}$ (Figure 2). The surface area (A) at the base of the mould remains constant (100 or 150 mm in diameter), while under the load applied by the gyratory compactor the height of the sample decreases. This corresponds to a volume reduction caused by the compression of the rubber and aggregate orientation that reduce the air voids content.

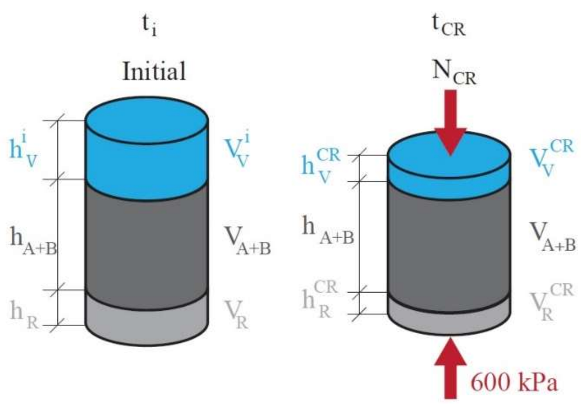

Figure 2. Configuration of the CR asphalt sample before and after compaction.

The difference between the compaction of a traditional and CR mixture is expressed using a *correction factor* for N_{design} denoted as α. In the framework of this work, α is defined as the coefficient that multiplies the design number of gyrations (N_{design}) necessary to compact a sample of traditional asphalt mixture to obtain the design number of gyrations required to compact a sample of CR mixture (N_{CR}) (Eq. 1).

$$N_{CR} = \alpha \cdot N_{design} \quad (1)$$

α is calculated as the ratio between the target voids expected for a sample of asphalt mixture without rubber ($\%voids$) at N_{design} and the percentages of the final voids achieved by the same asphalt mixture with crumb rubber ($\%voids_{CR}$) at N_{CR} (Eq. 2).

$$\alpha = \frac{\%voids}{\%voids_{CR}} \quad (2)$$

The percentage of the target voids ($\%voids$) is established at the beginning of the process. It should be defined as the design voids of the corresponding traditional asphalt mixture (without rubber), bearing in mind that the volumetric properties have an influence on the mechanical performance of the mixture (fatigue and rutting resistance).

On the other hand, the $\%voids_{CR}$, defined in Eq. 3, is the percentage of final voids obtained after the compaction in the CR mixture at $t = t_{CR}$

$$\%voids_{\ CR} = \frac{V_V^{CR}}{V_V^{CR} + V_{A+B} + V_R^{CR}} \quad (3)$$

where:

V_{A+B} = volume of aggregates and bitumen that remains constant before and after compaction [m^3].

V_V^{CR}= final volume of air voids at N_{CR} (at the end of compaction) [m^3].

V_R^{CR}= final volume of the rubber at N_{CR} (at the end of compaction) [m^3].

The following calculations have the objective of identifying the unknown values V_V^{CR} and V_R^{CR} and V_{A+B} necessary for the determination of $\%voids_{CR}$ and therefore α.

The final volume of air voids is calculated by subtracting the decrease in the rubber volume from the volume of the target voids. Thus, the final volume of air voids (V_V^{CR}) can be written as:

$$V_V^{CR} = V_V - |\Delta V_R| = V_V - |(V_R^{CR} - V_R)| \tag{4}$$

where V_V is the volume of the target voids ($\%voids$), ΔV_R is the variation in the volume of rubber between the time $t = t_i$ and $t = t_{CR}$ because V_R is the volume of rubber at time $t = t_i$. Considering rubber as a pure elastic material and assuming normal compressive stress applied to the sample, it is possible to apply Hooke's law:

$$\sigma = E_R \varepsilon_R = E_R \left| \frac{h_R^{CR} - h_R}{h_R} \right| \tag{5}$$

where E_R is the Young modulus of the rubber, σ is the vertical stress (600 KPa), and h_R and h_R^{CR} are respectively the initial and final height of the rubber layer (Figure 2). Thus, in order to obtain the final volume of the rubber it is necessary to calculate the final height of the rubber:

$$h_R^{CR} = \left(\frac{\sigma}{E_R} + 1 \right) h_R \tag{6}$$

Recalling *A* as the area of the plate of the mould, writing V_R^{CR} as $A \cdot h_R^{CR}$ and substituting Eq. 6 in Eq. 4, it is possible to obtain the volume of voids at the end of compaction:

$$V_V^{CR} = V_V - \left(V_R - A \left(\frac{\sigma}{E_R} + 1 \right) h_R \right) = V_V - V_R \left(1 - \left(\frac{\sigma}{E_R} + 1 \right) \right) \tag{7}$$

$$V_V^{CR} = V_V - \frac{\sigma}{E_R} V_R \tag{8}$$

To obtain V_V it is possible to use the following expression:

$$\%voids = \frac{V_V}{V_V + V_{A+B} + V_R} \tag{9}$$

Thus, V_V can be isolated:

$$V_V = \frac{\%voids \ (V_R + V_{A+B})}{1 - \%voids} \tag{10}$$

The volume of "aggregates + bitumen" and the initial volume of rubber can be obtained respectively as $V_{A+B} = \frac{M_A}{\rho_A} + \frac{M_B}{\rho_B}$ and $V_R = \frac{M_R}{\rho_R}$ where M_A, M_B and M_R are the masses of aggregates, bitumen and rubber and ρ_A, ρ_B and ρ_R are the densities of those three materials.

Once all the elements of Eq. 3 (V_V^{CR}, V_{A+B} and V_R^{CR}) are known it is possible to write Eqs. 11 and 12 to obtain $\%voids_{CR}$ and α.

$$\%voids_{CR} = \frac{\frac{\%voids\ (V_R + V_{A+B})}{1 - \%voids} - \frac{\sigma}{E_R} V_R}{\frac{\%voids(V_R + V_{A+B})}{1 - \%voids} - \frac{\sigma}{E_R} V_R + V_{A+B} + V_R^{CR}} = \%voids + \frac{\sigma}{E_R} \frac{\frac{M_R}{\rho_R}(\%voids - 1)}{\frac{M_R}{\rho_R} + \frac{M_B}{\rho_B} + \frac{M_A}{\rho_A}} \tag{11}$$

$$\alpha = \frac{\%voids}{\%voids_{CR}} = \frac{\%voids(\frac{M_R}{\rho_R} + \frac{M_B}{\rho_B} + \frac{M_A}{\rho_A})}{\%voids(\frac{M_R}{\rho_R} + \frac{M_B}{\rho_B} + \frac{M_A}{\rho_A}) + \frac{\sigma}{E_R}\frac{M_R}{\rho_R}(\%voids - 1)} \tag{12}$$

Once α is known N_{CR} can be calculated as defined in Eq. 1.

2.3. Energy balance (storage energy)

The rubber storage energy during the compaction phase is calculated as (Eq. 13):

$$W_R = \int_V \sigma \varepsilon dV = \sigma \varepsilon V_R = \sigma V_R \frac{h_R^{CR} - h_R}{h_R} = \sigma V_R \frac{\left(\frac{\sigma}{E_R} + 1\right) h_R^{CR} - h_R}{h_R} = V_R \left(\frac{\sigma^2}{E_R}\right) \tag{13}$$

Where ε is the deformation of the rubber during the compaction phase. Thus, the storage energy results equal to:

$$W_R = \frac{M_R}{\rho_R}\left(\frac{\sigma^2}{E_R}\right) \tag{14}$$

W_R is the energy storage and transmitted to the sample once the compaction ends.

3. MAXIMUM CONTENT OF RUBBER IN ASPHALT MIXTURES

An additional step in the present methodology allows the maximum amount of rubber for a given recipe of asphalt mixture to be estimated. The limitations of the rubber content could come from different sources: a *physical/mathematical limit* or a *design limit*. The latter exists because the number of gyrations during the mix design procedure should simulate the compaction of the asphalt mixture in the field. For this reason, the factor α should have an upper limit, because N_{CR} should represent a reasonable number of gyrations for the compaction phase.

3.1. Physical/mathematical limit

Given the physical aspects, the volume of voids must be strictly positive, thus Eq. 8 could be rewritten as an algebraic inequality (Eq. 15) and therefore Eq.16:

$$V_V - \frac{\sigma}{E_R} V_R > 0 \tag{15}$$

$$V_V > \frac{\sigma}{E_R} V_R \tag{16}$$

The percentage of volume of the rubber before compaction ($\%V_R$) can be written as:

$$\%V_R = \frac{V_R}{V_V + V_R + V_{A+B}} \tag{17}$$

Therefore:

$$V_R = (V_V + V_R + V_{A+B}) \cdot \%V_R \tag{18}$$

And the volume of voids can be written as (see Eq. 9):

$$V_V = (V_V + V_R + V_{A+B}) \cdot \%voids \tag{19}$$

If Eqs. 18 and 19 are inserted in Eq. 16 it is possible to obtain:

$$\%V_R < \frac{E_R}{\sigma} \%voids \tag{20}$$

Eq. 20 defines the maximum upper limit of rubber content in the asphalt mixture. It can be seen that the maximum percentage of rubber depends proportionally on the target voids content.

The physical/mathematical limit should be interpreted as a theoretical threshold because the percentage of final voids cannot be equal to 0%. Nevertheless, it should be noted that the calculation above refers to the sample just after compaction, when the release of the rubber deformation is not yet occurred. Indeed, in the post-compaction phase the release of the deformation of the rubber causes the increase of the voids content of the asphalt mixture. Therefore, the required density should be measured once the volumetric stability of the sample is reached.

3.2. Design limit

The *physical/mathematical limit* analysed above should be combined with compaction limitations. N_{CR} should have an upper limit ($N_{CRlimit}$) corresponding to the number of gyrations (N_{max}) to reach a density that should never be exceed in situ (98%). Indeed, even if N_{CR} does not have a physical limit, the design of an asphalt mixture cannot envisage an infinite number of gyrations, because it should be compatible with the field compaction.

Therefore, the maximum possible number of gyrations ($N_{CRlimit}$) is introduced:

$$N_{CRLimit} = \alpha_{Limit} \cdot N_{max} \tag{21}$$

where α_{Limit} is the correction factor that corresponds to the selected $N_{CRLimit}$. α_{Limit} is defined as in Eq. 22:

$$\alpha_{Limit} = \frac{\%voids}{\%voids_{CR}} \qquad \%voids_{CR} = \frac{\%voids}{\alpha_{Limit}} \tag{22}$$

Substituting Eq. 9 and Eq. 3 in Eq. 22 it is possible to obtain the following relationship:

$$V_V^{CR} = \frac{1}{\alpha_{Limit}} V_V \frac{V_V^{CR} + V_{A+B} + V_R^{CR}}{V_V + V_{A+B} + V_R} \tag{23}$$

To simplify the calculation a variable substitution is used. Indeed, $Y = \frac{V_V^{CR} + V_{A+B} + V_R^{CR}}{V_V + V_{A+B} + V_R}$ is the ratio between the volumes of all the components at the end of the compaction and the target volume of the sample. Thus, Eq. 23 becomes:

$$\frac{1}{\alpha_{Limit}} V_V \cdot Y = V_V^{CR} \tag{24}$$

Substituting V_V^{CR} as defined in Eq. 24 in Eq. 8 it results:

$$\frac{V_V}{\alpha_{Limit}} \cdot Y = V_V - \frac{\sigma}{E_R} V_R \tag{25}$$

Simplifying Eq. 25 and recalling Eq. 20 it is possible to obtain:

$$\%V_R = \frac{E_R}{\sigma} \%voids \left(1 - \frac{1}{\alpha_{Limit}} \cdot Y\right) \tag{26}$$

Eq. 26 allows the maximum amount of rubber to be obtained, which depends on the α_{Limit} combining then the physical and the design limit.

Analysing Eq. 26 it can be seen that:

$$\%V_R = \frac{E_R}{\sigma} \%voids \left(1 - \frac{1}{\alpha_{Limit}} \cdot Y\right) < \frac{E_R}{\sigma} \%voids \tag{27}$$

because:

$$\left(1 - \frac{1}{\alpha_{Limit}} \cdot Y\right) < 1 \tag{28}$$

Indeed, α_{Limit} is always higher than 1 and $Y = \frac{V_V^{CR} + V_{A+B} + V_R^{CR}}{V_V + V_{A+B} + V_R}$ is always slightly lower than 1 because $V_R^{CR} < V_R$ just after compaction and $V_V^{CR} < V_V$ because the compaction is higher in order to take into account the release of the rubber. Thus, as highlighted in Eq. 27, the maximum allowable amount of rubber determined with the *design limit* is always included in the range of the maximum allowable limit imposed by the *physical/mathematical limit*. Moreover, *Y* is slightly lower than 1 because the difference between the numerator and the denominator is small; for this reason, *Y* could be considered equal to 1. This allows a further simplification of Eq. 27 and it is possible to arrive at the final formula for the determination of the maximum allowable amount of rubber (Eq. 28).

$$\%V_R \leq \frac{E_R}{\sigma} \%V_V \left(1 - \frac{1}{\alpha_{Limit}}\right) \tag{28}$$

4. CASE STUDY

4.1. Materials

The calculations above were applied for the mix design optimisation of a CR asphalt mixture used as a sub-ballast layer and in particular to determine the number of gyrations (N_{CR}) when 1.5% and 2% of rubber of the mass of the mixture is added replacing part of the aggregates. The target grading curve has been selected as the median curve between the limits defined by the envelope specification required by the Italian standards [38] as shown in Table 1.

Table 1. Bituminous sub-ballast grading curve

Sieve [mm]	Grading envelope of bituminous sub-ballast (passing material) [%]		Target grading curve (passing material) [%]
	Low	High	
25.4	100	100	100
19.1	80	100	90
9.52	54	76	65
4.0	36	56	46
2	23	40	31.5
0.42	10	22	16
0.175	7	16	11.5
0.074	6	10	8

The characteristics of the materials used for the fabrication of the bituminous sub-ballast are summarised in Table 2.

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

Bitumen			
Property		Standard	Value
Penetration at 25 °C (pen. grade 50–70)		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
Equiviscosity T Brookfield [°C]	0.28Pa·s	EN 12695:2000	143.1
	0.17Pa·s	AASHTO T316-04	156.2

Aggregates *(limestone)*		
Property	Standard	Value
Los Angeles abrasion loss [%]	EN 1097-2:2010	20.8
Bulk specific gravity coarse aggregates [g/cm^3]	EN 1097-3:1998	2.82
Bulk specific gravity sand [g/cm^3]	EN1097-6:2013	2.84
Bulk specific gravity filler [g/cm^3]	EN1097-7:2009	2.70
Crumb rubber		
Property	Standard	Value
Fraction 1 [mm] 60%	-	0.42–2
Fraction 2 [mm] 40%	-	2–4
Bulk gravity [g/cm^3]	C.N.R. UNI-1 and ASTM 128	1.154

The bituminous sub-ballast is composed of a dense-graded bituminous mixture with a maximum aggregate size of 22–25 mm [39], similarly to the base course for road pavements.

Although the composition is similar to a base course, typically the air voids content in the bituminous sub-ballast layer decreases to 1–3 % to ensure a higher impermeability of the layer [40]. For this reason, the target voids content for both mixtures, with and without crumb rubber, has been established as being equal to 3%.

4.2. Experimental procedure and sample preparation

Two CR mixtures with two percentages of rubber were prepared: 1.5% and 2% by the weight of the mixture. These mixtures were denoted respectively as CR-1.5 and CR-2.0.

The preparation of the samples was conducted following these steps:

- The aggregates were washed, dried and heated at 180 °C for at least 3 hours. The crumb rubber was kept at room temperature.
- The aggregates and the crumb rubber were mixed for 15 seconds in order to disperse the rubber homogeneously in the mixture.

- The bitumen (penetration grade 50/70) was heated at 130 °C for 1 hour. It was added and mixed for 1 minute. Afterwards, the filler was added to the mixture.
- The mould was preheated at 150 °C, the asphalt mixture was poured into the mould and compacted with the gyratory compactor at 145 °C.
- Once the compaction was finished, the samples were kept confined in the mould for 24 hours. A load of 5 kg was applied on the top of the specimens to confine them completely [41]. The objective was to provide enough time for the asphalt mixture to reach thermal stability.

Probably, certain chemo-physical phenomena occur at high temperatures (mixing and compaction temperatures). Nevertheless, the analytical calculation developed in this paper does not take temperature into account as a parameter and the possible chemical interactions between rubber and bitumen. For this reason, the samples were kept confined until they reached room temperature and the calculation above was applied to determine the relaxation of the rubber when it achieves thermal equilibrium. Afterwards, the samples were left at room temperature for six days unconfined to allow the rubber to recover (curing time). Therefore, in order to verify the evolution of air voids content, they were measured three times:

- Just after compaction
- After 24 h from the end of the compaction – thermal equilibrium
- After 7 days from the end of compaction – curing time

This procedure can be adopted in the laboratory using the gyratory compactor in a controlled environment. Certainly, the conditions could change if the compaction process was considered at the construction site or even with a different laboratory sample shape (slab compaction).

5. RESULTS AND DISCUSSION

A preliminary study was conducted to determine the additional quantity of bitumen necessary during the compaction phase to obtain a compaction curve that overlapped as much as possible with the traditional mixture curve. For this purpose, a reference optimised mixture for bituminous sub-ballast was prepared and compacted at N_{design} = 100 with 4% of bitumen by the weight of the mixture. The results (Figure 3) indicate that, for the same N_{design} = 100, the CR mixture with 1.5% of rubber needs 1.5% of bitumen more than the traditional mixture without rubber to achieve approximately the same void content. Thus, if the optimal traditional mixture contains 4% of bitumen by weight of the mixture, a similar voids content at the end of the compaction process is obtained using 5.5% of bitumen when 1.5% of crumb rubber is added to the mixture. Instead, with 2% of rubber the bitumen content of the mixture is 6% in order to obtain a similar voids content to the traditional mixture at the end of the compaction phase.

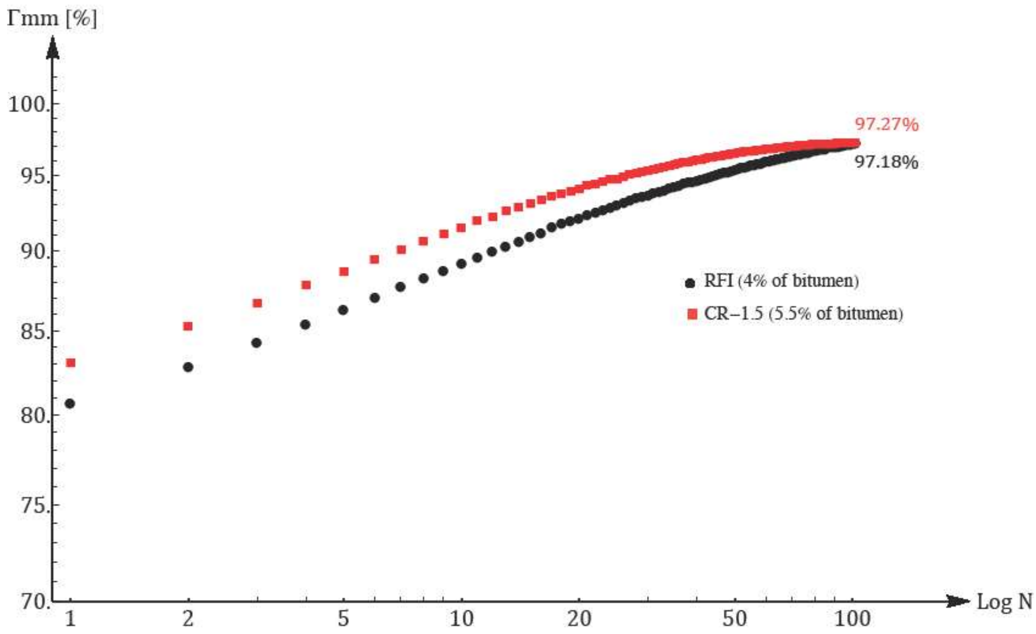

Figure 3. Example of comparison between the compaction curves of CR-1.5 with 5.5% of bitumen and the traditional RFI mixture with 4% of bitumen.

Looking at Figure 3, one may think that there is no need to increase the number of gyrations and the CR mixture is adequately compacted at N_{design} = 100. Nevertheless, after the compaction with the traditional N_{design}, the non-confined samples were subjected to a non-uniform expansion or evident damage, due to the uncontrolled rubber recovery and bitumen-rubber interaction at high temperatures.

This is why it was important to calculate an additional compaction and confine the samples until the thermal equilibrium had been reached. Thus, to take into account the deformation recovered by the rubber in the post-compaction phase the *correction factor α* and N_{CR} were calculated. Table 3 reports the results of the *correction factor α*, N_{CR} and the intermediate values obtained by applying the analytical method proposed in paragraph 2.2. The percentage of voids ($\%voids$) to achieve is established at the beginning of the compaction phase; $\%voids_{CR}$ corresponds to the calculation of voids content just after the compaction phase, before curing.

Table 3. Summary of calculated values for estimation of *correction factor α* and N_{CR}

Type of mixture	Traditional RFI	CR-1.5	CR-2.0
Percentage of aggregates by weight of the mixture [%]	96	93.5	92
Percentage of bitumen by weight of the mixture [%]	4	5.5	6
Percentage of rubber by weight of the mixture [%]	-	1.5	2
Rubber Young modulus [Mpa]	-	2	2
N_{design} [-]	100	100	100
$\%voids$ [%]	3	2.81	2.81
$\%voids_{CR}$ [%]	2.81*	1.91	1.47
α [-]	-	1.47	1.73
N_{CR} [-]	-	147	173

*The percentage of target voids was selected as the voids obtained for the traditional RFI mixture without rubber.

Therefore, the mix design optimisation of CR-1.5 and CR-2.0 was performed using N_{CR} equal to 147 and 173, respectively. Two percentages of bitumen for each mixture were used. Table 5 summarises the results of air void content measured in three different steps: just after compaction, after 24 hours and after a week. The values obtained in Table 4 correspond to the average of the results for three samples.

Table 4. Summary of results of voids content just after compaction, after 24 hours and after 7 days from the end of compaction

Type of mixture	Percentage of bitumen by weight of the mixture [%]	Percentage of voids measured just after compaction [%]	Percentage of voids measured after 24 h [%]	Percentage of voids measured after 7 days [%]
CR-1.5	5.0	2.73	2.98	3.75
	5.5	2.87	3.41	3.31
CR-2.0	6.0	2.65	2.96	3.46
	6.5	2.31	2.77	3.11

From Figure 4 it can be seen that the target voids were achieved with 6.04% of bitumen for CR-1.5 and 6.5% for CR-2.0.

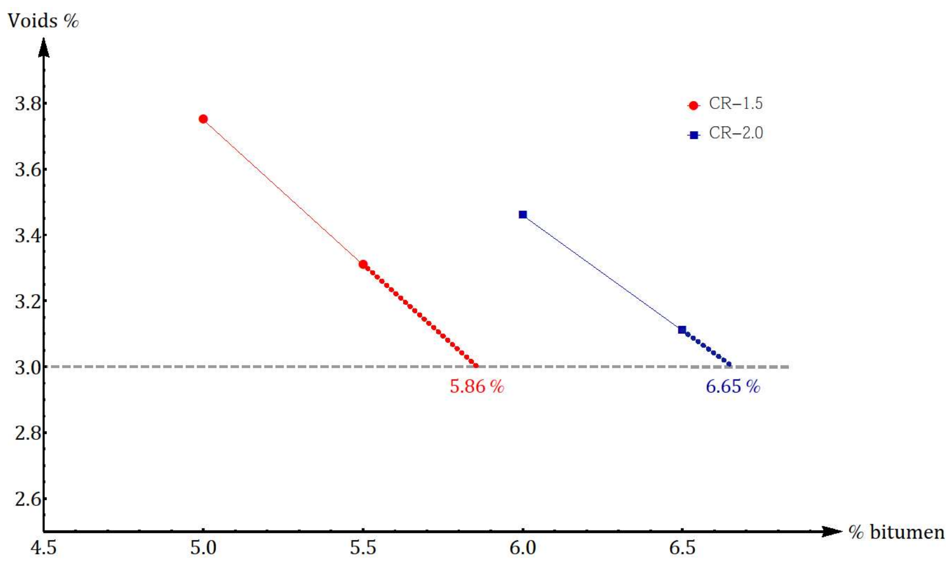

Figure 4. Results of voids content for CR-1.5 and CR-2.0 after the thermal stabilisation and curing time (7 days).

As can be seen from Figure 5, the voids content obtained for CR-1.5 with 5.5% of bitumen using the compaction adjustment proposed in the methodology is equal to 3.31%. The difference with the initial target voids content (3%) is equal to 10.3%. Thus, to achieve the 3% of voids it is necessary to add more bitumen. In the case of CR-2.0 with 6% of bitumen the difference between the voids content established at the beginning of the process and the voids measured is equal to 8.7%. The differences between the voids established at the beginning of the compaction and the voids measured at the end of the process are acceptable for the Italian standard [38].

Thanks to the formula developed (Eq. 26), it is also possible to calculate the maximum amount of rubber once the maximum number of gyrations is established as being compatible with the field compaction. If, for instance, a limit of 320 gyrations ($N_{CRlimit} = 320$) is considered, it means that $\alpha_{Limit} = 2$ (with $N_{max} = 160$). Therefore, using Eq. 26 it is possible to assess that the maximum amount of rubber to obtain the target voids equal to 3% is 2.16%. Finally, the energy dissipation calculated with Eq. 14 is equal to 12 991 Nm.

6. SUMMARY OF FINDINGS AND PERSPECTIVES

The present paper proposes an analytical approach to the mix design optimisation of bituminous mixtures containing crumb rubber performed using a gyratory compactor. The method takes into account the deformation release of the rubber after compaction for the calculation of the expected voids content. Therefore, it is possible to estimate and control the final voids content by applying a *correction factor* that adjusts the number of gyrations based on the target voids to be achieved. The formula includes different input parameters such as the characteristics of the materials, the Young modulus of the rubber and the target voids to achieve.

Based on the results, the analytical approach is considered successful in adjusting the required number of gyrations established by Superpave in order to compact asphalt mixtures containing rubber. The advantage of applying this methodology is that, by relying on theoretical calculation of rubber deformation release, the method provides a base for estimating an increase in compaction level when crumb rubber is added to the mixtures. The target voids required by standards can be established at the beginning of the process.

Additionally, in terms of a *physical/mathematical limit* and/or a *design limit*, due to a correspondence between the number of gyrations and the compaction in the field, it is possible to calculate the maximum amount of rubber for the asphalt mixture of interest.

In conclusion, this study exploits the consolidated principles of the theory of elasticity for tailoring a theoretical methodology for the mix design optimization of CRM mixtures. It provides promising results in estimating the final voids content after thermal stabilisation and curing in asphalt mixtures with crumb rubber. The approach developed could be applied to every type CR mixture once the input parameters (Young modulus of the rubber, mass and density of the materials involved and the target voids) are established.

Further studies are ongoing to improve the methodology determining the effect of temperature on the behaviour of the rubber and the mutual interactions between rubber and bitumen. Indeed, the chemical interaction between rubber and bitumen that may occur during the fabrication and compaction processes at high temperature can create distortions in the system and alter the parameters considered (Young modulus of the rubber).

Moreover, once the relationship between the evolution of the compaction (density) and the energy applied for the compaction is defined, it is possible to adapt the theoretical approach that can be extended to other compaction methods or field compaction.

Acknowledgments

The research presented in this paper was carried out as part of the Marie Curie Initial Training Network (ITN) action, FP7-PEOPLE-2013-ITN. This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant number 607524.

Disclosure statement

The authors declare that they have no conflict of interest.

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