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Effect of crumb rubber in dry process on mix design of asphalt mixtures

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ABSTRACT

This study aims to achieve a further improvement in the mix design of crumb rubber modified (CRM) mixtures maximizing the use of End-of-life tires. The paper contributes to the deeper understanding of the mechanisms characterizing the mix design process of rubberized asphalt (dry process). In particular, it has been verified that an analytical approach can be applied to determining the recovered deformation of the crumb rubber in the post-compaction phase. Knowing the deformation recovered by the rubber allows adjusting the compaction process by using a correction factor in order to finally meet the requirements of voids content for the asphalt mixture considered. It has been seen that the correction factor depends on the crumb rubber quantity and size, the bitumen content and the type of asphalt mixture. Moreover, once the target voids have been established, a mathematical formula can be applied to determining the maximum allowable amount of rubber that can be added to the asphalt mixture. Finally, based on the results obtained in the laboratory, a full-step protocol has been proposed in order to produce and compact rubberized asphalts.

Keywords: mix design, crumb rubber, gyratory compactor, rubberized asphalt

1. INTRODUCTION

The potentiality and the interest in reusing the scrap material coming from End-of-life (EoL) tires are demonstrated by several recent research efforts [1-4]. The dry process became recently a very attractive technology because of its production simplicity compared to the wet process [5]. Nevertheless, the research needs to investigate and validate the use of this material in civil engineering construction in order to cover the gap related to the high uncertainty of its performance. Indeed, the mechanical properties, the crumb rubber type and gradation, the binder and rubber content, the mixing and compaction energies and temperature are only some of the parameters that make the production process complex and unstable [6-7]. Crumb Rubber Modified (CRM) mixtures are designed to improve the stability of a gap-graded aggregate matrix exploiting the elastic properties of crumb rubber (rubber grains act as aggregates). Moreover, fine particles of rubber during the mixing time at high temperatures allows a certain modification of the bitumen [8].

Indeed, when the rubber is added to the asphalt mixture by means of the dry process, the grains of rubber absorb part of the volatile parts of bitumen (paraffin and maltenes) and swell up. This process of maturation, called “maceration”, leads to obtain a stiffer bitumen [9-11]. This effect has an important impact on the mechanical performance of mixtures containing CR compared to conventional asphalt, especially in the mixture response to plastic deformation [12-14].

The swelling of rubber particles due to the absorption of the volatile parts of the bitumen is not the only phenomenon that causes the volume instability of the CRM mixtures. Indeed, the rubber is mainly an elastic material, thus when a stress is applied, the rubber is subjected to a deformation, but once the stress is removed, it comes back to its original configuration. This raises problems during the mix design and compaction of these mixtures.

The Marshall stability and flow method, developed and valid for conventional mixtures, is not appropriate for designing CRM mixtures because of their lower stability and higher flow [8]. Therefore, the CRM mixture must be designed in terms of percentage of air voids, starting from the void content of a reference mixture and taking into account the elastic properties of the rubber. Indeed, in CRM mixtures, the crumb rubber releases the deformation accumulated during the compaction process; in dense graded mixtures, this may turn out in a non-negligible swelling of the sample and cause an increase in the amount of voids in the post-compaction phase. Consequently, the range of the admissible voids content for asphalt mixtures could be exceeded.

2. OBJECTIVES AND RESEARCH STAGES

This paper aims to quantify the recovered deformation of the rubber and to control this phenomenon by modifying adequately the compaction process in order to achieve a desired void content.

Specifically, the objectives of this paper are:

a) To develop a theoretical approach for the optimization of mix design for rubberised asphalt (dry process) considering the crumb rubber behaviour during the compaction and post-compaction phases.

b) To adjust the compaction process with the final aim of meeting the requirements for voids content.

c) To give an overview of characteristics and possible phenomena occurring during CR mixtures compaction (gyratory compactor and slab) in the laboratory.

In order to achieve these objectives, the following steps have been carried out:

1. To quantify the increase in bitumen demand when CRM mixtures are produced. This preliminary phase aims to identify the bitumen content in a CRM mixture that allows its compaction curve to be similar to that of a conventional mixture. At the end of the compaction phase, having traditional and CRM mixtures the same void content, allows having the same starting point for both mixtures when the post-compaction phase starts. This helps isolating and highlighting the contribution of the crumb rubber deformation release on increasing the voids content during the post-compaction phase.
2. To define a *correction factor (α)* for determining the reduction of the voids content to be achieved during the compaction phase, that takes into account the rubber elastic recovery. An analytical method has been defined to calculating how the desired voids content should be reduced in CRM mixtures, during the compaction phase, 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).

3. To observe the evolution of the voids content during the thermal stabilization and the curing phase, i.e. the time required by the rubber to recover its initial volume after compaction (Figure 1).

3. CORRECTION FACTOR (α)

A three-layered system has been used to separate and highlight the contribution of the rubber in the volume expansion (Figure 1).

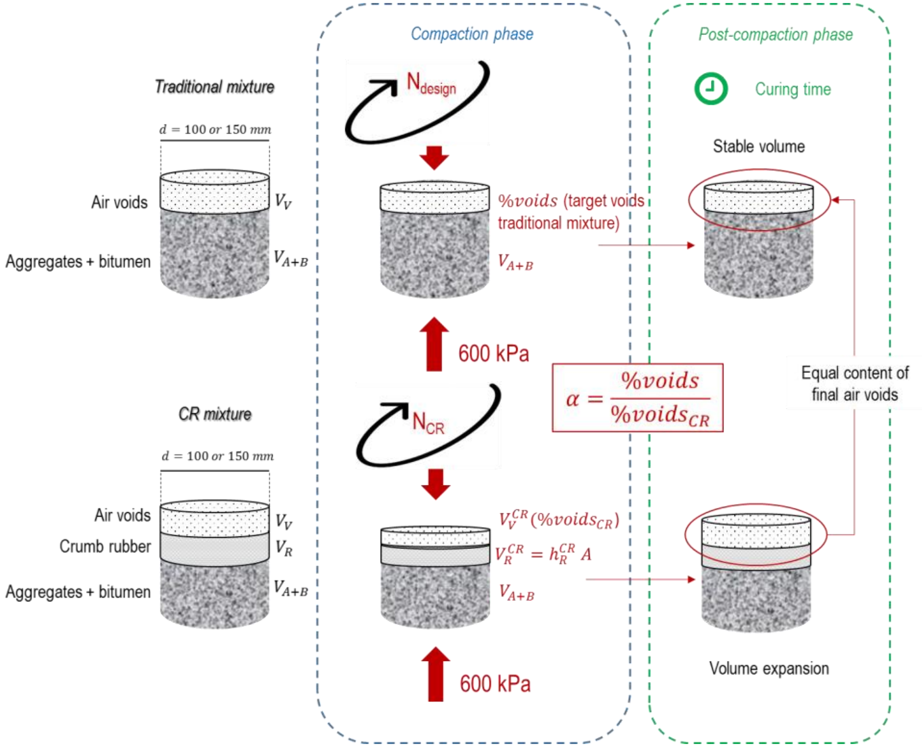

FIGURE 1 Schematic representation of compaction and post-compaction phase.

The correction factor α is calculated as the ratio between the target voids percentage expected for a sample of asphalt mixture without rubber ($\%voids$) and the final voids percentage to be achieved by the same asphalt mixture with crumb rubber after compaction ($\%voids_{CR}$), that is

$$\alpha = \frac{\%voids}{\%voids_{CR}} \tag{1}$$

where: $\%voids_{CR}$ is expressed as $\%voids_{CR} = V_V^{CR} / (V_V^{CR} + V_{A+B} + V_R^{CR})$, being V_{A+B} the cumulative volume of aggregates and bitumen, which remains constant before and after compaction, V_V^{CR} the final volume of air voids at the end of compaction and V_R^{CR} the final volume of the rubber at the end of compaction. The percentage of the target voids ($\%voids$) is established at the beginning of the process, and should be defined as the design voids of the corresponding traditional asphalt mixture (without rubber).

In order to calculate α, the two unknown parameters V_V^{CR} and V_R^{CR} should be determined, being V_{A+B} the same of the mixture without rubber.

The final volume of air voids, at the end of compaction, is calculated starting from the volume of the target voids, by adding the volume contraction of the sample and subtracting the volume contraction of the rubber. Thus, the final volume of air voids (V_V^{CR}) can be written as

$$V_V^{CR} = V_V - |\Delta V_R| - |\Delta V_S| = V_V - |V_R^{CR} - V_R| - |V_s^{CR} - V_s| \tag{2}$$

where V_V is the volume of the target voids ($\%voids$), V_R and V_S are the volumes of the rubber and the sample at the end of post compaction phase, V_S^{CR} is the volume of the sample at the end of compaction, ΔV_R and DV_S are the volume contractions of the rubber and the sample respectively, considered equal to the volume expansions in the post compaction phase.

Rubber is considered an elastic material and normal compressive stress is considered applied to the sample during the compaction (the shear stress is considered negligible for the rubber deformation recovery); in the hypothesis that the rubber is a continuum medium inside the sample, therefore the Hooke's law is applied as follows

$$\sigma = E_R \varepsilon_R = E_R \left| \frac{h_R^{CR} - h_R}{h_R} \right| \tag{3}$$

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 1). Isolating the final height of the rubber, recalling A as the area of the plate of the mould, writing V_R^{CR} as $A \cdot h_R^{CR}$, the final volume of the rubber is determined as

$$V_V^{CR} = V_V - \frac{\sigma}{E_R} V_R \tag{4}$$

V_V can be determined by using the expression $\%voids = V_V/(V_V+V_{A+B}+V_R)$. Thus, V_V can be isolated and results

$$V_V = \frac{\%voids\ (V_R + V_{A+B})}{1 - \%voids} \tag{5}$$

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 are known it is possible to rewrite Eq. (1), that is the correction factor α, as follows

$$\boldsymbol{\alpha = \frac{\%voids}{\%voids_{CR}} = \frac{\%voids|\Delta V_s|(\%voids - 1) + \frac{M_R}{\rho_R} + \frac{M_B}{\rho_B} + \frac{M_A}{\rho_A}}{\%voids\left(\frac{M_R}{\rho_R} + \frac{M_B}{\rho_B} + \frac{M_A}{\rho_A}\right) + \left(|\Delta V_s| + \frac{\sigma}{E_R}\frac{M_R}{\rho_R}\right)(\%voids - 1)}} \tag{6}$$

4. CASE STUDY APPLICATION

The analytical approach has been applied for optimizing a dense-graded bituminous mixture with a maximum aggregate nominal size of 16 mm. The grading curve of the asphalt mixture is reported in Table 1 and the bitumen content is 4.8% of the weight of the mixture.

TABLE 1 Grading curve of the asphalt mixture.

Sieve [mm]	Target grading curve (passing material) [%]
16	100
14	94.4
12	81.8

10	58.3
8	49.0
4	33.9
2	32.2
1	23.3
0.5	17.2
0.25	12.8
0.063	7.6

The target voids content for the mixtures, the reference and the CRM mixture, has been established as being equal to 3%.

The characteristics of the materials, bitumen and aggregates, used for the production of the bituminous sub-ballast are summarised in Tables 2 and 3, respectively.

TABLE 2 Characteristics of the bitumen

Property	Standard	Value
Penetration at 25°C (pen. Grade 35-50) [dmm]	EN1426	40
Softening point [°C]	EN1427	52.6
Bulk gravity [g/cm^3]	EN15326	1.034

TABLE 3 Characteristics of the aggregates.

Property	Standard	Value	
Bulk specific gravity sand coarse aggregates [g/cm3]	EN1097-6	0/2	2.859
		2/4	2.859
		4/6	2.910
		6/10	2.888
		10/14	2.89
Bulk specific gravity filler [g/cm3]	EN1097-7	2.671	

The crumb rubber size is 0.4-2.4 mm and its bulk specific density is equal to 1.141 g/cm^3.

5. RESULTS AND DISCUSSION

5.1.Voids content

A preliminary study was conducted for determining the additional quantity of bitumen required, in the compaction phase, to achieve a compaction curve that is as much as possible similar to the reference one. The reference mixture was prepared and compacted with 4.8% of bitumen by the weight of the mixture and 3% of final target voids. The measured voids content in the gamma bank (mean of several samples) is 3.27%. The rubberised mixture has been obtained by modifying the reference mixture. This modification consists on replacing a portion of natural aggregates with crumb rubber of the same size fraction. The quantity of crumb rubber added to the mixture is 1.5% by the volume of the sample. This first stage showed that if the optimal traditional mixture contains 4.8% of bitumen by weight of the mixture, a similar voids content at the end of the compaction process is achieved by using 5.83% of bitumen when 1.5% of crumb rubber is added to the mixture.

At this point of the study, the correction factor (α) can be calculated as shown in Eq. (6) with the following material quantities M_A = 7.317 kg, M_B = 0.479 kg, M_R = 0.240 kg, ρ_A = 2.86 kg/m3, ρ_B = 1.03 kg/m3, ρ_R = 1.141 kg/m3, E_R = 1.50 MPa and *%voids* = 3%. The value obtained for the correction factor α is equal to 1.69. In other words, the crumb rubber mixture has to achieve 1.69 times lower voids content to arrive, after the curing phase, to the target voids of the reference mixture. By establishing the target voids content equal to 3.27% and applying the methodology proposed in the paper, the final voids content of CR mixture was 3.52%. The difference is approximately equal to 8%.

5.2. Effects of different laboratory compaction procedures

Hereafter, certain observation and discussions will be reported as results of several compaction experiments carried out on the CR mixtures.

Figure 2a, shows three different samples with 1.5% of rubber by volume and different bitumen contents. The sample containing the same bitumen percentage as the reference mixture is broken. Indeed, it should be noted that when crumb rubber is added to the mixture, rubber particles absorb partially the bitumen, therefore it is necessary to add more bitumen to allow the integrity of the sample. Figure 2b shows two samples compacted in different conditions. The sample on the right has been compacted by using the analytical approach and the methodology proposed in the paper, the one on the left has been over-compacted. From Figure 2b it may be concluded that over-compaction may generate problems, because the grains of rubber drop out the sample after compaction.

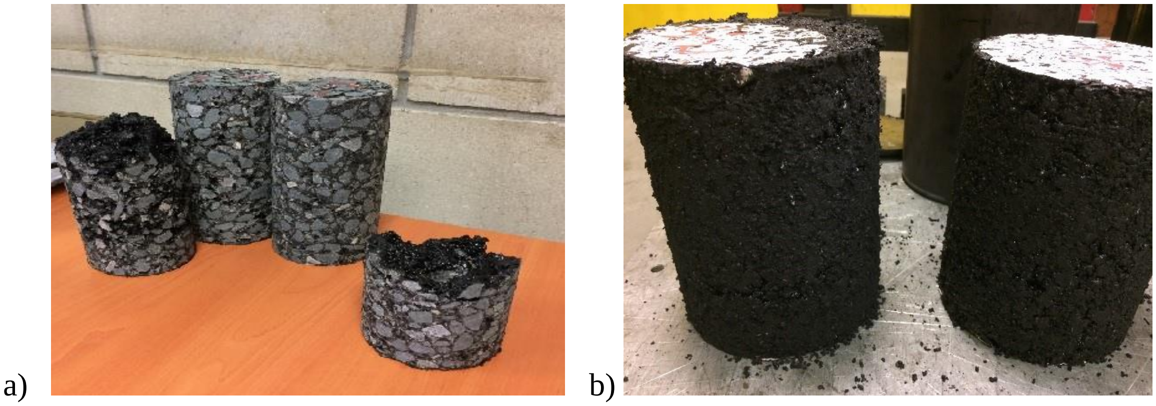
a) b)

FIGURE 2 a) Sample breakage due to a poor quantity of bitumen and b) over-compaction of CRM sample (on the left).

The proposed procedure may be adopted in the laboratory by using the gyratory compactor in a controlled environment. Certainly, the conditions may change if the compaction is conducted at a construction site or even with a different type of device in the laboratory. Indeed, in the case of slab compaction, it has been experimentally observed that it is not necessary to apply the correction factor. In this case, replicating the same conditions as for the reference mixture, the compaction leads to obtain approximately an equal content of voids for the CR mixture.

6. CONCLUSIONS

Based on the results, the analytical approach is considered successful in adjusting the required percentage of voids for compacting of asphalt mixtures containing rubber. The advantage of applying this methodology is that, by relying on theoretical calculation of the 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. In conclusion, this study exploits the consolidated principles of the theory of elasticity for tailoring a theoretical methodology for the mix design optimization of crumb rubber 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 of CRM mixtures once the input parameters (Young modulus of the rubber, mass and density of the materials involved and the target voids) are established.

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