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Stone Mastic Asphalt (SMA) with Crumb Rubber according to a new Dry-Hybrid technology: a laboratory and trial field evaluation

Dr. Cesare Sangiorgi

Associate Professor, DICAM-Roads, Dept. of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale Risorgimento 2, 40136, Bologna, ITALY, email: cesare.sangiorgi4@unibo.it

Dr. Piergiorgio Tataranni (Corresponding Author)

PhD Student, DICAM-Roads, Dept. of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale Risorgimento 2, 40136, Bologna, ITALY, email: piergiorg.tataranni2@unibo.it

Dr. Andrea Simone

Associate Professor, DICAM-Roads, Dept. of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale Risorgimento 2, 40136, Bologna, ITALY, email: andrea.simone@unibo.it

Dr. Valeria Vignali

Assistant Professor, DICAM-Roads, Dept. of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale Risorgimento 2, 40136, Bologna, ITALY, email: valeria.vignali@unibo.it

Dr. Claudio Lantieri

Research Assistant, DICAM-Roads, Dept. of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale Risorgimento 2, 40136, Bologna, ITALY, email: claudio.lantieri2@unibo.it

Prof. Giulio Dondi

Full Professor, DICAM-Roads, Dept. of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale Risorgimento 2, 40136, Bologna, ITALY, email: giulio.dondi@unibo.it

Abstract. Today the use of recycled and second-hand materials can be considered as a suitable solution for the construction or the rehabilitation of road pavements. The increasing interest in this process lead to the study and the evaluation of different waste materials, not directly connected to the construction field, among these Crumb Rubber from end-of-life tires. To date, this recycled material has been added into bituminous mixes for road pavements according to several technologies, for the production of different mixtures. In the present paper, the crumb rubber was used for the production of Stone Mastic Asphalt (SMA) according to a new dry-hybrid technology. A full laboratory investigation and a trial field study are here presented. A complete physical and mechanical characterization was carried out to define a specific mix design. Once defined these properties, a full-scale test section was constructed: specific in situ tests and collection of samples were planned. In both the laboratory and trial field phases, tests results were always compared to those obtained with a traditional SMA mixture. In an environmental prospective, fumes and emissions during laying were

also analyzed. The goal of this research project was to analyze and evaluate the different physical, mechanical and functional characteristics induced by the use of Crumb Rubber for the production of SMA mixtures according to the proposed new dry-hybrid technology. As overall result, the presence of Crumb Rubber does not seem to negatively affect the volumetric properties of the mixture. SMA1.20 shows mechanical properties comparable to the reference mixture and higher if compared to SMA0.75. As for the acoustic properties, both the rubberized surfaces reduce the emission of noise if compared to the traditional SMA layer. The monitoring of pollutants during paving operations confirms the effective environmental benefits deriving from the use of the new dry-hybrid technology here proposed.

1. Background

Due to the increasing road transport registered in the last years, the disposal and recovery of End-of-Life Tires (ELT) has aroused growing interest, in order to protect and safeguard the environment. Until few years ago, the landfill was the main destination of ELTs and it still is for some countries, according to their national laws. An EU directive of 2006 ratifies the ban for ELTs disposal to landfills, recognizing the high potential value of this type of recycled rubber. Crumb Rubber (CR) comes from the mechanical milling and size reduction of ELTs: depending on the productive operations, it is named Ambient Crumb Rubber (ACR) or Cryogenic Crumb Rubber (CCR) [1; 2]. Generally, the first one is the most used in several applications, due to the cheaper and simplified production process. The use of rubber into asphalt mixtures is known since the 1950s, but the first application which brought scientific evidence was the Asphalt Rubber in the 1960s. Over the years, its mix design and mechanical properties has been deeply analyzed and improved and today it can be considered as a suitable alternative to traditional bituminous mixtures for course layers. The good performance achieved and the growing interest of market and governments in eco-friendly materials boosted the development of new technologies for the incorporation of CR within asphalt concretes [3]. To date, CR is mainly added into bituminous mixtures according two different production process: "wet" and "dry" [4; 5]. The first technology is based on the process invented by Charles McDonald for the production of Asphalt Rubber. In this case, the rubber is added to the traditional bitumen and acts as a modifying agent. The melting and mixing process of CR and binder is given by the means of a mechanical stirring system that works in a range between 190 and 218 °C for an interval between 45 and 60 min [6]. According to this method, the bitumen's rheological properties are improved in terms of resistance to rutting, fatigue and thermal cracking, as confirmed by specific studies and applications. The negative prospective, is related to the high productions costs and energy consumption due to the high temperatures and the long mixing time. In the dry technology, instead, CR is added directly to the bituminous mixture as an additional aggregate fraction. Thus, there is no substantial interaction between rubber and bitumen so that binder could be modified. According to this technology, the mix design phase is extremely important, considering the influence of the CR on the aggregates grading distribution. Furthermore, for the optimum bitumen content, the absorption property of rubber must be taken into consideration. The dry method has been developed over the last 30 years, mainly for the production of Cold Mix Asphalt, with significant reductions in terms of costs and environmental impact. Nowadays, researches and practical applications have shown the high potential of CR for the production of eco-friendly bituminous mixtures with high performances in terms of durability, road noise attenuation and resistance to cracking [7-10].

2. Objective

The main objective of the present research is to give scientific evidence on the use of CR for the production of a Stone Mastic Asphalt (SMA) according to a new dry-hybrid technology. This is a new production process in which CR acts as active filler as a part of the aggregates grading distribution. Comparing to the traditional dry method, in this technology the rubber is added to the aggregates mixture as partial substitution of fillers. Furthermore, the use of SBS (styrene-butadiene-styrene) modified bitumen in combination with additives and paraffinic wax, allows to achieve high workability reducing mixing and production temperatures. This involve a reduction in costs related to in-plant production and the decreasing in emissions and negative environmental externalities. Thus, without significantly modifying the traditional production process for Hot Mix Asphalts (HMA), it is possible to produce high performance bituminous mixtures. The mutual effect of the elastic behavior given by rubber and the high performance conferred by the modified binder, results in a rise in mechanical properties at high temperatures [11; 12]. Moreover, the use of high workability PmB bitumen, allows the reduction of mixing and laying temperatures, reducing the binder oxidation. In the present paper, the aforementioned technology was used for the production of SMA mixtures with different amounts of CR. SMA mixtures were developed in Germany in the 1960's and today represent a valid design solution as course layer for high and heavy traffic roads [13; 14]. The high performances of SMAs come from its mix design: the use of high quality aggregates according to a gap-graded gradation together with modified bitumen provides high resistance to plastic deformations [15]. In this research, CR according to two different dosages was added to the bituminous mixture as partial substitution of limestone filler. The mechanical properties of the two different mixtures produced were evaluated in a laboratory characterization followed by the construction of a real-scale trial field. The properties of the experimental mixtures were always compared to those registered for a traditional SMA. Results show suitable mechanical performance together with high functional properties and low hazardous emissions. The final purpose of this research is to give scientific evidence on the use of CR and high workability PmB bitumen into SMAs according to a new Dry-Hybrid Technology.

3. Materials and Experimental program

3.1. Materials

Two different SMA mixtures were produced with different amount of CR (0-0.4 mm gradation) in partial substitution of limestone filler. In the first mixture (labelled SMA0.75), the amount of CR was fixed at 0.75 % by the weight of aggregates, while the dosage of rubber for the second mixture (labelled SMA1.20) was equal to 1.20 %. Starting from the optimum binder content of the reference SMA (labelled SMAnR) the amount of bitumen for the experimental mixtures was fixed considering the absorption properties of CR and limestone filler. Table 1 summarizes the components of each SMA by the weight of aggregates.

The mix design for the reference SMA was in line with some Italian technical specification. Figure 1 shows the particle-size distributions, while Table 2 summarizes the rheological properties of the used modified bitumen. Cellulose microfibers re-compacted in granules, using bitumen as binder were added to the SMAnR, to improve its workability and avoiding the drain-down of bitumen, considering its high dosage. The amount of fibers was the 0.3 % by the weight of aggregates.

3.2. Experimental program and methods

The experimental program is divided in two different connected phases: a laboratory mechanical characterization and a test track analysis.

In the lab phase, the three different SMAs were studied, starting from their mix design. The physical and mechanical properties were assessed on Marshall and SGC (Superpave Gyratory Compactor) specimens. Durability properties were analyzed by means of Cantabro and ITSR test. Once defined the SMAs properties, the two different mixtures were laid as wearing course on an existing road for the construction of a real scale test track. In situ tests were planned at specific intervals for the evaluation of the surface's properties and noise attenuation. The quality of in-plant and paving operations was evaluated by the study of mechanical properties on samples prepared with material taken from the paving screed.

During in-plant production and paving operations, fumes and emissions were analyzed to evaluate the actual risks to which workers and people are exposed.

3.2.1 Laboratory characterization

For each mixture, four samples were prepared with Marshall compaction (EN 12697-30): Marshall tests (EN 12697-34) were carried out on these specimens. The volumetric analysis was based on the evaluation of the air voids content (EN 12697-8) on samples prepared with three different compaction energies: 25, 50 and 75 blows on each side. The SMAs physical characterization was supported by the Indirect Tensile Strength (ITS) characterization according to EN 12697-23 standard. The mechanical properties of the different mixtures were also assessed by the means of Indirect Tensile Stiffness Modulus (ITSM) following the EN 12697-26 standard. During this dynamic mechanical characterization, three SGC samples (70 gyrations) were tested for each mixture. Before being tested, all the specimens were kept in a climatic chamber for four hours at three reference temperatures: 5, 20 and 35 °C. The stiffness modulus was evaluated through a pulse loading with a 124 ms rise-time, to generate a horizontal deformation of 7±2 μm. The durability of the SMAs was investigated through the ITSR (EN 12697-12) and the determination of particles loss after Cantabro test (EN 12697-17).

For the aforementioned tests, eight Marshall specimens were prepared for each mixture. It is worth noting that the mixing and production temperature for both Marshall and SGC specimens was always kept equal to 160 °C.

3.2.2 Trial field

Once defined the physical and mechanical properties of the 3 different SMAs, a real scale test track was constructed on an existing two-lane road section. The trial field covered 300 meters in which the existing wearing course was fully milled on both the 3 m wide lanes. For one lane, the traditional SMAnR was laid and compacted for a final thickness equal to 4 cm. Whereas, the other lane was divided in two 150 m long consecutive sections: one for SMA0.75, one for SMA1.20. A bituminous tack coat was spread on the laying surface to improve the bonding between the existing asphalt concrete and the new one. A thermographic camera controlled the laying process: the temperature of the three mixture was always around 130 °C immediately behind the paver, before compaction operations. For each SMA, a specific quantity of material was taken from the paver screed: three specimens were prepared with gyratory compaction (ASTM D6925) and other three with Marshall compaction (EN 12697-30). Mechanical tests (Marshall compression, ITS and ITSM tests) and physical analysis (air voids content) were carried out on these specimens and the results were compared to those obtained during laboratory analysis. Surface properties and their development were evaluated according specific tests, planned at regular intervals: at 60, 270 and 420 days after the construction of the trial field. Skid resistance was analyzed by the means of the British Pendulum test (EN 13036-4) and the macro-texture (Mean Texture Depth, MTD) was assessed by means of the sand patch test (EN 13036-1). The evaluation of the acoustic properties conferred by the three different SMAs was based on the Close Proximity Index measurement (CPX, ISO/DIS 11819-2), according to two different test repetitions. Furthermore, taking into account the environmental benefits given by the possibility of lowering the mixing and production temperatures, fumes and emissions were analyzed during paving operations. Measurements of respirable dust particles and Polycyclic Aromatic Hydrocarbons (PAHs) were done during the laying process, together with the analysis of adhesive pads attached to workers' clothes for the evaluation of the dermal exposures. While these measurements assessed the quality of the air directly exhaled by workers, in addition, fixed devices positioned along the trial field carried out environmental sampling.

4. Laboratory tests

4.1. Air voids analysis

The compactability and workability properties of the three different mixtures were evaluated by the means of Marshall compaction. For each SMAs, four specimens were prepared with three different compaction energies: 25, 50 and 75 blows per side. The air voids content (Va) of each specimen was evaluated in compliance with EN 12697-8 standard. Average results and their ranges are shown in Table 3.

Among the mixtures, SMAnR shows the lowest air voids content. This is mainly due to its different gradation: the material passing the 2 mm sieve is 4 % more, if compared to the other experimental mixtures. This aggregates distribution confers a more dense structure to the SMAnR. Between the experimental SMAs, SMA1.20, which has the higher binder content, shows the lower air voids value. Nevertheless, both the proposed SMAs have an air voids content in line with the limit traditionally imposed by the technical specification for SMAs (Va < 5 %).

4.2. Marshall analysis and Indirect Tensile Strength (ITS) tests

For each mixture, four samples were prepared with Marshall compaction (EN 12697-30) with 50 blows on each side. The temperature during compaction was kept constant and equal to 160 °C. Marshall tests (EN 12697-34) were carried out on these samples after being placed in a 60 °C water bath for 30 minutes. Average results and ranges for Marshall quotient are presented in Table 4.

Between the experimental mixtures, SMA1.20 shows mechanical properties that are comparable to the reference mixture. Even if lower, the stability and the Marshall quotient for SMA0.75 are similar to the values generally attributed to traditional Hot Mix Asphalts, taking into account the lower compaction energy (50 blows). The mechanical characterization included Indirect Tensile Strength (ITS) evaluation, according to EN 12697-23 standard. Four specimens for each SMA were first prepared by means of Marshall compaction (50 blows per side) and then tested. All the samples were kept in a climatic chamber set at 25 °C for 4 hours before testing. Average results and ranges for ITS values are shown in Table 5.

ITS results confirm the mechanical values obtained from the Marshall analysis. The reference mixture shows the higher indirect tensile strength, which is comparable to the SMA1.20 value. It is worth noting that both the experimental mixtures exceed the ITS limit specified in the most common Italian technical specifications for SMAs (ITS > 1.00 MPa).

4.3. Mechanical dynamic analysis: Indirect Tensile Stiffness Modulus (ITSM) test

Indirect Tensile Stiffness Modulus (ITSM) tests were carried out to investigate the mechanical response to dynamic loads, in compliance with EN 12697-26 standard, according to the indirect tensile configuration. For each mixture, three SGC specimens (70 gyrations) were analyzed. Tests were performed at 5, 20 and 35 °C for the evaluation of the thermal sensitivity of the SMAs. Results are given in Table 6 and average values in Figure 2.

Results confirm the mechanical properties analysed in the previous step of the experimental program. The traditional SMA has the highest stiffness. This trend is in line with the higher ITS values and the lower air voids content. The dynamic mechanical characterization of both experimental mixtures follows the same trend emerged in the whole laboratory analysis. SMA1.20 shows higher ITSM values at all temperatures. Taking as reference the stiffness values at 20 °C, both the experimental SMAs exceed the limit imposed by the Italian technical specifications for this type of asphalt concrete (ITSM > 3500 MPa at 20 °C). In terms of thermal sensitivity, the mechanical behaviour of the experimental mixture is similar to the SMAnR one. In wider terms, the three mixtures show closer values at low temperatures and larger difference at high temperature. The presence of CR within the bituminous mixture according to the new dry-hybrid technology does not seem to affect negatively its mechanical behaviour and thermal sensitivity.

4.4. Water damage: Indirect Tensile Strength Ratio (ITSR) and Cantabro test

It is a well-known fact that water is one of the most influent parameter responsible for the deterioration of asphalt concretes. The water damage can be evaluated by the ratio of Indirect Tensile Strength tests (EN 12697-12) both in dry and wet conditions. Six samples for each SMAs were prepared with Marshall compaction (50 blows) and then placed in a water bath at 40°C for 72 hours prior to testing. Results are presented in percentage, as ratio between ITS in wet conditions and ITS in dry conditions (Table 7).

All the mixtures exceed the ITSR limit specified in the technical specifications for SMAs (ITSR > 75 %), even if the prescribed limit is related to Marshall specimens compacted with a higher number of blows (75). Between the experimental mixtures, SMA1.20 confirms the higher mechanical properties.

The study of SMAs durability after water damage is supported by Cantabro test (EN 12697-17). Generally, this method is used for determining the Particle Loss (PL) of porous asphalt mixtures. However, it is also used for the purpose of research as an estimator of the abrasiveness of asphalt concretes. In this study, five Marshall specimens (50 blows) for every SMA were kept in a water bath for 4 days and then tested. Average results and ranges are given in Table 8.

From the analysis of data, there is no significant difference in terms of Cantabro values between the mixtures.

Despite the lack in PL limits for gap-graded mixtures from technical specifications, some researches and studies suggest values lower than 10-12 % [16; 17]. SMA1.20 presents the lowest PL value, probably due to the higher binder content. In any case, the experimental mixtures show excellent abrasion resistance, especially taking into account the low compaction energy used for the production of samples.

A more detailed investigation on long-term durability of these experimental mixtures is needed to support these preliminary outcomes in terms of properties conferred by the use of CR according to this Dry-Hybrid Technology.

5. Trial field

After the mechanical and physical characterization of the different SMAs, the research plan provided for the in-plant production of the mixtures for the construction of a real-size trial field. The three different SMA were laid on a 300 m long section of an existing two-lane road. The existing surface layer was fully milled and a bituminous tack coat was spread before laying the new asphalt mixtures. On one lane SMAnR was laid, while the other lane was divided in two consecutive 150 m long sections, each one paved with the two experimental SMA (Figure 3). The final design thickness of the new surface layer was set at 4 cm.

A thermographic camera was used to monitor the asphalt temperature during the laying process. Taking into account the reduced in-plant production temperature (160 °C) needed with this new dry-hybrid technology, as verified by thermographic camera, the in situ temperatures of mixtures were always approaching 130 °C (Figure 4).

To assess and to compare the development of SMAs properties, in situ tests were planned in three dates, corresponding to 60, 270 and 450 days of cumulative traffic. During the laying operations, material from paving screed was collected and compacted in lab for further physical and mechanical tests. The evaluation of fumes and emissions produced during the construction of the trial field was based on the analysis of pads attached to workers' clothes and environmental sampling.

5.1. Physical and mechanical characterization

For each asphalt mixture, samples material was taken from the paving screed during laying operations. SGS specimens were prepared in lab to evaluate the quality of in-plant production and the compliance with the SMAs properties assessed in the first step of research. The physical characterization is based on the air voids content analysis (EN 12697-8) depending to the number of gyrations (10, 50 and 130). The production temperature was always kept equal to 160 °C. Table 9 shows the average results and ranges of three samples for each SMA.

All the mixtures show the same workability properties: there are no significant difference between the experimental mixtures and the reference one. The final air voids contents are comparable and in line with the values commonly linked to this type of hot mix asphalt.

With the same material, additional Marshall samples were prepared with the same setting and procedures used during the preliminary laboratory phase (160 °C, 50 blows). After being conditioned for 4 hours at 25 °C, three specimens for each SMA were tested for Indirect Tensile Strength. Average results and ITS ranges are presented in Table 10.

From a general point of view, all the SMAs show a reduction in ITS values if compared to the data obtained during the laboratory mechanical characterization. This slight decrease (avg. 12 %) is mainly due to the higher variability related to in-plant production, if compared to the preparation of samples in the lab. However, even in this case, ITS values for experimental mixtures exceed the limits imposed by the technical specifications for SMAs.

5.2. Texture and Skid resistance analysis

It is well knows that friction between tyres and road surface involves two main components: adhesion and hysteresis. The first phenomenon is connected to the microtexture of pavement, while the second one is related to its macrotexture [18]. Measurements of both parameters were performed for the evaluation of the surface properties of the three different SMAs. Skid resistance tests with pendulum (British Pendulum Number, BPN) and Mean Texture Depth (MTD) were performed at regular intervals (20 measuring points on each road section). Tests were repeated after 60, 270 and 450 days from the laying to assess and compare the texture development of the different asphalt mixtures.

5.2.1. Skid resistance

Skid resistance test is used for the evaluation of the microtexture of road pavements [19]. The most common instrument for in situ test is the Pendulum Tester [20]. All the tests were performed and repeated in 20 fixed measuring points for each trial field's section. Data were adjusted according to the pavement surface temperature, in compliance with EN 13036-4, and are expressed as PTV (Pendulum Test Value). For each sections, average results and ranges are shown in Table 11 and plotted in Figure 5.

Taking into account some Italian technical specifications, the following threshold PTV values were considered:

- PTV > 55 after laying (reference for test after 60 days);
- PTV > 50 between 6 and 12 months (reference for test after 270 days);
- PTV > 40 after one year (reference for test after 450 days).

Both the experimental SMAs comply with the aforementioned limits in every test session. From the comparison of PTV values, SMAnR and SMA1.20 seem to follow the same trend. Even if PTV results for SMA 1.20 are lower for each repetition, the variation of skid resistance during time can be considered equal to the one registered for the reference mixture. Both surfaces show a reduction close to 10 % 450 days after laying. SMA0.75 exhibits the smallest reduction of PTV after 270 days (7 %) but the lowest skid resistance in the last test session (reduction of 15 %). It is worth noting that the values measured in 20 points for each section were consistent for every test session, with low variance and standard deviation.

5.2.2. Mean Texture Depth results

The evaluation of pavement texture was based on the volumetric patch method, in compliance with the EN 13036-1 standard. For each section, the same 20 measuring points fixed for skid resistance measurements were tested. According to the Italian Technical Specification, the measured MTD should be greater than 0.50 mm for SMAs. Average results and ranges are presented in Table 12 and in Figure 6.

Considering the aforementioned MTD limit for SMAs, it is clear that all the surface layers have high roughness. Immediately after the laying, the reference SMA shows a mean MTV value equal to 0.75 mm, while both the experimental mixtures have average values around 0.70 mm. After 270 days, SMA1.20 show a slight decrease in MTD, while values for SMAnR and SMA0.75 can be considered constant. In the last test session, the difference between the experimental SMAs is increased and equal to 0.06 mm. Generally, SMAnR shows the highest macrotexture in terms of MTD. However, the rubberized sections exceed the aforementioned MTD limit suggested by the Italian specification for this type of road surface. Moreover, data are comparable to those recorded in similar researches [21; 22]

5.3. Noise analysis

The evaluation of the noise given by tyres-pavement interaction is based on the Close Proximity Index measurement (CPX, ISO/DIS 11819-2). Two different test sessions were fixed to evaluate the development of the acoustic properties of the three different road surfaces. This method is based on the acquisition of sound pressure signal by the means of a couple of microphones fixed close to the rear wheel of a moving vehicle. The aim of the test is the evaluation of the level of noise produce by tyres-pavement contact [23; 24]. Different measurements are made at various constant speeds and results are expressed as CPX Level (Lcpx). Test repetitions were fixed at day 270 and 450. Considering that the trial field is in an urban area, the adopted test speed was 50 km/h. Average results are presented in Table 13. It is worth noting that all the values have been adjusted according to the surface temperature, as prescribed by the ISO standard.

From results, it is clear that both the rubberized road surfaces reduce the emission of noise if compared to the traditional SMA layer. If SMAnR mixture is taken as a reference, these reductions are equal to 1.6 dB(A) after 270 and 450 days for SMA0.75; 1.1 dB(A) after 270 days and 1.2 dB(A) after 450 days for SMA 1.20. Similar researches [25; 26] on noise performance of gap-graded mixtures containing crumb rubber, showed comparable Lcpx values at 50 km/h (86-88 dB(A)).

5.4. Emissions analysis

The potential environmental benefits given by the new dry-hybrid technology were evaluated through an in-deep emissions analysis. Releases of pollutants were monitored and analysed during paving operations. Two methods were used: a personal sampling and an area sampling (Figure 7). The first one is related to the measure of the exposure level to workers (respirable dust particles sampling, PAHs sampling and dermal exposure evaluation), while the second one is a measurement of the clean level in the work environment. It is worth noting that for the emission analysis, results are presented for "standard pavement" and "rubberized pavement", without distinction for the experimental SMAs.

5.4.1. Respirable dust particles sampling results

The portion of airborne particles with diameter up to 4 µm can be considered as respirable dust particles. This type of particles can negatively affect the respiratory system with potential serious consequences on the human health. The respirable dust particle sampling have been carried out according to EN 481 and EN 13205-1 standards. According to the American Conference of Governmental Industrial Hygienist (ACGIH) guidelines, the limit concentration of respirable dust particles is equal to 3 mg/m^3. During the paving operations the inhalation exposure of workers behind the paver was evaluated, which were considered as the most exposed workers to asphalt fumes. Results are shown in Table 14.

The rubberized pavement has the highest concentration of respirable dust particles directly inhaled by the workers behind the paver. However, this amount of potentially dangerous particles, even if triple if compared to the standard SMA, is considerably lower than the alert threshold.

5.4.2. PAHs sampling results

The PAHs are hydrocarbons that are composed of multiple aromatic rings. Considering the wide number of PAH components, the analysis is related to 11 priority pollutants suggested by the European and Italian codes. However, in the present paper there are shown only results for Benzo[a]pyrene (B(a)p) concentration, being considered as carcinogenic by IARC (International Agency for Research on Cancer). For the airborne particles, the sampling was carried out by membrane filtration, in compliance with the most common standards for this type of analysis (NIOSH, Manual of Analytical Methods). For the vapour phase sampling, the standard indicates the absorption of PAHs on specific sampler. In this case, PAHs analysis was related to workers with different tasks: roller driver, paver driver and worker behind the paver. As for the limit concentration, the authors took as a reference the Technical Standard Concentration of B(a)p suggested by the German standard, equal to 2000 ng/m^3. Results are presented in Table 15.

For both pavements, the PAHs concentrations are fully below the limit imposed by the German standard. For every analysed tasks, the concentrations of B(a)p are always lower during the paving operations for rubberized mixtures. The reduction in B(a)p emission is equal to 73 % for the roller driver which is the most exposed worker to PAHs. For the paver driver and for the worker behind the paver the decrease in B(a)p emissions are of 81 % and 5 %.

5.4.3. Dermal exposure results

This kind of analysis is needed for the evaluation of the dermal exposure of workers to PAHs during paving operations. Taking as references the most common standard for dermal exposure analysis (CEN/TR 15278, CEN/TS 15279, EPA/600/8-91/011B, EPA/600/R-09/052F, EPA/600/R-07/040F, NIOSH CDC), 4 polypropylene pads have been attached to workers to absorb every pollutants potentially harmful for skin. Pads were applied to neck, chest, wrist and calf, which are strategic areas from a sanitary point of view. In this case, the sampling has been carried out just on workers behind the paver. B(a)p concentration values are presented in Table 16.

As already verified from the different samplings, the dermal exposure for workers during paving operations is substantially reduced with rubberized mixtures. The reduction in B(a)p concentration is of 23 %.

5.4.4. Incremental Carcinogenic Risk evaluation

The Incremental Carcinogenic Risk (ICR) has been calculated as the sum of the Incremental Risk related to inhalation (Ri) with the Incremental Risk for dermal exposure (Rd) according to the following equations:

$$R_i = SF_i \cdot \frac{\left(C_p + C_v\right) \cdot I_R \cdot HE \cdot EF \cdot ED}{BW \cdot AT \cdot 365_{day/year}} \quad (1)$$

Where: SF_i is the slope factor for inhalation; C_p is concentration of the substance absorbed into particulate; C_v is the concentration of the substance in the vapour state. I_r is the inhalation rate; HE is the exposure duration in hours; EF is the exposure frequency; ED is the exposure duration; BW is the body weight and AT is the averaging time.

$$R_d = SF_d \cdot \frac{C_{pad} \cdot HE \cdot EF \cdot BF \cdot S \cdot ED}{ET \cdot BW \cdot AT \cdot 365_{day/year}} \quad (2)$$

In (2) equation: SF_d is the slope factor for dermal exposure; C_{pad} is the concentration of substance measured on pads; BF indicate the dermal absorption; S is the dermal surface exposed to substance and ET is the duration of pads exposure.

Values in Table 17 are related to the ICR calculated for B(a)p and other 11 priority pollutants.

The evaluation of ICR confirms the data obtained in the previous samplings. The carcinogenic risk seems to be higher for paving operations related to traditional mixture. It is worth noting that according to the European Chemical Agency

(ECHA), a cancer risk indicator between 1.0E-5 and 1.0E-6 is considered as a tolerable risks level. In the light of the above, in both cases no exceeded threshold values was recorded.

5.4.5. Environmental sampling results

The environmental sampling was carried out by the means of fixed air samplers, close to the area involved in the paving operations. As for the sampling related to workers, the evaluation of PHAs is based on the analysis of the atmospheric particulates collected on filters and the volatile fractions absorbed on polyurethane foam (PUF). The monitoring was performed by setting the sampler's aspiration system at 200 l/min, for a period equal to or longer than the duration of the personal sampling (ISO 12884; US EPA TO9). Taking as a reference the Italian legislation, the limit for B(a)p concentration is equal to 1 ng/m^3. Moreover, the Carcinogenic Target Risk was evaluated, which represents the ambient concentration of PAHs corresponding to an increase in the probability of cancer equal to one case in a million, for a long exposure. The United States Environmental Protection Agency (USEPA) fixes different B(a)p concentration limits for the residential air and for the worker ambient air. Data are presented in Table 18.

From the analysis of data, it is clear the reduction (equal to 88 %) of B(a)p emissions during paving operations with rubberized mixtures. From an overall point of view, with none of the analyzed mixtures the Italian B(a)p concentration limit was reached. Moreover, for both pavements the recorded benzo(a)pyrene concentrations were far from the residential air limit and worker ambient air limit related to the Carcinogenic Target Risk.

6. Conclusions

In the present paper, a new dry-hybrid technology is proposed for the addition of crumb rubber into SMA mixtures. According to this technology, the rubber is added to the aggregates mixture as a partial substitution of filler, together with the use of SBS modified binder. The presence of additives allows to produce Warm Mix SMA, with consistent reduction in costs related to in-plant production and in emissions. Two experimental SMAs with different amount of crumb rubber were here analyzed. The first step of the research program was based on the physical and mechanical laboratory characterization of the experimental mixtures. In the second phase, a full-scale trial field was constructed. In situ tests were performed in different sessions to evaluate the development of the mechanical properties of mixtures and to assess the pavements functional characteristics. Data were always compared to those obtained for a traditional SMA. Moreover, emissions of pollutants were monitored during paving operations to evaluate the effective environmental benefits deriving from the combined effect of lower working temperatures and the use of crumb rubber with the new dry-hybrid technology. According to the experimental results presented in this study, the following conclusions can be drawn:

- The presence of crumb rubber according the new dry-hybrid technology does not seem to negatively affect the volumetric properties of the mixture. Even if the air voids contents are higher for the experimental SMAs, values are in line with the limit traditionally imposed by technical specifications for this type of mixtures (Va < 5 %). SMA1.20 has a lower air voids content, if compared to SMA0.75. The different porosity between the experimental mixtures and the reference one is mainly due to a small difference in aggregates gradation.
- The mechanical characterization is based on static (Marshall and ITS) and dynamic (ITSM) tests. As overall result, SMA1.20 shows mechanical properties comparable to the reference mixture and higher if compared to SMA0.75. This trend is in line with the previous volumetric analysis: higher mechanical characteristics are generally related to lower air voids content. It is worth noting that for both the experimental mixtures the Marshall, ITS and ITSM results exceed the limit imposed by the most common technical specifications for SMA mixtures. If the thermal sensitivity is taken into account, the presence of crumb rubber does not seem to modify the mechanical behavior of mixtures in relation to the temperature variation.
- As for the evaluation of durability, ITSR and Cantabro test were performed on samples after water treatment. Both the experimental SMA confirm the good mechanical properties: in no case the threshold values are reached. In confirmation of the previous tests, SMA1.20 shows the higher mechanical properties.
- Tests on samples prepared with material collected during paving operations, confirm the good physical and mechanical properties of the experimental mixtures. Those results are a further confirmation that all the processes, from the new dry-hybrid in-plant production to the paving, are correct and completely feasible even if paving temperatures were always around 130 °C.
- Skid resistance and MTD values are in line with parameters typically recorded for gap-graded mixtures. The difference between SMA1.20 and SMA0.75 surface is mainly due to the different content of binder. However, even after 450 days, surfaces properties are always higher than the threshold limits suggested by the most common Italian technical specifications. As for the acoustic properties, both the rubberized surfaces reduce the emission of noise if compared to the traditional SMA layer (after day 450, 88.4 dB(A) for SMAnR Vs. 86.8 dB(A) for SMA0.75 and 87.2 dB(A) for SMA1.20). There is not significant difference between the experimental mixtures and the slight reduction of the noise emissions for the SMA0.75 is mainly due its surface texture.
- The monitoring of pollutants during paving operations confirms the effective environmental benefits deriving from the use of the new dry-hybrid technology. Every sampling related to workers shows a substantial reduction

in emission of respirable dust particles and B(a)p for rubberized pavements. Those results are confirmed from environmental sampling, which records a reduction in B(a)p emission close to 90 % for experimental mixtures. It is worth noting that the ICR for workers can be reduced to level suggested for population by the use of common dusk masks and working overalls.

In the light of the aforementioned results, the addition of crumb rubber to SMA according to the new dry-hybrid technology seems to be a viable solution for the production of eco-friendly mixtures with performances comparable to traditional SMA. Further tests are clearly necessary to evaluate the fatigue performance of these rubberized mixtures and to define a proper mix design in relation to its intended purpose.

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