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Improvement of Pavement Sustainability by the Use of Crumb Rubber Modified Asphalt Concrete for Wearing Courses

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Abstract: The main advantage of introducing crumb rubber in the production of asphalt mixtures is related to pavement's environmental sustainability. The addition of crumb rubber allows a significant amount of industrial waste to be recycled, and, in some specific cases, it allows the reduction of tire/road noise emissions. There are some other not unanimously recognized advantages related to this process, including the improvement of asphalt mixture mechanical properties and durability, as well as friction on pavement surface. This paper reports on a research project performed to evaluate the advantages of using crumb rubber in the production of low noise gap-graded asphalt concrete surfaces, by using both the wet and the dry processes, specifically designed to reduce rolling noise by optimizing surface texture. The study also compared the mechanical and functional performances of the mixes obtained by using the two technologies in order to assess their respective potentials for use as viable alternatives to other low noise asphalt surfaces that improve pavement sustainability by reducing environmental, social, and economic impacts. Results of laboratory and *in situ* tests, carried out on two specifically built field trials, clearly show these mixes can have optimal mechanical and functional performance as well reduce tire/road noise and warrant greater durability of wearing layers. Considering these findings, crumb rubber modified asphalt concrete can be classified as a construction material that can enhance the three dimensions of sustainability.

***Key words**: Crumb rubber; Dry process; Environmental sustainability; Low noise asphalt surfaces; Wet process.*

Introduction

Scrap tires form a major part of the world's solid waste management problem, and market groups forecast that in the coming years, the quantity of used tires will increase. At the same time, the increasing demand for road transportation has caused serious problems of noise pollution and road safety.

The principal advantage of using Crumb Rubber Modifiers (CRM) in the production of asphalt mixtures is the environmental sustainability of pavements related to the opportunity to recycle an industrial waste; in addition, the use of CRM allows the creation of asphalt surface layers in which rubber particles can improve mechanical properties of the mixtures, reduce noise emissions produced by tire vibrations, and increase pavement friction [1-4].

At the present time, the international scientific community is not unanimous in judging the positive effects of CRM in terms of road noise reduction. According to Sandberg and Ejsmont, there is no evidence that the insertion of small quantities of CRM within asphalt mixtures can significantly reduce tire/road noise [5].

There are two methods of adding CRM to hot mix asphalt concrete: the Dry Process (DP) and the Wet Process (WP). In the DP [6-9] the CRM is added to the aggregate mixture soon after it is mixed 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 [10-15]. In the WP, the CRM is added as a modifier to the bitumen in order to improve its performances. CRM and bitumen are mixed and left to react at high temperatures: the final result is known as "Asphalt Rubber" (AR) [16-18].

The two processes can be distinguished by the quantities and the gradation of the rubber used as well as the equipment needed to produce the mixes. The DP allows greater quantities of rubber to be recycled as compared to the WP. Moreover, in the WP, to allow the bitumen to react with CRM, it is necessary to use specific mixers for the production of the modified asphalt at high temperatures.

In the above framework, this paper reports on results of a research project performed to evaluate the advantages, in terms of pavement sustainability, of using CRM in the construction of specifically designed low noise gap graded asphalt mixtures by using both the wet and the dry processes. The project was developed by University of Pisa in collaboration with the Environmental Protection Agency of Tuscany Region, which contributed by evaluating acoustic performance of pavements.

In order to reduce tire/road noise, both the mixtures have been designed with the specific aim of optimizing pavement surface macrotexture by an appropriate selection of aggregate gradations. In order to assess their potential for use as a viable solution to enhance environmental, social, and economic sustainability of asphalt pavements, the study compares the mechanical and functional performances of the resulting mixes, evaluated by laboratory and in situ tests carried out in field trials.

The Use of CRM in Asphalt Mixes

The material widely used in car tires is Styrene-Butadiene-Rubber (SBR) that is a synthetic rubber copolymer consisting of styrene and butadiene, whereas the truck tires mainly contain natural rubber (NR). CRM used in this study comes from mechanical grinding of

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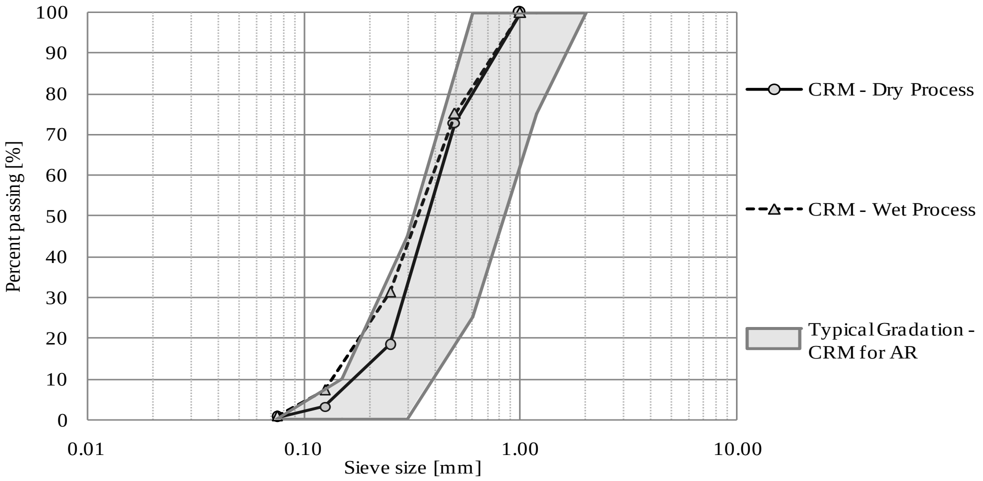


Fig. 1. Size Gradations of CRM.

scrap tires at room temperature; these scrap tires are comprised of 50% weight of truck tires and 50% weight of car tires. Fig. 1 represents size gradation of CRM used to produce gap graded mixes, according to the WP and DP, overlaid to the typical CRM gradations for production of the AR.

Both size gradations of CRM fulfill the requirements for the AR production [19]. As compared to the traditional DP, in which crumb rubber has dimensions in the range 0-6 mm [9], CRM in this study consists of small particles, characterized by a wide specific surface which allows a partial reaction with bitumen [12]. For this reason, we deal with CRM for both the mixes produced by the WP and the DP.

Description of the Experimental Program

The program's first step of mix design was to define the aggregate size gradations and the optimum asphalt contents to be used in the mixes; in the second step, laboratory and field tests were carried out to evaluate mixture performance.

The gap graded asphalt mixture produced by the dry process (GGD), has been laid on an experimental road section (roughly 2,500 m long) with the specific aim of reducing traffic noise on a urban road in the Municipality of Signa (Florence); the wearing course is 3 cm thick. The gap graded asphalt mixture produced by the wet process (GGW), has been used for an experimental pavement on a roughly 150 m long section within the "Leopoldo" [20] research project, with a 3 cm thick asphalt layer.

Cores were taken from both the pavements for quality controls on aggregate gradation, asphalt content, and air void percentage. The field mixtures are substantially the same of the design mixtures with regard to the aggregate gradations and the bitumen contents; as far as the air void contents, they are approximately 2% more than those of the design mixtures.

In order to check field performance of mixtures, pavement sections were tested to evaluate surface characteristics (friction and texture) and acoustic performance.

Mix Design

Mix design was carried out by the volumetric method. The optimum asphalt content was identified by optimizing the air void content.

Aggregate Gradation

Physical properties of aggregates and CRM were determined according to the UNI-EN (Italian Standards) 1097-6/7 procedures (Table 1).

Given the considerable difference between the specific gravity of CRM and natural aggregates, the grain size distribution of the GGD mix was composed by calculating volumetric proportions of the different materials (Table 2). The grain size distributions of both mixtures fulfill the aggregate gradations designed in this project for

Table 1. Aggregates Characteristics.

	GGD				GGW		
	Basalt 3/6	Sand 1	CRM	Filler 1	Basalt 4/6	Sand 2	Filler 2
Bulk Specific Gravity (kg/m^3)	2653	2625	1141	2650	2753	2629	2650
Apparent Specific Gravity (kg/m^3)	2759	2696	1141	2650	2863	2690	2650
Water Absorption (%)	1.45	1.01	0	0	1.39	0.86	0

Table 2. Aggregate Blending

	GGD				GGW		
	Basalt 3/6	Sand 1	CRM	Filler 1	Basalt 4/6	Sand 2	Filler 2
Proportions by Volume (%)	72.4	17.1	4.5	6.0	74.8	14.0	11.2
Proportions by Weight (%)	74.4	17.5	2.0	6.1	75.6	13.5	10.9

Table 3. Aggregate Grading of the Mixtures.

Sieve Size (mm)	GGD	GGW
8	100.0	100.0
6.3	100.0	91.8
4	80.9	43.1
2	23.9	21.8
1	18.2	17.4
0.5	14.6	15.0
0.25	11.5	13.3
0.125	9.9	10.7
0.063	8.9	7.6

gap graded asphalt concrete surfaces (Table 3, Fig. 2).

The two aggregate gradations are characterized by different values of the aggregate nominal size; in particular the maximum aggregate size is equal to 5.0 mm for the GGD mix, and it is equal to 6.0 mm for the GGW mix. This allows maximum Voids in Mineral Aggregate (VMA) of the GGD mix in order to introduce the maximum quantity of CRM into the mix [21]. The GGD mix contains 2.0% of CRM by weight of mineral aggregates, corresponding to 4.5% by volume, in replacement of mineral aggregates of the same size.

Optimum Asphalt Content and Volumetric Properties of the Mixtures

The aggregates of the GGD have been mixed with a 50-70 penetration grade Polymer Modified Asphalt (PMA), whereas aggregates of the GGW have been mixed with AR. The AR is composed of CRM, 20% by weight of the binder, and the remaining 80% of 50-70 penetration grade pure bitumen. In the production of the GGD mix, the temperature of the aggregates ranged between 170℃ and190℃, while that of the Polymer Modified Asphalt ranged between 160℃ and 180℃. The crumb rubber was added to the mix together with the filler at room temperature.

For the production of the GGW mix, both the temperatures of the aggregates and the AR ranged between 170℃ and 190℃.

The optimum Asphalt Content (AC) of the two mixes was determined by the gyratory compaction assessing the volumetric characteristics of four mixtures with asphalt contents ranging from 7.5% to 9.0% (Table 4). In determining the volumetric properties of the mixes, the aggregate absorption percentage was assumed to be equal to 1/3 of water absorption, as required by UNI-EN 12697-5.

The optimum AC was determined by minimizing the volume of air voids VA with the constraint that, at the compaction level N_{max}, VA must be higher than 2%. The optimum AC was equal to 8.5% for the GGW mix and equal to 9.0% for the GGD mix. Given the greater discontinuity of the aggregate gradation of the GGD mix, along with the maximum allowable AC, this mix shows a VA that is 4% higher than that of the GGW mix. In order to reduce the VA of the GGD mix, it would be necessary to increase the AC, but a higher AC would lead to a reduction of mechanical properties of the mix. For this reason, the optimum AC for the GGD mix was set up to 9.0%.

Fig. 3 shows the internal structure of the two mixtures. The gyratory compaction curves of the studied mixtures are compared in Fig. 4. Both curves show a linear increase of compaction degree; in particular, the GGW mix curve has a slightly steeper slope and a higher density than the curve referring to the GGD mix. This highlights that, at the same compaction temperatures, the GGW mix shows better compaction properties as compared to the GGD mix.

Mechanical Properties of the Mixtures

In order to characterize the mixes from a mechanical point of view, Indirect Tensile Strength (ITS) Tests, Stiffness Modulus Tests and Fatigue Resistance Tests have been carried out on specimens compacted by the Gyratory Compactor at $N_{design.}$

Indirect Tensile Strength

ITS measurements have been carried out at 25℃, according to UNI-EN 12697-23. ITS values (Table 5) are similar for both the mixes, and they are higher than the minimum value required by the national standards for gap graded asphalt mixes to be used as wearing courses. In order to evaluate moisture susceptibility, the

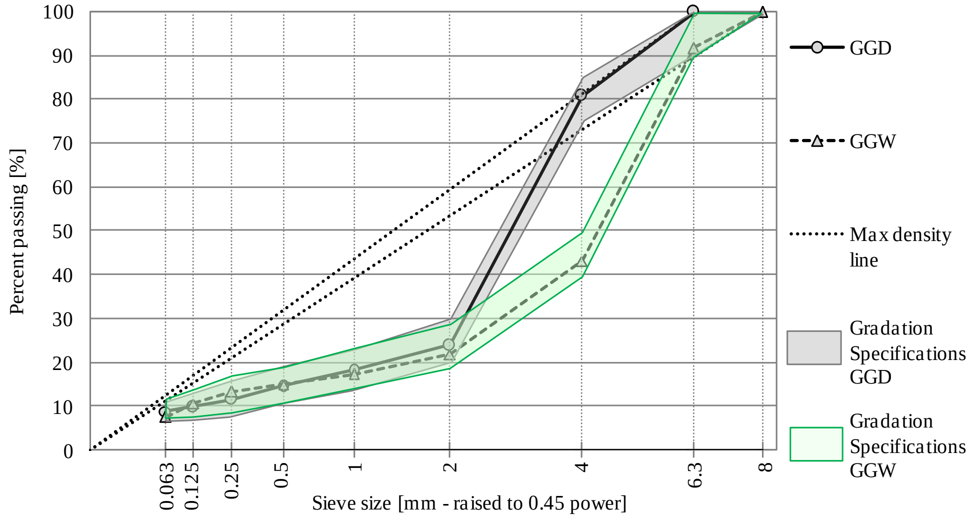


Fig. 2. Aggregate Size Gradations and Specifications of GGD and GGW.

Table 4. Optimum Asphalt Content Evaluation.

	Volumetric Properties – Gap Graded Asphalt Mixture by the Dry Process (GGD)							
	Number of Gyrations	VA [b] (%)	VMA [c] (%)	VFA [d] (%)	Gmb [e] (kg/m^3)	Gmm [f] (kg/m^3)	VG[g] (%)	VB[h] (%)
AC=7.5 % [a]	Ninitial=10	17.05	29.69	42.56	1947	2347	70.31	12.63
	Ndesign=50	10.73	24.33	55.89	2095	2347	75.67	13.60
	Nmax=130	7.87	21.90	64.07	2162	2347	78.10	14.03
AC=8.0 % [a]	Ninitial=10	16.08	29.62	45.70	1958	2333	70.38	13.53
	Ndesign=50	9.71	24.27	59.99	2106	2333	75.73	14.56
	Nmax=130	6.82	21.85	68.78	2174	2333	78.15	15.03
AC=8.5 % [a]	Ninitial=10	15.27	29.68	48.55	1965	2319	70.32	14.41
	Ndesign=50	8.92	24.41	63.45	2112	2319	75.59	15.49
	Nmax=130	6.06	22.04	72.50	2178	2319	77.96	15.98
AC=9.0 % [a]	Ninitial=10	14.75	29.99	50.79	1965	2305	70.01	15.23
	Ndesign=50	8.39	24.76	66.10	2112	2305	75.24	16.37
	Nmax=130	5.51	22.39	75.38	2178	2305	77.61	16.88
	Volumetric Properties – Gap Graded Asphalt Mixture by the Wet Process (GGW)							
	Number of Gyrations	VA [b] (%)	VMA [c] (%)	VFA [d] (%)	Gmb [e] (kg/m^3)	Gmm [f] (kg/m^3)	VG[g] (%)	VB[h] (%)
AC=7.5 % [a]	Ninitial=10	14.00	25.98	46.13	2191	2547	74.02	11.98
	Ndesign=50	6.81	19.79	65.60	2374	2547	80.21	12.99
	Nmax=130	3.95	17.33	77.21	2446	2547	82.67	13.38
AC=8.0 % [a]	Ninitial=10	13.01	26.30	50.51	2191	2519	73.70	13.28
	Ndesign=50	5.85	20.22	71.09	2372	2519	79.78	14.38
	Nmax=130	3.02	17.83	83.06	2443	2519	82.17	14.81
AC=8.5 % [a]	Ninitial=10	12.19	26.44	53.90	2197	2502	73.56	14.25
	Ndesign=50	5.01	20.43	75.47	2377	2502	79.57	15.42
	Nmax=130	2.17	18.05	87.96	2448	2502	81.95	15.88
AC=9.0 % [a]	Ninitial=10	11.70	26.86	56.43	2195	2486	73.14	15.16
	Ndesign=50	4.54	20.92	78.31	2373	2486	79.08	16.39
	Nmax=130	1.71	18.58	90.80	2443	2486	81.42	16.87

[a] asphalt content as percentage of mass of aggregates

[b] air voids

[c] voids in mineral aggregate

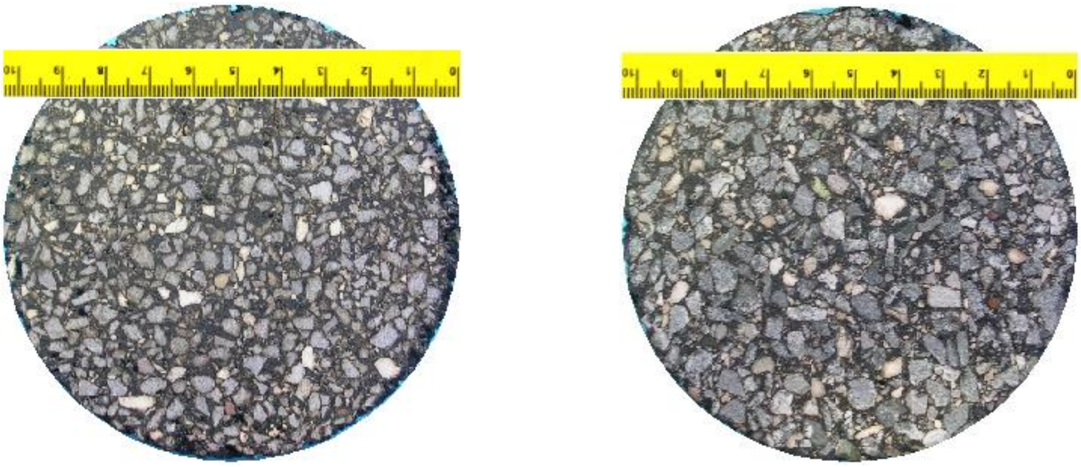
[d] voids filled with asphalt

[e] bulk density of the compacted mixture

[f] maximum density of the mix

[g] volume of aggregate, the bulk volume including the aggregate pores

[h] volume of effective asphalt binder



Gap Graded Asphalt Mixture by the Dry Process (GGD)

Gap Graded Asphalt Mixture by the Wet Process (GGW)

Fig. 3. Internal Structure of the Mixes.

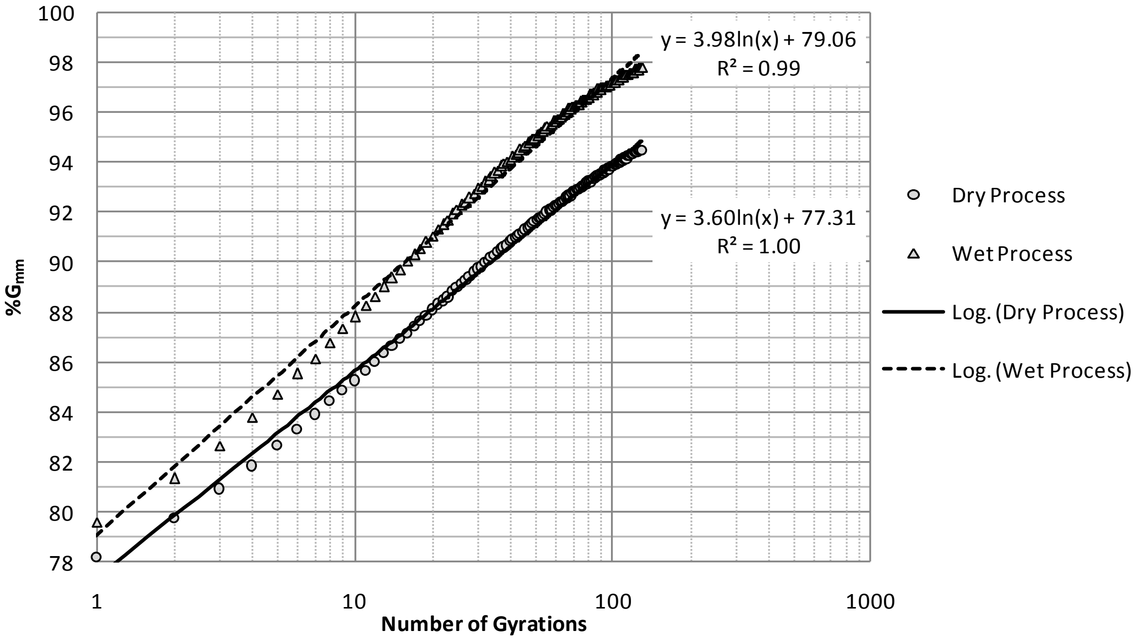
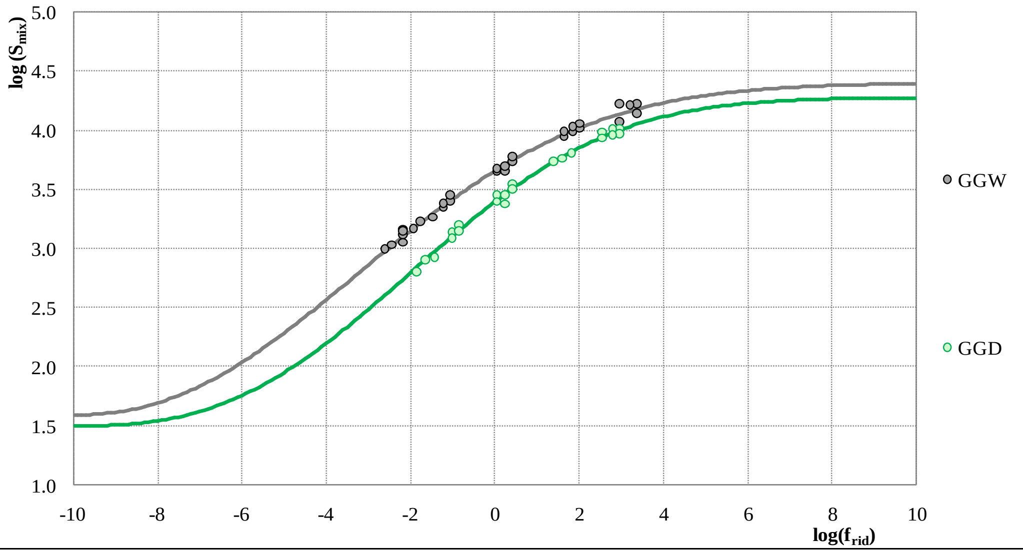


Fig. 4. Gyratory Compaction Curves of the Studied Mixtures.

Table 5. Indirect Tensile Strength Test Results.

Sample	GGD			GGW		
	ITS_d at 25℃ (N/mm^2)	ITS_w at 25℃ (N/mm^2)	ITSR (%)	ITS_d at 25℃ (N/mm^2)	ITS_w at 25℃ (N/mm^2)	ITSR (%)
1	0.70	0.62		0.80	0.76	
2	0.70	0.73		0.81	0.72	
3	0.78	0.69		0.74	0.73	
Mean Value	0.73	0.68	93.6	0.78	0.74	94.0
St. Dev.	0.05	0.06		0.04	0.02	
COV (%)	6.4	8.2		4.8	2.8	



Temperature (℃)	0			10			20		
Frequency (Hz)	1	2	10	1	2	10	1	2	10
M_R for GGD (MPa)	9637	10558	12594	5341	6152	8202	2482	2987	4434
M_R for GGW (MPa)	14876	15851	17944	9076	10082	12483	4541	5270	7212

Fig. 5. Master Curve.

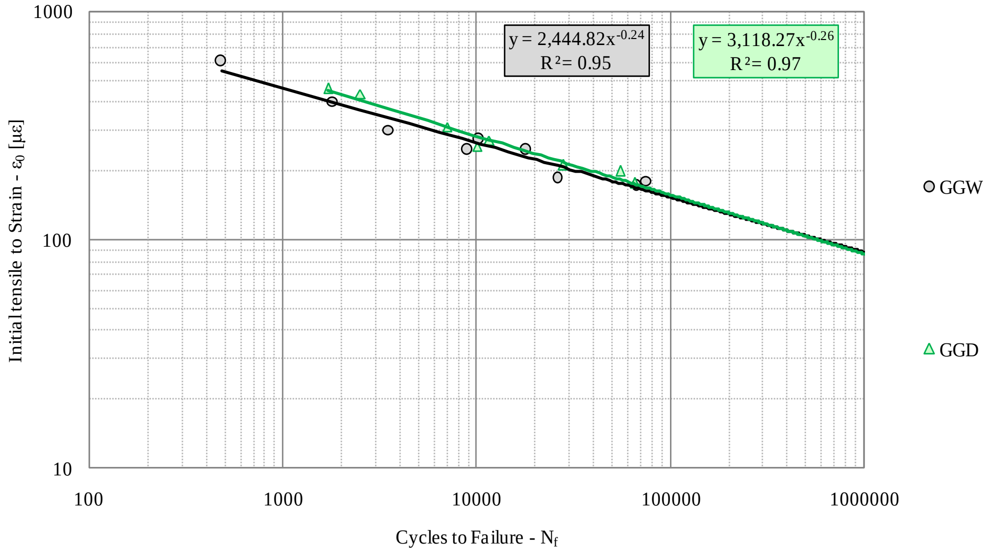


Fig. 6. Fatigue Resistance Curves.

Indirect Tensile Strength Ratio (ITSR), according to UNI-EN 12697-12, was determined. The results obtained (Table 5) clearly show that no problems pertaining to moisture susceptibility arise for the two mixes.

Stiffness Modulus

Master curves of mixture stiffness were determined through the Indirect Tensile Test on Cylindrical specimens (IT-CY), according to UNI-EN 12697-26 Annex C procedure. Tests were performed by using three pulse duration (75, 125, 200 ms), and at five temperatures (2, 10, 20, 35 and 40℃); samples were conditioned at test temperatures for at least 12 hours in a climatic chamber.

In this study, the sigmoidal model proposed by Medani and Molenaar in 2004 [22] was used to define the functional shape of the master curve, modifying the one introduced previously by Pellinen and Witczak. The shift factor was determined through the Arrhenius form.

Fig. 5 shows the master curves of the mixes determined by the above specified tests together with the Stiffness Modulus MR values calculated at some representative frequencies (1, 2, and 10 Hz) and temperatures (0, 10 and 20℃). The determined values highlight that the GGW mix shows an increase in MR as compared to the GGD mix; such increase can be due to the better mixture compaction in the field of high temperatures (low frequencies), whereas in the field of low temperatures (high frequencies), this increase is due to the greater stiffness of AR as compared to PMA blended with CRM.

Fatigue Resistance

The fatigue resistance was determined by the Indirect Tensile Test on Cylindrical specimens (IT-CY), according to UNI-EN 12697-24 Annex E. Tests were performed at 20℃ and at a load repetition time equal to 0.5 s.

Fig. 6 shows the plot of fatigue resistance curves for the two mixtures. The two curves are almost overlapping one another: this means that AR shows a fatigue attitude similar to that of PMA blended with the CRM.

Field Performance

Performances of the experimental wearing courses were evaluated in terms of surface characteristics, macrotexture, friction, and acoustic performance. Measurements were taken at different ages after laying in order to assess performance over time. Concerning the GGD mix, only the results measured on a 200 m long section are reported in Fig. 7.

Macrotexture

Surface macrotexture was recorded on 2D pavement profiles by using a mobile laser profilometer, which allows the continuous recording of the pavement profile at sampling intervals of 1 mm. The Estimated Texture Depth (ETD) was calculated [23] on the experimental section from the Mean Profile Depth (MPD) evaluated on the recorded profile. Fig. 7 shows the variation over time of macrotexture expressed in terms of ETD, averaged at every 10 m, together with the Mean Texture Depth (MTD) threshold value. The GGW mix shows macrotexture values higher than those of the GGD mix. This is due to the greater aggregate nominal size. Macrotexture of the two pavements increases over time, with this trend being more pronounced for the GGW mix.

By using the recorded profiles, we have calculated the one-third octave band mean texture spectrum (Ltx) which refers to the wavelength interval ranging between 2 mm and 250 mm, according to the ISO/CD 13473-4 and 5 procedures.

Fig. 8 shows the texture spectrum of the experimental wearing courses overlaid to the typical spectrum of a Dense Asphalt Concrete (DAC) with 12 mm maximum chipping size. In order to obtain a low noise asphalt surface, capable of reducing noise emissions at the tire/road interface as compared to noise levels of a traditional asphalt surface, the texture spectrum (Fig. 8) should have the following characteristics [20, 23]:

- the highest Ltx value should be found in the wavelength (λ)

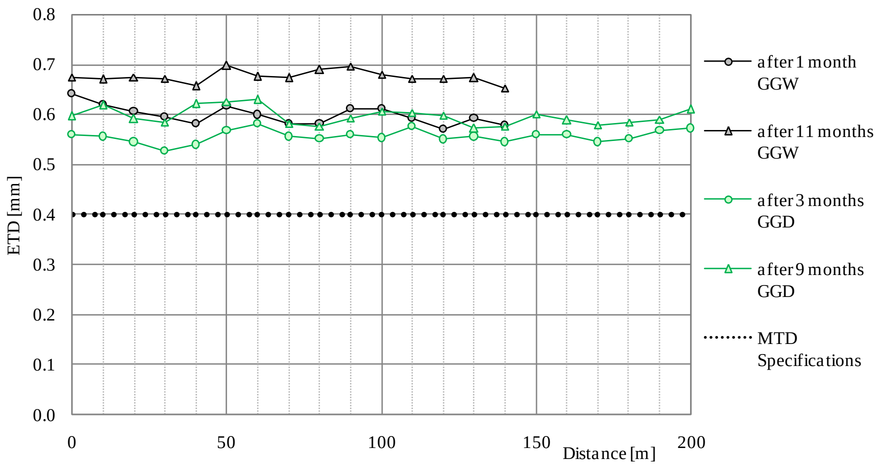


Fig. 7. Texture Profiles.

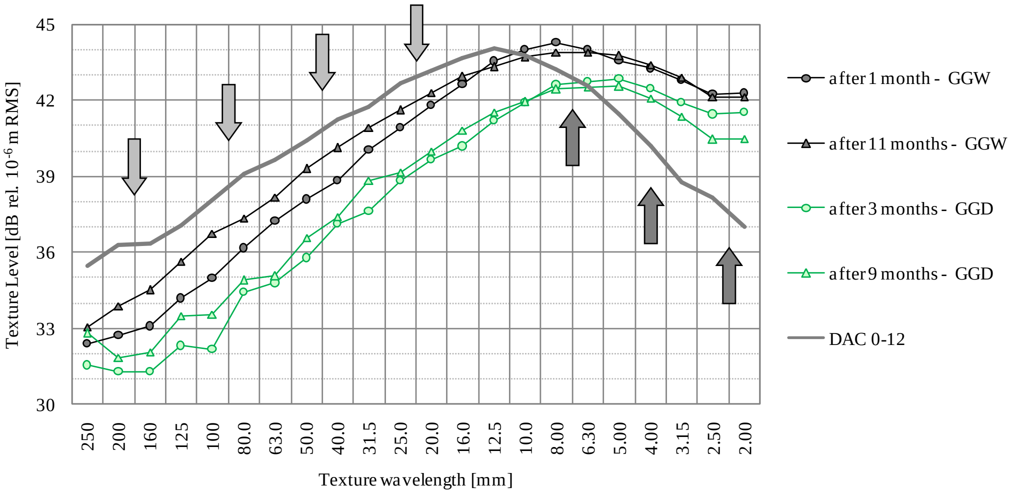


Fig. 8. Texture Spectrums.

field below 10 mm;

- Ltx values should tend to minimum values in the wavelength field λ > 10 mm.

Fig. 8 clearly shows the experimental mixes fulfill these requirements; in particular, as an effect of the greater nominal diameter of the aggregate gradation, the GGW mix shows higher texture levels than the GGD mix. Moreover, the greater stability of the GGD texture levels over time assures a better acoustic performance stability.

As described in the following sections, these results are confirmed by the measurement of rolling noise.

Friction

Friction measurements were performed by using the Skiddometer BV11. The tests have been carried out at a speed of 20 km/h by adequately wetting the pavement in order to create the 1 mm thick water film.

By using the World Road Association (PIARC) model, and after having suitably calibrated the model parameters for the specific device used in these tests, the Friction Number (F60) of the International Friction Index (IFI) has been determined on the basis of friction and macrotexture values.

Fig. 9 shows F60 measured values, averaged at every 10 m, together with the friction threshold expressed in terms of F60; the latter are determined from the national standards for a newly built traditional asphalt surface, which is characterized by a Speed Constant (Sp) equal to 33.85 km/h. The results show the optimum friction levels, which can be obtained by using CRM in the production of asphalt concrete, are approximately two times the levels required by the technical specifications [24]. The significant increase of friction has the relevant effect of improving road safety and reducing the related social impact.

Over time, friction level of the GGW mix shows a slight increase, whereas the GGD mix shows a reduction of about 10%. This can be attributed to the greater adhesion of the AR to the aggregate, and this determines more stable friction levels over time. On the contrary, the GGD mix shows reductions of friction levels, which is probably due to the removal of rubber particles by tires.

Acoustic Performance

The basic assessment of acoustical properties was carried out by in situ measurements, according to the ISO 13472-1 (“Adrienne”

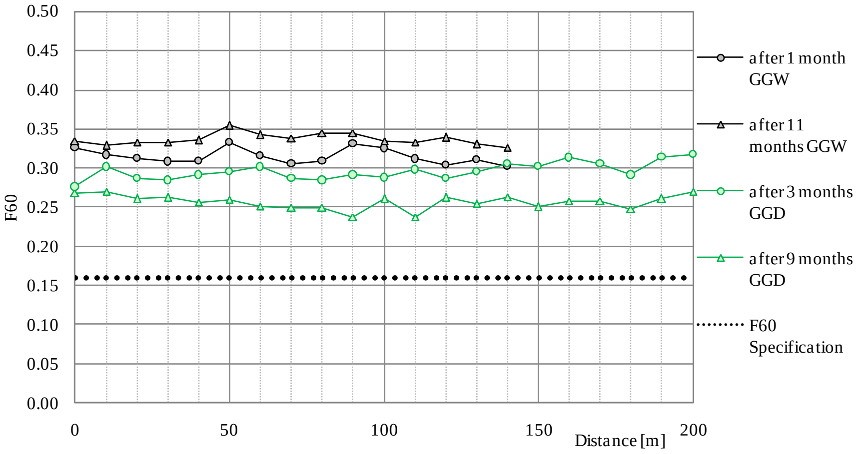


Fig. 9. Friction Performance.

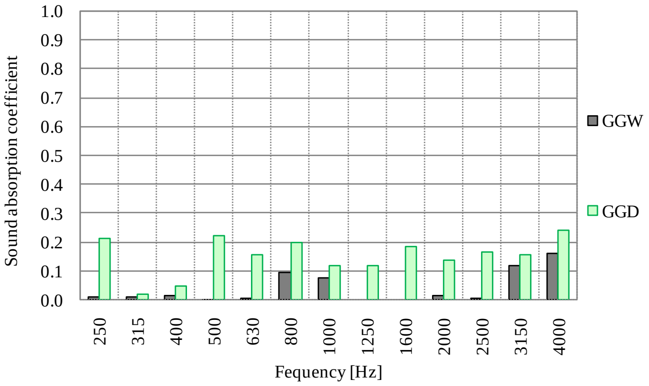


Fig. 10. Acoustic Performance for Normal Incident Waves (Adrienne Method).

Method) and to the ISO/CD 11819-2 (“Close-Proximity Index” Technique).

The Adrienne Method allows the evaluation of the sound absorption coefficient of the asphalt surfaces: the coefficient is defined as the rate of energy not reflected by the ground, which is measured for normal incidence of acoustical waves. Fig. 10 shows the difference in sound absorption performance between the two asphalt surfaces. The results show no meaningful absorption may be found in both the studied mixtures.

The Close Proximity Method (CPX) method allows the evaluation of the influence of pavement surface characteristics on noise generated by tire/pavement interaction. Acoustical measurements have been performed at a speed of 50 km/h, at different times, in order to assess acoustic performance over time.

The index used for this evaluation is the difference between the global Close Proximity Sound Index for Light Vehicles Traffic (CPXL) level measured on each experimental wearing course and that measured on a traditional dense asphalt surface, which is composed of a DAC with 12.0 mm maximum chipping size; these differences are about 4.5 dB(A) for the GGW mix and 5.5 dB(A) for the GGD mix (Fig. 11). The results highlight the benefits in terms of tire/road noise reduction, which can be obtained by using crumb rubber in the production of low noise asphalt surfaces. Reductions of about 5 dB(A) can be obtained only with low noise porous asphalt surfaces.

Fig. 11 also shows the normalized noise spectra of the two, which allow the evaluation of acoustic performance for each 1/3 octave frequency band. The studied mixtures show different attitudes: the GGW mix is characterized by lower noise emission levels in the field of low frequencies, whereas the GGD mix is characterized by lower noise emission levels in the field of high frequencies. This means that by using the GGW mix, it is possible to obtain greater reductions on noise produced by vibration mechanisms; on the other

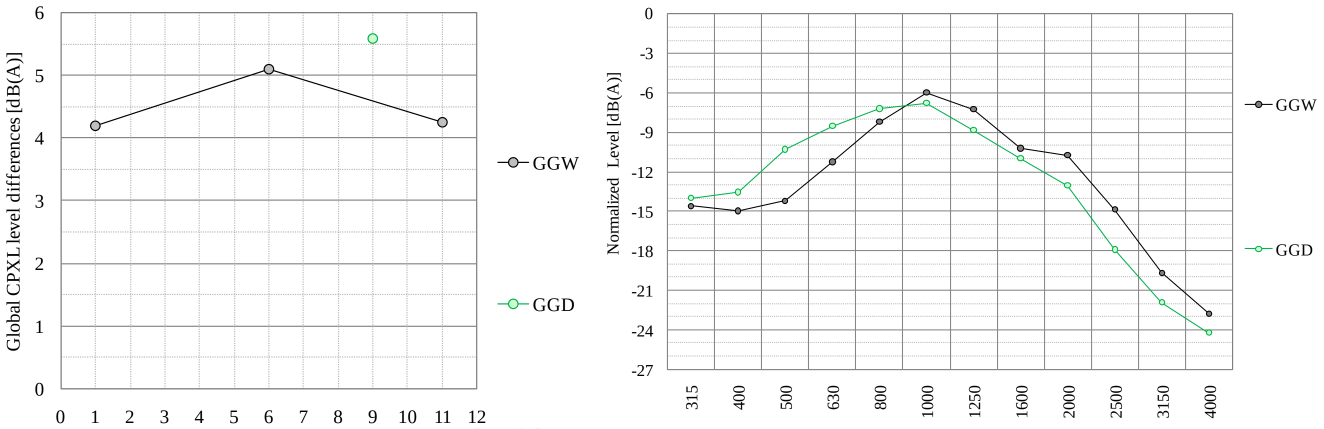


Fig. 11. Global CPXL Level Differences and Normalized Noise Spectrums.

hand, using the GGD mix creates greater reductions on noise produced by aerodynamic mechanisms.

Conclusions and Recommendations

This paper evaluated the possibility of using crumb rubber in the construction of low noise gap graded asphalt surfaces using both the WP and the DP. Accordingly, the study also aimed to define and compare the mechanical and functional performances of the resulting mixes in order to assess their potential for use as a viable solution to enhance environmental, social, and economic sustainability of pavements.

The results of laboratory and in situ tests showed that:

- The two mixtures are characterized by similar percentages of CRM: the GGW and the GGD mixes contain 1.8 % and 2.0% of CRM, by weight of mineral aggregates, corresponding respectively to 4.0% and 4.5% by volume.
- Given the greater discontinuity of the aggregate grading, the GGD mix is characterized by an optimum AC equal to 9.0%, whereas the GGW mix optimum AC is equal to 8.5%. Furthermore, at the same compaction temperatures, the GGW mixture shows better compaction properties as compared to the GGD mixture.
- The two mixtures show similar ITS values, which are higher than the minimum values required by the national standards for gap graded asphalt mixes to be used as wearing courses. No problems pertaining to moisture susceptibility arise for the two mixes.
- The GGW mix shows an increase in the MR as compared to the GGD mix. This increase in stiffness must be attributed to the better mixture compaction and the greater stiffness of AR as compared to the PMA blended with CRM.
- The AR shows a fatigue attitude similar to that of the PMA blended with the CRM.
- The GGW mix shows macrotexture values higher than those of the GGD mix, depending on the greater nominal diameter of the aggregate gradation. Over time, the macrotexture of the two mixes increases, and this tendency is more pronounced for the GGW mix.
- The friction levels recorded for both mixes highlight the increased level of safety for traffic that can be obtained by using CRM in the production of asphalt concretes. Over time, the friction level of the GGW mix shows a slight increase, whereas the GGD mix shows a slight reduction. This is due to the greater adhesion of the AR to the aggregate compared to the GGD mix, in which the CRM acts as an aggregate.
- Acoustic absorption coefficient measurements show no meaningful absorption may be found for both the mixtures.
- The differences between the global CPXL level measured on each experimental wearing course and that measured on a traditional DAC 0-12 surface are about 4.5 dB(A) for the GGW mix and 5.5 dB(A) for the GGD mix. It is important to highlight the benefits in terms of tire/road noise reduction that can be obtained by using crumb rubber in the production of low noise asphalt surfaces.

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