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Design and Construction of a Full-Scale Test Section with Asphalt Rubber Gap-Graded Wearing Course Mixture

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Abstract

A full-scale test section with asphalt rubber gap-graded wearing course mixture was designed and constructed on a major infrastructure as part of a regional research and implementation project. Standard and performance-related laboratory tests were carried out in order to select constituent materials, define the job-mix formula and monitor construction operations. Gaseous emissions of the bituminous mixture sampled during laying were analyzed to assess the potential risks to which labourers are exposed during paving. Environmental compatibility was also evaluated by performing laboratory leaching tests. Based on the results obtained in the investigation, technical guidelines were validated and enhanced.

Keywords: Asphalt rubber; gap-graded mixture; mix design; performance; gaseous emissions; leaching

1. Introduction

Bituminous mixtures containing asphalt rubber are used in paving applications as a result of their enhanced performance properties with respect to resistance to fatigue, permanent deformation, ageing and water damage. Moreover, when employed for the formation of wearing courses, they generally exhibit an excellent behaviour in terms of skid resistance and noise absorption [1, 2]. Due to positive performance records, world-wide diffusion of such mixtures is continuously increasing and several applications have been reported in Italy, especially on a local scale for maintenance and rehabilitation purposes [3, 4, 5, 6].

As part of a research and implementation project funded by the Province of Turin (Italy), a full-scale pavement test section was built on the Borgaro-Venaria, a new connector infrastructure located in the northern part of the metropolitan Turin area [7]. The open-graded friction course originally considered in design (5 cm

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thick) was substituted by a gap-graded wearing course mixture (3 cm thick) containing asphalt rubber. The rest of the pavement cross-section, constituted by a 5 cm binder course, a 9 cm base course, a 30 cm granular foundation and a prepared subgrade, was left unchanged. Construction operations were carried out on a total surface area of approximately 16,000 m^2 in a time period of three working days. The test section has a total length of 1.2 km, a carriageway width of 10 m, and includes two roundabouts.

Since the Province of Turin had no previous experience with this type of wearing course mixture, detailed investigations were carried out both in the preparatory phases of the project (materials selection and mix design) and during construction operations. Technical specifications adopted for the project were those previously developed by the Italian InterUniversity Road and Airport Research Center (CIRS) [4], supplemented by a number of performance-related tests and specific environmental evaluations.

This paper gives an overview of the results obtained during the laboratory and field investigation. Conclusions were drawn for the validation and enhancement of available technical specifications. Moreover, critical factors which need to be addressed with special care during all phases of design and construction were highlighted.

2. Experimental investigation

2.1. Methods

Preliminary activities of the project focused on materials selection and mix design of the gap-graded wearing course mixture. A trial section (2 strips, width 3 m, length 40 m) was then built in the area of the bituminous mixture production plant for the preliminary evaluation of composition and achievable compaction. Laying of the wearing course was finally carried out on the infrastructure. Details on the tests carried out in all phases of the project are given in the following paragraphs and are synthesized in Table 1.

As suggested by technical specifications [4], in the mix design phase and during construction of the trial section, aggregates were characterized in terms of their particle size distribution (EN 933-1), resistance to fragmentation (EN 1097-2) and particle shape (EN 933-3).

Asphalt rubber was provided by the only Italian producer, who initially supplied a sample for mix design and then transported it in three stages to the production plant (for the trial section, for the first two days of laying and finally for the conclusion of construction operations). Tests were carried out in all phases of the project for the determination of empirical properties (penetration at 25°C, EN 1426; ring-and-ball softening point, EN 1427), viscosity and complex modulus and phase angle master curves. Viscosity measurements were performed between 125 and 175°C by means of a Brookfield viscometer (DVIII-Ultra) equipped with a SC4-27 spindle operated at a shear rate equal to 6.8 s^{-1} (20 rpm) [8]. Temperature-viscosity data were then fitted to power-law functions. Oscillatory tests were carried out by means of an Anton Paar MCR-301 Dynamic Shear Rheometer (DSR), using 8 mm parallel plates (2 mm gap) in the 0-40°C temperature range, and 25 mm plates (1.5 mm gap) for temperatures comprised between 40 and 80°C [9]. At each temperature, frequency sweeps were performed (from 0.01 to 10 Hz) with a constant maximum strain equal to 0.5%. Master curves of the complex modulus and phase angle were built at 30°C by making use of the CAM and WLF models [10, 11]. Further tests on the binder were carried out in order to estimate its crumb rubber content. For such a purpose, the same equipment and ignition procedure employed for the determination of binder content of bituminous mixtures was employed (EN 12697-39). However, as explained in detail elsewhere [5], corrections were introduced in calculations to take into account the presence of residues of both the base bitumen and crumb rubber.

Identification of the gap-graded mixture job-mix formula was based on requirements for size distribution of aggregates and binder content [4], and on the analysis of volumetric (EN 12697-5,-6,-8) and mechanical properties of laboratory-compacted specimens. Marshall-compacted specimens were prepared by applying 50 blows on each side (EN 12697-30) and were subjected to tests for the evaluation of stability at 60°C (EN 12697-34), while gyratory-compacted specimens were prepared with 50 gyrations (EN 12697-31) [12] and were employed for the assessment of indirect tensile strength at 25°C (EN 12697-23). Additional tests were carried out after immersion in water for 15 or 7 days (respectively for Marshall and gyratory specimens). In all cases, mixtures were prepared at 190°C in a temperature-controlled high-capacity laboratory mixer and thereafter compacted at 160°C.

Performance-related evaluation of the bituminous mixture, either optimized in mix design or sampled from the construction site, focused on resistance to permanent deformation and to crack formation and propagation. Wheel-tracking tests (WT) were carried out on roller-compacted slabs (EN 12697-33, large size device) prepared with different values of target final thickness and density. Severe environmental and loading conditions were simulated by performing tests at 60°C with a maximum number of applied loading cycles equal to 30,000 (EN 12697-22). Semi-circular bending (SCB) tests were performed on half-discs 25 mm thick obtained from gyratory-compacted specimens prepared at selected density levels. In order to derive from test results information related to energy dissipated through crack propagation, notches of different length (up to a maximum of 30 mm) were cut at the mid-span of the specimens [13]. Tests were carried out at 20°C with an imposed displacement rate equal to 1 mm/min.

During construction of the test section, materials sampled from the production plant and from the laying site were subjected to tests for composition assessment (aggregate size distribution, binder content, crumb rubber content). Furthermore, since concerns were raised with respect to the toxicity of emissions in atmosphere during construction and in water (through leaching) during service life, additional chemical analyses were included in the investigation.

Fume samples were taken at the driver's seat of the paver and at the screed for the subsequent evaluation of their content of volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH). This was done by employing a pump (0.5 l/min discharge, 5 minutes total sampling time) by means of which fumes were adsorbed on active granular carbon cartridges which were stored at freezing temperature until analysis. These matrixes were then subjected to solvent extraction (with methylene chloride) in an ultrasound bath for a period of 60 minutes (EN 13649) [14]. Subsequent analysis was carried out in a gas-chromatographic apparatus Agilent 7890/5975, equipped with a HP5-MS capillary column (30m×0.25mm×0.25μm) by adopting different protocols for the determination of VOC and PAH content [5, 7].

Table 1. Experimental investigation

	Mix design	Trial section	Test section			Final pavement
			Day 1	Day 2	Day 3	
Characteristics of aggregates	×	×				
Asphalt rubber viscosity	×	×	×	×	×	
Asphalt rubber master curves	×	×	×	×	×	
Crumb rubber content		×	×	×	×	
Characteristics of Marshall specimens	×	×	×			
Characteristics of gyratory specimens	×		×			
Rutting behaviour	×		×			
Crack formation and propagation	×		×			
Mixture composition		×	×	×	×	
Composition of fumes			×	×	×	
Composition of leaching eluate			×			
Wearing course density						×
Pavement skid resistance and texture						×

Leaching tests were carried out on gyratory-compacted specimens prepared by applying a pressure of 600 kPa to 1,200 g samples for a number of gyrations sufficient to obtain a final height equal to 3 cm. Specimens were extruded from the moulds and thereafter treated as indicated in EN 12457-2. After being filtered through Whatman 0.45 micron membranes, obtained extracts were subjected to a static headspace technique for the determination of VOC and to solid phase extraction (SPE) to transfer PAH compounds from water to an organic solvent. Gas-chromatographic analyses were then carried out for the determination of VOC and PAH content, while content of heavy metals was evaluated by using a Perkin-Elmer Optima 2000 ICP-OES. Further analyses were carried out for the determination of anion content, chemical oxygen demand (COD) and other physical and chemical properties (pH and electrical conductivity).

After completion of construction operations, cores were taken from the gap-graded wearing course in order to check achieved level of compaction. Furthermore, skid resistance was assessed by making use of the British Pendulum test (EN 13036-4) and mean texture depth (MTD) was evaluated by means of the sand patch test (EN 13036-1).

3. Results and discussion

3.1. Constituent materials

In the preparatory phases of the project, several candidate granular materials were analyzed for use in the gap-graded mixture. Due to availability and costs, mix design and construction of full-scale sections (trial and test) were carried out with different materials. In both cases aggregates were provided in three size fractions (0/5, 5/10 and 10/15 mm) and were evaluated in terms of their particle size distribution, Los Angeles coefficient (LA) and flakiness index (FI). Results were complied with technical specifications [4], even though aggregates employed in mix design exhibited a better resistance to fragmentation (LA = 12.2 vs 19.0) an a more polyedric shape (FI = 9.7 vs 15.0).

Empirical and rheological properties of asphalt rubber recorded during the project are given in Table 2 and in Fig. 1. Viscosity and master curve data were fitted to the models given in equations (1) to (3).

Viscosity Power Law
$$\eta(T) = \alpha_T \cdot T^{-\beta_T} \tag{1}$$

CAM
$$|G^*(f)| = G_g \cdot \left[1 + \left(\frac{f_c}{f}\right)^k\right]^{-\frac{m}{k}} \tag{2}$$

WLF
$$log\left(a_{(T,T_{ref})}\right) = \frac{-C_1 \cdot \left(T - T_{ref}\right)}{C_2 + T - T_{ref}} \tag{2}$$

where η(T) is viscosity at temperature T (in °C), |G*(f)| is the norm of the complex modulus (in Pa) at loading frequency f (in Hz); G_g is the glassy modulus ($logG_g = 9.1$); T_{ref} (in °C) is the reference temperature (equal to 30°C); $a_{(T,Tref)}$ is the shift factor at temperature T; α_T, β_T, f_c, k, m, C_1 and C_2 are model parameters.

Table 2 also contains the results of tests carried out on asphalt rubber for the assessment of crumb rubber content (%CR), which the producer declared to be equal to 18% (on the weight of the total binder).

Table 2. Empirical properties, rheological model parameters and crumb rubber content of the asphalt rubber binder

	Mix design	Trial section	Test section		
			Day 1	Day 2	Day 3
Penetration at 25°C [dmm]	41.3	59.2	57.6	67.9	65.8
Softening point [°C]	64.7	62.1	60.5	56.1	57.6
α_T	1.0E+15	3.0E+15	1.5E+14	1.1E+14	7.4E+13
β_T	5.1	5.4	4.8	4.9	4.7
$\log(G_g)$	9.1	9.1	9.1	9.1	9.1
$\log(f_c)$	5.8	4.4	5.3	4.3	5.2
K	0.19	0.14	0.2	0.2	0.17
M	0.60	0.74	0.7	0.8	0.68
C_1	11.8	12.7	13.1	11.8	12.6
C_2	117.3	120.1	121.9	116.0	119.9
%CR [%]	18.0*	14.9	16.5	16.7	16.7

(*) Value declared by the producer

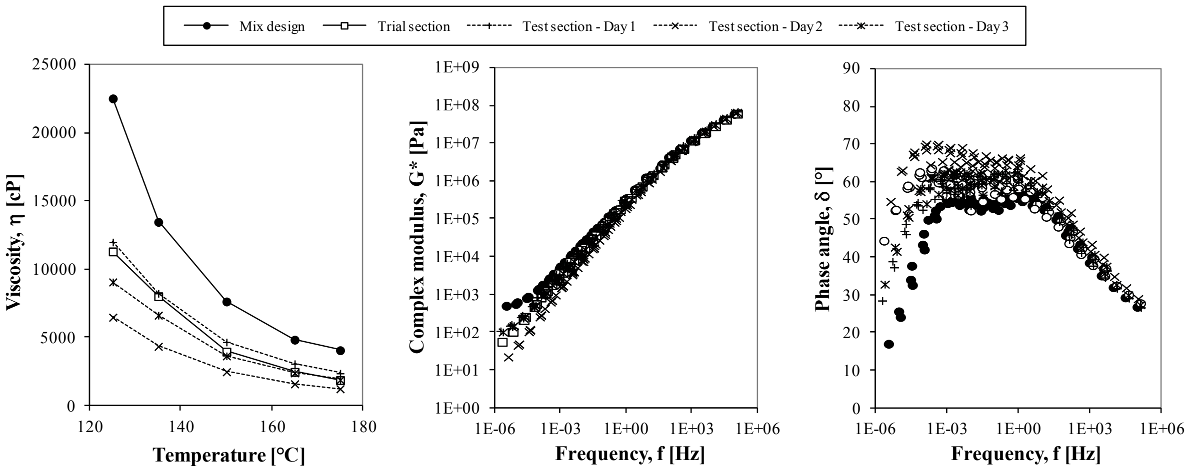

Fig. 1. Complex modulus and phase angle master curves of the binder

Rheological behaviour of asphalt rubber is characterized by an intermediate elastic plateau clearly visible in the phase angle plot and revealed by the flex which is found in the representation of complex modulus data (Fig. 1). Moreover, viscosity decreases as a function of temperature, with values at 175°C which in most cases (except for the sample taken at the plant during the second day of construction of the test section) are comprised within the acceptance range indicated by ASTM standard D6114 (1,500÷5,000 cP).

Experimental results show that when compared to samples retrieved from the production plant during construction operations, asphalt rubber employed in the mix design study was characterized by the greatest crumb rubber content, by the highest viscosity and by the stiffest and most elastic response (Table 2). Observed production variability may be due to the sampling technique but may also be related to non-homogeneity of the material which was produced in the industrial plant (in Tuscany), cooled down and transported to the bituminous mixture plant (located in Piedmont, 380 km away) and then slowly reheated and homogenized before being employed for the production of the gap-graded bituminous mixture. Crumb rubber contents listed in Table 2 represent a raw estimate of actual composition but in any case they show that improvements may be needed to more closely control asphalt rubber production and handling.

3.2. Gap-graded bituminous mixture

Recipes of the gap-graded mixture considered in the mix design study and adopted as job-mix formula during production were defined by combining available fractions in order to obtain a total size distribution as close as possible to the central distribution contained in acceptance envelopes [4]. In mix design, binder content was varied within the acceptance range (7.0-9.5%), while for plant production, regardless of the fact that aggregates were changed, optimal binder content derived from mix design (8.0%) was adopted.

Mixture recipes are given in Fig. 2, which also contains the results of tests carried out during the project to check particle size distribution. Results of the volumetric and mechanical tests performed on laboratory-compacted specimens are listed in Table 3, which shows average values of binder content from ignition (%B), density (ρ), theoretical maximum density (TMD), percent air voids (%v), voids in the mineral aggregate (VMA), voids filled with bitumen (VFB), Marshall stability (S), Marshall flow (f), indirect tensile strength (ITS), stability ratio (SR_{15days}) and indirect tensile strength ratio ($ITSR_{7days}$).

Particle size distribution of the design mixture is comprised within acceptance limits, while the job-mix formula leads to a distribution which is slightly too coarse in the 8-10 mm range (Fig. 2). Results obtained from sieve analyses carried out on aggregates extracted from mixtures sampled during paving operations were coherent with the job-mix distribution, thus indicating an excellent production consistency. On the contrary, asphalt rubber dosage was quite variable, probably as a result of viscosity variability (Fig. 1) and of the characteristics of the pumping system which was set up for the project and exhibited some problems during production. The highest and lowest binder content values were registered for the mixtures placed on the trial section (9.0%) and during the second day on the test section (7.3%), respectively. Values close to target were recorded in the first and third day of construction (respectively 8.3% and 8.1%).

Results obtained in the mix design phase highlight the fact that for any given binder content the level of compaction achieved with the Marshall apparatus is lower than that corresponding to gyratory compaction. Moreover, both stability and indirect tensile strength do not exhibit clear trends as a function of binder content. Optimal asphalt rubber content was chosen equal to 8.0%, which corresponds to a void content of 6.5% of Marshall specimens (mean value of the acceptance range indicated by technical specifications). For all mixtures an acceptable resistance to water damage was recorded, with stability and ITS ratios always greater than 93%. Even though aggregates and recipes were changed, results obtained during construction of the trial and test sections were coherent with those of the mix design phase.

	Mix design	Job-mix
Fraction 0/5	26%	30%
Fraction 5/10	25%	16%
Fraction 10/15	49%	54%
Asphalt rubber	8.0%	8.0%

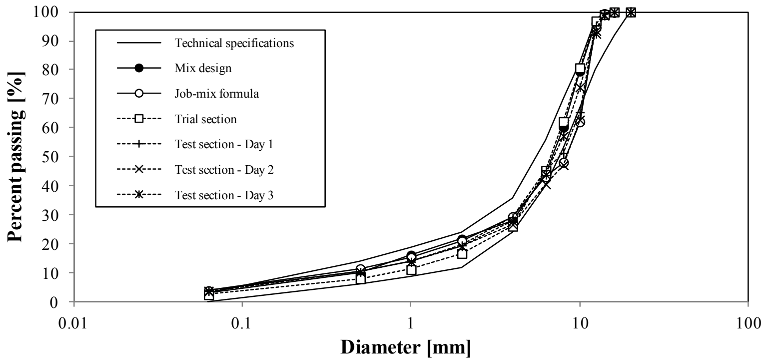

Fig. 2. Recipes of the gap-graded bituminous mixture and results of particle size distribution analyses

Table 3. Volumetric and mechanical properties of laboratory-compacted specimens

	Mix design								Trial section	Construction Day1	
	Marshall specimens (M)				Gyratory specimens (G)				M	M	G
%B [%]	7.3	8.3	8.6	9.5	7.3	8.3	8.6	9.5	9.0	8.3	8.3
ρ [g/cm^3]	2.311	2.329	2.331	2.355	2.327	2.369	2.388	2.392	2.285	2.352	2.343
TMD [g/cm^3]	2.518	2.473	2.455	2.438	2.518	2.473	2.455	2.438	2.424	2.472	2.472
%v [%]	8.3	5.8	5.1	3.4	7.6	4.2	2.8	1.9	5.8	4.8	5.2
VMA [%]	24.7	24.6	24.6	25.2	24.2	23.1	22.7	24.0	24.2	22.5	22.8
VFB [%]	66.6	76.4	79.6	86.5	68.6	82.9	88.0	92.1	76.3	78.5	77.2
S [kN]	7.5	7.4	6.8	7.7	-	-	-	-	7.2	8.5	-
f [mm]	3.7	3.3	4.3	3.5	-	-	-	-	2.7	4.1	-
ITS [N/mm^2]	-	-	-	-	0.96	0.87	1.03	0.89	-	-	1.19
SR_{15days} [%]	96.0	105.4	102.9	101.3	-	-	-	-	-	96.1	-
$ITSR_{7days}$ [%]	-	-	-	-	98.7	105.6	93.8	109.8	-	-	103.7

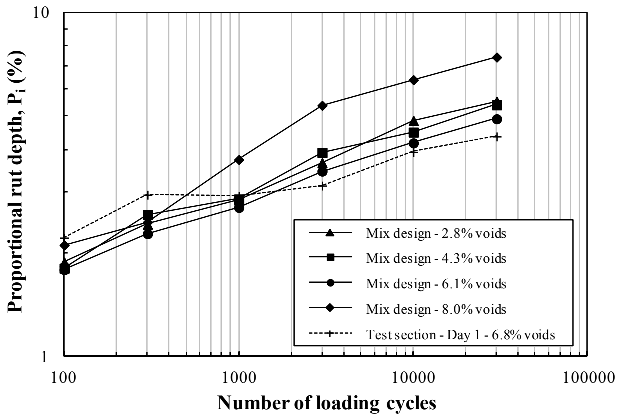

Fig. 3. Wheel-tracking test results

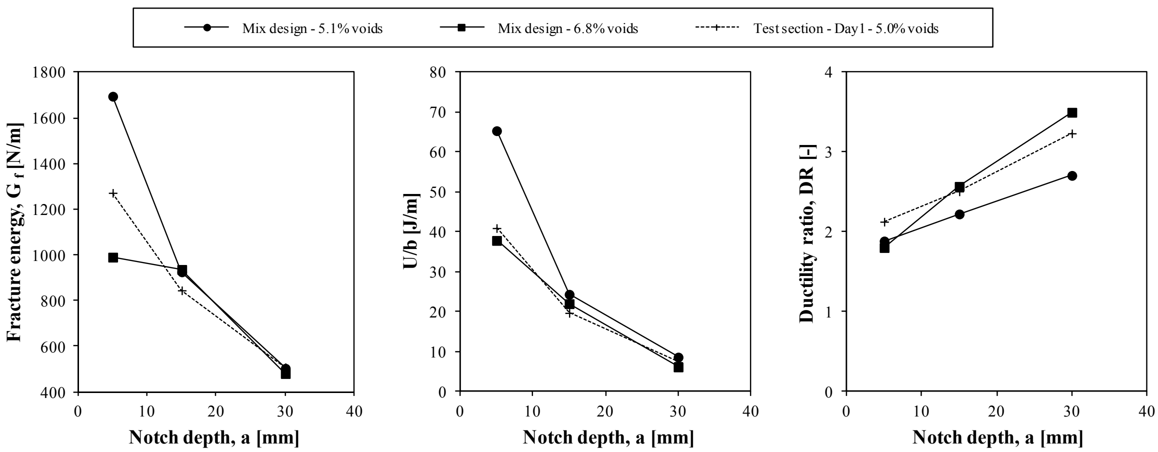

Fig. 4. Semi-circular bending test results

In order to assess the sensitivity of rutting behaviour to achieved compaction level, as part of the performance-related component of mix design, wheel-tracking tests were carried out on slabs of the optimal mixture (8.0% asphalt rubber) prepared with an initial thickness of 5 cm and different target values of density and void content. Results are given in Fig. 3, which also contains data obtained for the mixture sampled during the first day of construction of the test section. In this case slabs were prepared with a thickness of 3 cm in order to replicate field conditions, adopting a target void content of 6.8% (evaluated geometrically), which corresponds to the value obtained from Marshall compaction increased by 2 percentage points. Such a compaction level represents the minimum accepted by technical specifications [4].

Test results, represented in terms of proportional rut depth (P_i) as a function of applied loading cycles, show that the design mixture is indeed very sensitive to compaction, with an abrupt response change at 8% void content. Due to its different composition in terms of aggregate structure, the mixture sampled from the field exhibited a lower rate of rutting, with the lowest value of final permanent deformation. Effects due to variable slab thickness were not analyzed in the study and may also be responsible for the different behaviour of the two mixtures.

With respect to crack formation and propagation, semi-circular bending (SCB) tests were performed on the optimal design mixture compacted with the gyratory equipment at 50 and 30 gyrations, thus obtaining void contents respectively equal to 5.1 and 6.8%. In the case of the mixture sampled in the field, in order to assess its maximum crack resistance potential, a target void content of 5.0% was chosen, which corresponds to the minimum value admitted by technical specifications [4].

Results of the SCB tests are shown in Fig. 4 where they are expressed, as a function of notch depth (a), in terms of fracture energy (G_f), expressed as the ratio between energy dissipated to total collapse and initial ligament cross-section, and ductility ratio (DR), given by the ratio between energy at collapse and energy at peak load. Plots of energy at peak load (U) divided by specimen thickness (b) are also provided since the slope of interpolating lines can be used for the calculation of the so-called J-integral (J_c), an overall quantification of fracture resistance.

It can be noted that the behavior of the design mixture is sensitive to compaction level. In particular, by reducing void content a better behavior is obtained only with respect to resistance to crack formation, with increasing values of fracture energy and J-integral for small notch depths only. Resistance to crack propagation, revealed by the data recorded at greater notch depths, is not significantly affected by compaction and in fact as void content decreases, a reduction in ductility is observed. Fracture behavior of the mixture sampled on site and compacted at its minimum allowable void content (5.0%) is approximately equivalent to that of the design mixture with 6.8% air voids.

3.3. Emissions

Results of the analyses performed on gaseous emissions sampled at the test section and on the eluate retrieved from laboratory leaching tests are given in Tables 4 and 5. Organic compounds in Table 4 are ordered, from top to bottom, by increasing molecular weight. These compounds are those which are toxic among all substances potentially detectable by means of gas-chromatographic techniques. Test results listed in Table 5 are divided in sections which correspond to anion content, heavy metals, chemical oxygen demand (COD) and electrochemical properties (pH and electrical conductivity); whenever possible, they are compared to limits set by Italian regulations, the respect of which allows a material to be defined as “inert” from an environmental point of view [15].

Fumes sampled at the paver’s screed and at the driver’s seat showed completely different VOC and PAH contents (Table 4). In particular, a higher content of all VOC compounds, with the only exception of 1,2,4-trimethylbenzene, was found at the screed, while the concentration of PAH substances was greater at the driver’s seat. This scenario can be explained by considering that concentration of volatile compounds (VOC) is mainly dependent upon the distance between the emitting source and the receiver, shorter in the pavement-screed system than in the truck-driver one, while the concentration of heavier toxic hydrocarbons (PAH) is more sensitive to temperature, higher in front of the paver than at the screed.

Table 4. Results of analyses of gaseous emissions at the paver (D: driver's seat; S: screed)

VOC (μg/m^3)		
	D	S
benzene	2.6	< 0.1
toluene	5.4	13.4
ethylbenzene	< 0.1	< 0.1
bromobenzene	< 0.1	< 0.1
styrene	< 0.1	< 0.1
1,2,4-trimethylbenzene	7.6	6.1
1,3,5-trimethylbenzene	5.9	17.1
p-xylene	11.8	157.3
1,3,5-trichlorobenzene	< 0.1	< 0.1
1,2,4-trichlorobenzene	< 0.1	< 0.1
p-isopropyltoluene	1.4	57.3
butylbenzene	< 0.1	3.1
total VOCs	34.3	264.9

PAH (μg/m^3)		
	D	S
naphtalene	7.9	5.2
acenaphtylene	1.8	1.2
2-bromonaphtalene	10.3	9.2
acenaphtene	2.3	1.4
fluorene	1.3	1.0
phenanthrene	2.0	1.1
anthracene	1.8	0.6
fluoranthene	3.1	0.9
pyrene	3.0	0.9
benzo[a]anthracene	6.1	2.2
chrysene	3.6	0.8
benzo[a]pyrene	5.3	3.5
benzo[b]fluoranthene	3.6	0.8
dibenzo[a,h]anthracene	< 0.1	< 0.1
indeno[1,2,3-cd]pyrene	8.9	< 0.1
benzo[ghi]perylene	3.6	1.2
total PAHs	64.4	30.0

Table 5. Results of leaching tests

VOC (μg/kg)	
	L
benzene	2.32
toluene	3.86
ethylbenzene	< 0.1
bromobenzene	1.85
styrene	1.19
1,2,4-trimethylbenzene	18.45
1,3,5-trimethylbenzene	8.95
p-xylene	2.67
1,3,5-trichlorobenzene	1.49
1,2,4-trichlorobenzene	2.69
p-isopropyltoluene	0.36
butylbenzene	0.37
total VOCs	44.16

PAH (μg/kg)	
	L
naphtalene	4.78
acenaphtylene	0.15
2-bromonaphtalene	2.23
acenaphtene	0.23
fluorene	0.23
phenanthrene	0.71
anthracene	0.23
fluoranthene	0.38
pyrene	0.62
benzo[a]anthracene	< 0.1
chrysene	< 0.1
benzo[a]pyrene	4.63
benzo[b]fluoranthene	1.63
dibenzo[a,h]anthracene	< 0.1
indeno[1,2,3-cd]pyrene	< 0.1
benzo[ghi]perylene	2.83
total PAHs	18.66

Metals		
	Test	Limit
Nitrate [mg/l]	< 0.1	50
Fluoride [mg/l]	< 0.1	1,5
Sulphate [mg/l]	1.24	250
Chloride [mg/l]	0.538	100
Ba [μg/l]	18.4	1000
Cu [μg/l]	18.6	50
Zn [μg/l]	11.0	3000
Co [μg/l]	< 0.6	250
Ni [μg/l]	3.48	10
As [μg/l]	< 5.3	50
Cd [μg/l]	< 0.25	5
Cr [μg/l]	1.04	50
Pb [μg/l]	< 4.2	50
Al [μg/l]	< 0.28	
Fe [μg/l]	1.45	
Mn [μg/l]	8.88	
COD [mg/l]	9.3	30
pH	7.95	5.5-12
CE [μS/cm]	8	

Table 6. Results of tests carried out on cores and on the pavement surface

	Trial section	Test section		
		Day 1	Day 2	Day 3
%B [%]	9.0	8.3	7.3	8.1
ρ [g/cm^3]	2.255	2.342	2.260	2.202
TMD [g/cm^3]	2.424	2.472	2.486	2.474
%v [%]	7.0	5.3	9.1	11.0
VMA [%]	25.2	22.9	24.0	27.2
VFB [%]	77.8	77.0	62.6	59.7
SN	-	63	64	61
MTD	-	0.71	0.76	0.64

The American Conference of Governmental Industrial Hygienists (ACGIH) [16] defines a maximum exposition limit equal to 0.5 mg/m^3 (considering 8 h/day, 5 days/week), measured on the benzene-soluble fraction of inhaled aerosol. German regulations refer to a maximum concentration of total hydrocarbons in emissions equal to 10 mg/m^3. Data collected at the test section cannot be directly compared to such limits; however, by considering the sum of total VOC and PAH contents, composition of analyzed fumes seem to be compatible with the limits illustrated above.

Results of leaching tests performed on the gap-graded mixture comply to Italian regulations (Table 5) [16]. Compliance is found also in the case of metals such as zinc and iron, which are present in significant amounts in crumb rubber [17]. However, they are not dissolved in water due to the fact that they are fixed in the rubber matrix and further encapsulated in bitumen. As expected, VOC content of the leaching solution is distinctively higher than PAH content since compounds of the former type are characterized by a lower molecular weight and hence by a greater solubility in water. Even though no acceptance limits are provided for VOC and PAH, the low value of COD suggests that the mixture can be considered "inert" even from the viewpoint of total organic substances.

3.4. Pavement

Results of tests performed on cores taken from the test section and on the pavement surface are listed in Table 6. Achieved compaction was quite variable as a result of the concurring effects due to variations in composition, aggregate size distribution, binder viscosity and air temperature. Compaction was carried out by means of a 140 ton steel roller with mixture temperature always greater than 165°C. Surface properties of the pavement were in line with expectations, with average values of skid number (SN, equal to 63) and mean texture depth (MTD, equal to 0.71 mm) which are typical for gap-graded mixtures. In any case, since measurements were performed immediately after construction, a short-term enhancement of skid resistance is expected due to the removal of surface binder films covering aggregates.

4. Conclusions

Experimental data collected during the design and construction of the full-scale pavement section surfaced with a gap-graded bituminous mixture containing asphalt rubber constitute a valuable reference database for future full-scale applications. Technical specifications have proven to be compatible with characteristics of available materials but certainly require an enhancement with the inclusion of acceptance limits referred to performance-related tests and chemical analyses of fumes and leaching eluates. Quality control improvements may be needed with respect to asphalt rubber production and field compaction. Moreover, reference values of rutting and crack propagation test results may be useful to optimize mix design. In such a context, it will be interesting to understand more clearly the effects of compaction level, loading conditions and temperature for a better assessment of potential field performance. In any case, the full-scale test section will be continuously monitored in time to provide further technical information which can be used in the future for the design and construction of other asphalt rubber wearing course layers.

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