5th INTERNATIONAL CONFERENCE
BITUMINOUS MIXTURES AND PAVEMENTS
Thessaloniki, Greece, 1-3 June 2011

MIX DESIGN AND PERFORMANCE EVALUATION OF CRM-MODIFIED ASPHALT CONCRETE MIXTURES

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ABSTRACT
This study reports the results of experimental tests carried out to define the volumetric composition of Asphalt Concrete (AC) mixtures that allows to include, by the dry process, scrap tire Crumb Rubber Modifier (CRM) as a substitute of 2% to 4% in weight of mineral aggregates. A 0/30 mm gap graded mixture for base layers, modified by introducing CRM, has been designed by using the volumetric method. In order to characterize mixture from a mechanical point of view, we carried out tests for the evaluation of Indirect Tensile Strength (ITS), stiffness modulus and fatigue resistance; volumetric and mechanical performance of the CRM-modified mixture were compared with those of a reference mixtures. The tests proved the CRM-modified mixture has mechanical properties better than those of the reference mixture, especially in terms of fatigue resistance whilst the CRM doesn't interact with bitumen; the fatigue resistance of CRM-modified mixture appears to be better than that of traditional dense asphalt concrete mixtures.

KEY WORDS: Crumb rubber modifier, dry process, mix design.

1. INTRODUCTION

The use of crumb rubber in asphalt pavements dates back to its initial applications in the sixties when Charles MacDonald tested the advantages of using rubber as an additive of the bitumen for asphalt mixtures [1]. By mixing crumb rubber and bitumen and leaving to the mix the time to react, it was possible to obtain a binder characterised by new and improved properties as compared to the original components. This test allowed the development of one of the classical processes of tyre rubber use in asphalt mixtures, known as Wet Process [2].

In the same years in Sweden, asphalt mixtures for surface layers were produced by using limited quantities of scrap tyre crumb rubber coming from scrap tyres in substitution of a fraction of the aggregates. Such mixtures named as "Rubit" ([3], [4] and [5]) represent the other process to introduce crumb rubber in the production of asphalt mixtures: the Dry process. This technology was later patented for use in the United States in 1978 under the trade name "PlusRide" [6].

In the Dry process [2] the crumb rubber is added to the aggregate mixture before the mixing with the bitumen; in this way the rubber acts as an aggregate and, at the same time, as a modifying agent since it partially reacts with the bitumen. In the Dry process, also known as "rubberized asphalt process", crumb rubber with dimensions between 0-6 mm is added to the aggregate mixture in percentages ranging between 3% to 6% in weight of the aggregates. The final result is an asphalt mixture characterised by a gap graded gradation with a high bitumen percentage, ranging between 8-10%, whose voids are filled with the bituminous mastic made up of bitumen, filler and crumb rubber.

In the Wet process, the crumb rubber is added as a modifier to the bitumen in order to improve its performances. Crumb rubber and bitumen are mixed and left to react at high temperatures: the final result is known as "Asphalt Rubber (AR)" [7]. The AR is used as a modified bitumen in the production of porous asphalt concretes (open graded) and gap graded asphalt concretes characterised by binder percentages ranging between 7 and 9%, to which corresponds a crumb rubber percentage of 1 – 1.5% on the mixture weight.

The two processes can be distinguished for the quantities and the gradation of the rubber used as well as for equipments needed to produce the mixes. The Dry process allows to recycle greater quantities of rubber as compared to the Wet process. Moreover, for the need of allowing the reaction between bitumen and crumb rubber, in the Wet process it is necessary to use specific mixers for production of the modified asphalt at high temperatures.

Considering the production methods, in the Dry process the interaction between crumb rubber and the binder is limited; it can be only appreciated in an indirect way by observing the behaviour of the asphalt mixtures. In the case of the Wet process modification of bitumen can be evaluated by measurement of the rheological properties of the AR. The literature indicates that the rubber absorbs the lighter fractions of the bitumen more readily [8], indicating that the proportion of asphaltenes in the residual binder increases and thus changes the rheological properties of the residual binder. Within the Dry process, the reaction between crumb rubber and bitumen is usually reduced by limiting the time at which the two components are maintained at the high mixing temperatures used to produce the asphalt mixture [9]. However, recent research has shown that during the mixing period as well as during transportation and laying, crumb rubber swells and reacts with bitumen changing the properties of the residual bitumen, the shape and stiffness of the rubber and consequently the performance of the asphalt mixture ([10], [11] and [12]).

The advantage of using crumb rubber in production of asphalt mixtures by the dry process is principally related to the improvement of environmental sustainability of roads considering this technology allows to recycle an industrial by-product; on the other effects, such as improvement of fatigue resistance and reduction of noise and vibration emissions as well as the increase of friction, at the present time, the international scientific community is not unanimous in judging the positive effects of crumb rubber.

The undisputed advantages of the Dry process in terms of ease of production and opportunity to reuse large amount of waste materials, have led the Authors to begin a research with the aim of evaluating mechanical and functional performances of AC mixtures for base layers specifically designed to contain high percentages of scrap tires CRM introduced in the mix by dry process.

2. DESCRIPTION OF THE EXPERIMENT

The experiment involved a first step of mix design to define the grain size distribution and the maximum percentage of CRM that can be introduced in the mixture without penalizing volumetric and mechanical properties. In the second step, the optimal asphalt content of a CRM-Modified Asphalt Concrete mixture (CRM-MAC) for base layers containing the allowable percentage of CRM was determined; volumetric and mechanical properties of this mixture were compared with a Reference Asphalt Concrete mixture (RAC), composed only of mineral aggregates, having the same aggregate size gradation and bituminous content of the CRM-MAC.

The material widely used in car tires is Styrene-Butadiene-Rubber (SBR), that is a synthetic rubber copolymer consisting of styrene and butadiene. It has good abrasion resistance and good aging stability when protected by additives; in the case of car tires, it is blended with Natural Rubber and called SBR/NR.

Physical properties of scrap tires CRM used in this study are reported in Table 1.

Table 1 Physical properties of CRM

CRM	γ_{rd} (g/cm^3)	γ_a (g/cm^3)	W_A (%)	Porosity (%)
SBR/NR	1.125	1.141	0.962	1.367

Figure 1 shows size gradation of CRM used in this study; the material is 100% passing the 1 mm sieve and the minimum particle size is greater than 0.06 mm.

In order to take into account the different specific weight of CRM and aggregates, mix design was carried out by the volumetric method.

The grain size distribution of mixtures was defined considering it should have enough volume of air voids (VAV) to be filled with CRM in percentages ranging between 2-4%.

3.1 Determination of CRM allowable percentage

In order to evaluate the influence of aggregate size gradation on compaction and volumetric properties of CRM-MAC, two different mixtures were composed: one of them is a typical continuous aggregate size gradation for Dense Base (DB) layers (figures 2 and 3) while the other is a Gap Graded mixture (GG).

Aggregate size gradations reported in these figures are expressed in terms of passing percentages by weight and contain 2% of CRM.

The CRM and aggregate mixtures were blended with a 50-70 penetration grade bitumen (Table 2) by using 3 different bitumen contents (4%, 4,5% and 5%).

Compaction curves of dense CRM-MAC are reported in Figure 4 and they have a non linear behaviour confirming known difficulties to compact these mixtures. Volumetric composition of these mixtures is reported in Table 3; VAV is less than 2% showing these mixtures don't have enough VAV to include CRM even in low percentages.

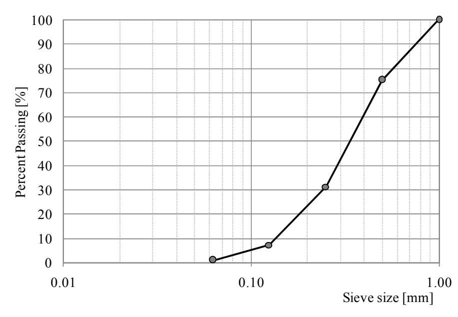

Figure 1 Size gradation of CRM

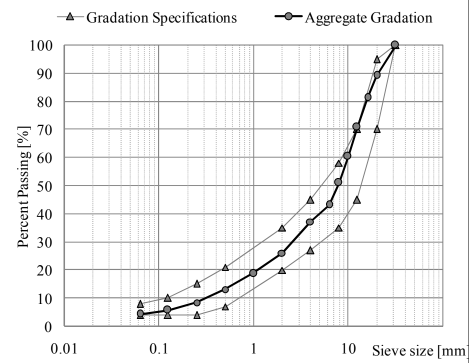

Figure 2 Aggregate size gradation for DB layers

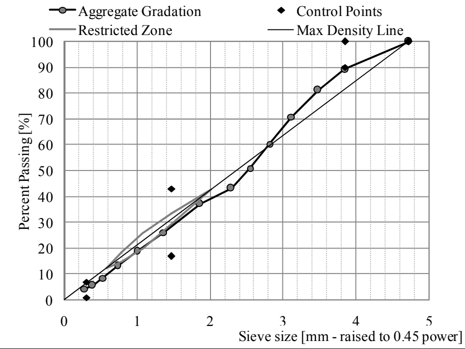

Figure 3 Superpave gradation limits

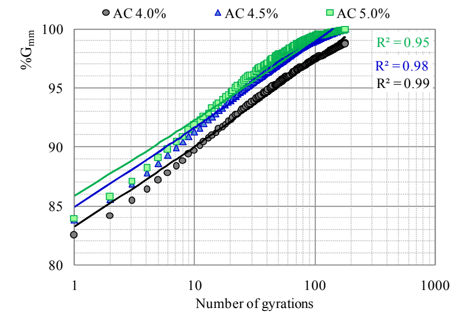

Figure 4 Compaction curve of a CRM-MAC

Table 2 Aspahlt Binder Characteristics

	Measure	Value	Reference
Penetration at 25 °C	dmm	50 – 70	UNI EN 1426
Softening point, Ring & Ball	°C	46 – 54	UNI EN 1427
Fraass breaking point	°C	≤ -8	UNI EN 12593
Dynamic viscosity at 60 °C	Pa·s	≥ 145	UNI EN 12596
Solubility in organic solvents	%	≥ 99	UNI EN 12592
Flash point (Cleveland open cup)	°C	≥ 250	EN ISO 2592
Specific gravity at 25 °C	g/cm^3	1.00 – 1.10	EN ISO 3838
Resistance to hardening RTFOT (163 °C)			UNI EN 12607-1
Loss in mass	%	0.5	
Retained penetration at 25 °C	%	≥ 50	UNI EN 1426
Increase in softening point	°C	≤ 11	UNI EN 1427

Table 3 Volumetric composition of dense CRM-MAM

AC	VAV	VMA	VFA	G_{mb}	G_{mm}
(%)	(%)	(%)	(%)	(g/cm^3)	(g/cm^3)
4	1.31	9.84	86.64	2.41	2.44
4.5	0.00	9.68	100	2.43	2.43
5	0.00	10.76	100	2.43	2.41

AC= asphalt content as percentage of mass of aggregates
VAV= volume of air voids
VMA= voids in mineral aggregate
VFA= voids filled with asphalt
G_{mb}= bulk density of the compacted mixture
G_{mm}= maximum density of the mix

Considering these results, it is clear that in order to include CRM in mixtures it is needed to increase the VAV; for this reason, 3 new mixtures were designed having a GG aggregate size gradation. Figure 5 reports the plot of the mixture A aggregate size gradation. It contains 4% of fine CRM in replacement of mineral aggregates of the same size. For these 3 mixtures we used two different gradations of CRM: 0.06-1mm (fine) and 2-4 mm (coarse) particle size.

Compaction curves of these mixtures are reported in Table 6; linearity of curves confirms their better compaction properties compared to the DB.

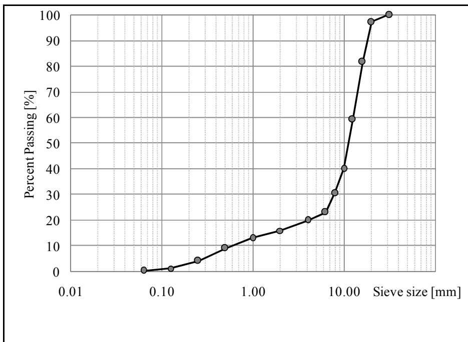

Figure 5 Mixture A

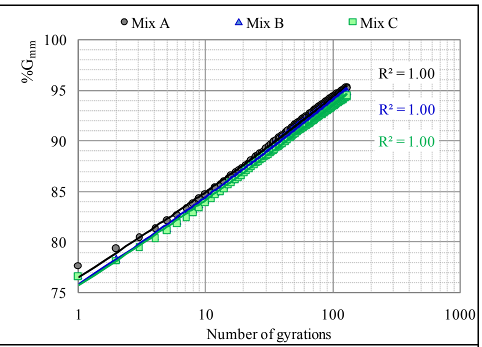

Figure 6 Compaction curves

Volumetric compositions of the 3 mixtures are reported in Table 4. Data show the better compaction is obtained for mixture A, where 4% of fine CRM was used. Results confirm that void dimensions in the aggregate mixture are too small and not enough to include some of the coarse CRM, making mixture compaction more difficult.

Table 4 Volumetric composition of gap graded CRM-MAC

Mixture	CRM (fine)	CRM (coarse)	VAV (%)	VMA (%)	VFA (%)	G_{mb} (%)	G_{mm} (%)
A	4%	-	4.75	15.59	69.56	2.23	2.34
B	3%	1%	5.17	15.97	67.61	2.22	2.34
C	2%	2%	5.59	16.33	65.80	2.21	2.34

Better properties of mixture A compared to the other 2 mixtures are confirmed by mechanical tests. Indirect Tensile Strength (ITS) decreases progressively from mixture A (ITS= 0.36 MPa) to Mixture B (ITS= 0.30 MPa) and mixture C (ITS= 0.25 MPa).

These results considering, it is evident the introduction of coarse CRM determines a decrease of mixture compaction properties as well as of mechanical properties; it is for this reason the optimal mixture was studied by adding only the fine CRM, and in order to improve compaction the maximum percentage of CRM was reduced to 3%. By this way only part of the mineral filler was replaced by the CRM.

3.2 Mix design of an optimal CRM-MAC for base layer

In order to evaluate effects of CRM on mixture performance, volumetric and mechanical properties of a gap graded RAC mixture, composed of only mineral aggregates, were compared with those of a CRM-MAC obtained by replacing the 3% by weight of mineral aggregates (0.06- 1 mm size) with an equal amount of fine CRM (6.7% by volume). Aggregate size gradation by weight of both mixtures is reported in figure 7; the percentage of mineral filler in the RAC is 10%. The optimal bitumen content for both mixtures is that determined on the CRM-MAC by the volumetric method. Figure 8 is a plot of compaction curves for 3 different bitumen contents (6.5%, 7.25% and 8%) and the same CRM content (3% by weight). The analysis of these data allows to determine the optimal bitumen content of this mixture that is 6.5%; for this bitumen content, the VAV @ N_{max}=130 gyrations is greater than 2% (VAV=3.07%).

Comparison of volumetric properties of the RAC with those of CRM-MAC is reported in Table 5. VAV in the RAC is about twice that determined on CRM-MAC; considering that the difference between the 2 mixture is only the replacement of 6.7% by volume of mineral aggregates with CRM, it appears CRM has a beneficial effect on compaction of mixture at the same bitumen content. The internal structure of a CRM-MAC sample is represented in figure 9.

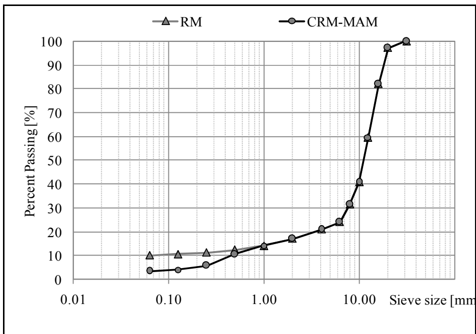

Figure 7 Aggregate size gradation by volume of RAC and CRM-MAC

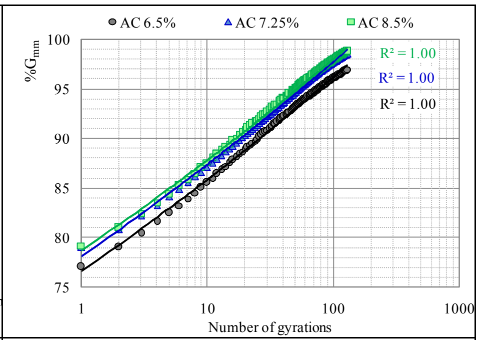

Figure 8 Compaction curves of CRM-MAC

Table 5 Volumetric properties of mixtures

Mixture	VAV	VMA	VFA	G_{mb}	G_{mm}
	(%)	(%)	(%)	(g/cm³)	(g/cm³)
CRM-MAC	3.07	16.08	80.90	2.27	2.34
RAC	6.06	19.10	68.26	2.27	2.42

4. MECHANICAL PROPERTIES OF MIXTURES

Mechanical properties of mixtures were determined by Indirect Tensile Strength, Resilient Modulus and Fatigue resistance tests carried out on specimens compacted by the gyratory compactor at N_{design}.

The values of Indirect Tensile Strength (ITS) measured on unconditioned specimens (ITSdry) and on specimens after conditioning in water (ITSwet) clearly show that both mixtures, as a consequence of the high bitumen content, don't have problems related to moisture susceptibility. Moreover, the CRM-MAC has a good mechanical resistance to be used for base layers (Table 6).

Table 6 Indirect Tensile Strength Test UNI EN 12697-12 and 23

Mixture (%)	ITS_d at 25°C (N/mm^2)	ITS_w at 25°C (N/mm^2)	ITSR (%)
RAC	0.32	0.29	90.6
CRM-MAC	0.42	0.40	95,2

The stiffness modulus and fatigue resistance were determined by the Indirect Tensile on Cylindrical specimens (IT-CY) procedure. Stiffness modulus was determined according to EN 12697-26 standard by tests carried out @ 1.8 Hz frequency and 20 °C (Figure 9). The mixtures have a quite similar stiffness modulus ranging from 3760 Mpa for CRM-MAC to 3460 MPa for the RAC. Stiffness modulus of these mixtures is lower than a traditional dense asphalt base with a continuous aggregate gradation and the same bitumen penetration grade.

Fatigue resistance was determined according to EN 12697-24 standard. Figure 10 shows the plot of fatigue resistance curves for the two mixtures; the CRM-MAC has significantly better performance compared to the RAC. Fatigue resistance of the RAC and CRM-MAC is expressed by the relationships (1) and (2) respectively:

$$Log(N_f) = 2745 - 0.34Log(\varepsilon_0) \text{ with } R^2 = 0.99 \quad (1)$$

$$Log(N_f) = 5938 - 0.34Log(\varepsilon_0) \text{ with } R^2 = 0.98 \quad (2)$$

The 2 curves are parallel but they are shifted on the x-axis of one order of magnitude; number of cycles to failure for CRM-MAC is about 10 times that of the RAC.

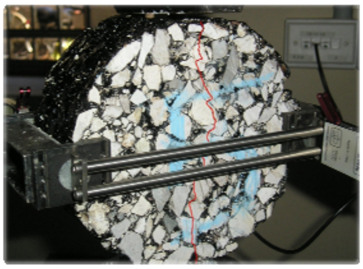

Figure 9 Test configuration for the evaluation of stiffness modulus and fatigue resistance

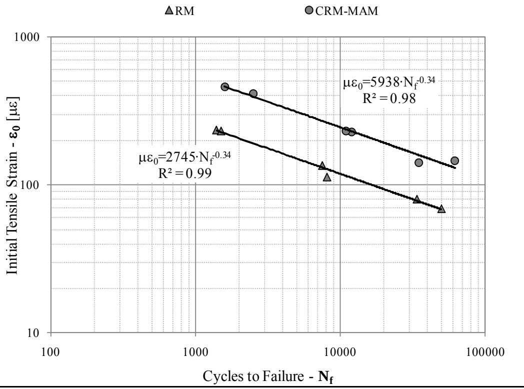

Figure 10 Fatigue resistance curves

5. CONCLUSIONS

Results obtained in this study confirm some findings reported in literature:

- CRM-MAC must have a gap graded aggregate grain size distribution to create voids capable of including crumb rubber;
- Crumb rubber size can influence significantly mixture compaction; in order to avoid these problems, it is better to use only fine CRM (0/0.06 mm) in percentages by weight lower than 4%;
- Introduction of 3% by weight of CRM in asphalt mixtures has a beneficial effect in terms of compaction allowing to reduce VAV compared to the RAC composed of only mineral aggregates and with the same bitumen content;
- The beneficial effect on mixture compaction contributes to increase ITS of the mixture as well as its fatigue resistance;
- The most relevant advantage of using CRM-MAC is the improvement of mixture flexibility that allows to increase fatigue resistance of one order of magnitude compared to that of the RAC.

The study is currently ongoing to evaluate performance of CRM-MAC for wearing courses specifically designed to reduce rolling noise.

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