Action 3.2

Characterization of bituminous mixtures containing crumb rubber from ELTs

POLITECNICO DI TORINO

Project partners

Patrimonio s.r.l.

With the contribution of

Contents

Introduction

To avoid the occurrence of performance problems in field applications, an adequate laboratory characterization of bituminous mixtures containing scrap tyre rubber was included in the project. Investigations were performed in order to give quantitative support both to mix design and to the prediction of field performance.

MATERIALS AND METHODS

By taking into account the results obtained in Actions 2.4 and 2.5, bituminous mixtures were prepared by employing aggregates of different origins and asphalt rubber binders containing several crumb rubber types. Materials were chosen in order to have a representative spectrum of possible design and construction options, focusing on the preparation of mixtures of the same type of those planned to be laid on site during the implementation phase of the project (Actions 4.1 and 4.2).

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 and EN 933-4). Asphalt rubber binders, provided by the only Italian producer, were subjected to tests for the determination of flow (viscosity) and viscoelastic (complex modulus and phase angle) parameters.

Viscosity measurements were performed between 125 and 190℃ 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) [1]. 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 4-34℃ temperature range, and 25 mm plates (1.5 mm gap) for temperatures comprised between 34 and 82℃ [2]. 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 34℃ by making use of the CAM and WLF models [3,4].

For each aggregate type – asphalt rubber combination, identification of the job-mix formula was based on requirements for size distribution of aggregates and binder content set in current Technical Specifications [5-8], and on the analysis of available data provided by hot mix plants. In particular, the following wearing course mixture types were considered in the study:

- Standard gap-graded mixtures (BV, ZA) [5,6];
- Low binder content gap-graded mixtures (TB) [5];
- Coarse gap-graded mixtures (SG) [7];
- Fine dense-graded mixtures (CE) [8];
- Coarse dense-graded mixtures (SD) [8].

All mixtures were prepared at 190℃ (laboratory or plant mixing) and compacted with different techniques at 175℃.

The experimental investigation, carried out in the Road Materials Laboratory and in the Environmental Chemistry Laboratory, included the following tests:

Compaction tests

- Marshall compaction (MC) tests carried out by applying 50 blows on each specimen face (EN 12697-30) with 101.6 mm diameter moulds;
- Gyratory compaction (GC) tests carried out by imposing 50 gyrations (EN 12697-31) with 150 mm diameter moulds;
- Roller compaction (RC) tests (EN 12697-33, large size device), carried out by preparing slabs (50 cm × 18 cm) with different values of target final thickness and density.

Volumetric tests

- Tests on loose mixtures (EN 12697-5) for the evaluation of theoretical maximum density (TMD);
- Tests on laboratory-compacted specimens for the evaluation of density (ρ, EN 12697-6), percent air voids (%v, EN 12697-8), voids in the mineral aggregate (VMA) and voids filled with bitumen (VFB).

Simple QA/QC mechanical tests

- Marshall tests at 60℃ (EN 12697-34) for the evaluation of Marshall stability and flow (on MC specimens);
- Indirect tensile strength tests at 25℃ (EN 12697- 23) (on GC specimens);
- Marshall and indirect tensile strength tests repeated after water immersion for 7 and 15 days (to assess water sensitivity).

Performance-related mechanical tests

- Wheel-tracking (WT) tests carried out on RC slabs at 40 and 60℃ with a maximum number of applied loading cycles equal to 30,000 (EN 12697-22), in order to assess potential resistance to rutting;
- Semi-circular bending (SCB) tests performed at 20°C on half-discs 50 mm thick (EN 12697-44) obtained from notched GC specimens, in order to assess potential resistance to crack formation and propagation.

Environmental tests

- Leaching (LCH) tests carried out on loose mixtures (EN 12457-2), followed by chemical analyses on the resulting eluate for the determination of pH, electrical conductivity, anions, heavy metals, COD (chemical oxygen demand), VOC (Volatile organic compounds) and PAH (Polycyclic aromatic hydrocarbons);
- Potential gaseous emission (PGE) tests carried out on mixtures subjected to a controlled-heating procedure, followed by chemical analyses of sampled fumes for the determination of VOC (Volatile organic compounds) and PAH (Polycyclic aromatic hydrocarbons).

All tests listed above were carried out according to procedures described in EN standards, with the only exception of:

- SCB tests performed in the first part of the Action (on mixtures BV and TB);
- PGE tests, which were conceived during the project;
- Chemical analyses carried out on LT eluates and PGE fumes.

SCB tests were initially performed according to an internal protocol of the Road Materials Laboratory which, when compared to the EN procedure, requires the preparation of thinner specimens (25 mm vs. 50 mm), the adoption of a lower displacement rate (1 mm/min vs. 5 mm/min) and variable notch depths (5, 15 and 30 mm vs. 10 mm).

Following previous research work on the analyses of gaseous emissions sampled on site [9], PGE tests were carried out according to a procedure which was developed with the purpose of eliminating any bias of site-specific factors. Thus, 30 kg samples of loose bituminous mixtures are subjected to a standard controlled heating conditioning (30 minutes at 170℃) in a closed, vertical-axis mixer. Fumes are then taken from the upper part of the mixer by employing a pump (0.5 l/min flow rate, 5 minutes total sampling time) by means of which they are adsorbed on active granular carbon cartridges. These matrixes are then subjected to solvent extraction (with methylene chloride) in an ultrasound bath for 60 minutes (EN 13649) [10]. Subsequent analyses are 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.

LCH tests required the development of specific protocols since the current EN standard does not provide guidance for analysis of bituminous mixtures. Thus, filtered eluates 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 heavy metals were evaluated with a Perkin-Elmer Optima 2000 ICP-OES. Further analyses were carried out for the determination of anion content, chemical oxygen demand (COD) and characteristic physical-chemical parameters (pH and electrical conductivity).

A synthetic description of the experimental investigation is given in Table 1.

Table 1. Synthesis of experimental investigation

	BV	TB	ZA	CE	SG	SD
Tests on aggregates						
Resistance to fragmentation	x				x	x
Flakiness index			x	x		
Shape index			x	x		
Tests on asphalt rubber binders						
Viscosity	x	x	x	x	x	x
Complex modulus and phase angle	x		x	x	x	x
Compaction tests						
Marshall	x	x	x	x		
Gyratory	x		x	x	x	x
Roller	x	x	x	x	x	x
Volumetric tests	x	x	x	x	x	x
Simple QA/QC mechanical tests						
Marshall stability and flow	x	x	x	x		
Indirect tensile strength	x					
Water sensitivity	x	x				
Performance-related mechanical tests						
Wheel-tracking	x	x	x	x	x	x
Semi-circular bending	x	x	x	x	x	x
Environmental tests						
Leaching	x		x	x		
Potential gaseous emission	x		x	x		

RESULT

Tests on aggregate

Results obtained from tests carried out on aggregates are shown in Figure 1 and in Table 2.

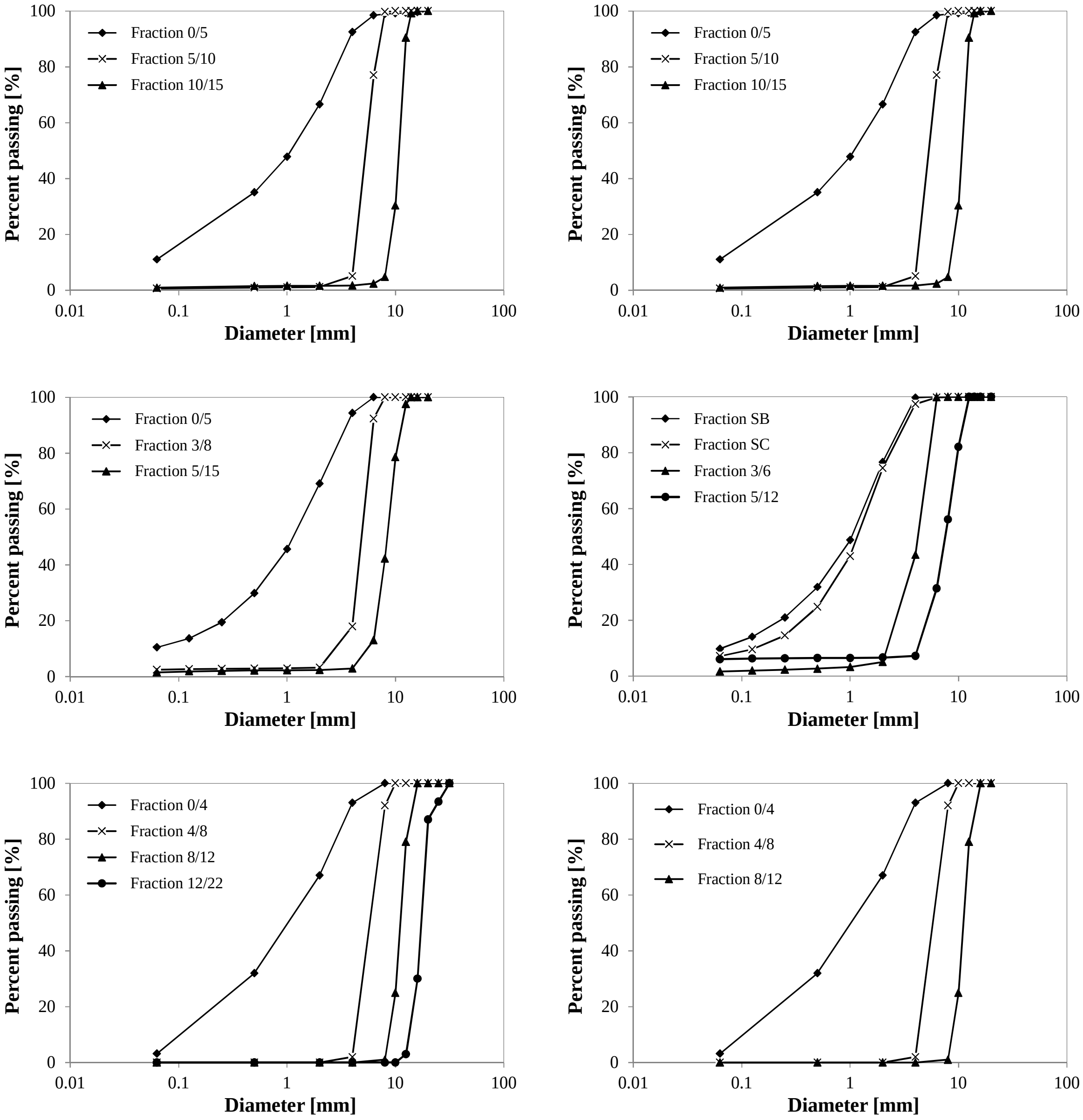


Figure 1. Particle size distributions of aggregates employed for preparation of bituminous mixtures

Table 2. Characterization of aggregates employed for preparation of bituminous mixtures

	BV	**TB**	**ZA**	**CE**	**SG**	**SD**
Los Angeles index (%)	19	-	-	-	19	19
Flakiness index (%)	15	-	17	27	-	-
Shape index (%)	-	-	9	17	-	-

Tests on asphalt rubber binders

Results of viscosity and oscillatory tests carried out on asphalt rubber binders were analysed by fitting experimental data with the following models:

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
$$log\left(a_{(T,T_{ref})}\right) = \frac{-C_1 \cdot (T - T_{ref})}{C_2 + T - T_{ref}} \tag{3}$$

where $\eta(T)$ is viscosity at temperature T (in ℃), $|G^*(f)|$ is the norm of the complex modulus (in Pa) at loading frequency f (in Hz); G_g is the glassy modulus ($\log G_g = 6.1$); T_{ref} (in ℃) is the reference temperature (equal to 34℃); $a(T,T_{ref})$ is the shift factor at temperature T; α_T, β_T, f_c, k, m, C_1 and C_2 are model parameters.

Average results obtained from model fitting, shown in Figures 2 and 3, are synthesized in Table 3. The same asphalt rubber binder (indicated as ZA/SG/SD) was employed for bituminous mixtures ZA, SG and SD.

Table 3. Model parameters of asphalt rubber binders

	BV	**TB**	**ZA/SG/SD**	**CE**
α_T	1.5E+14	2.7E+14	5.3E+14	1.7E+16
β_T	4.8	4.9	5.1	6.3
$\log(G_g)$	6.1	-	6.1	6.1
$\log(f_c)$	5.1	-	5.6	4.3
K	0.15	-	0.17	0.19
M	0.71	-	0.74	1.00
C_1	11.3	-	10.0	11.3
C_2	111.4	-	106.4	120.6

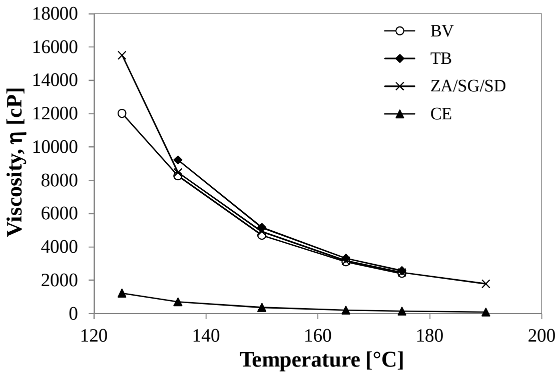


Figure 2. Temperature-viscosity curves of asphalt rubber binders

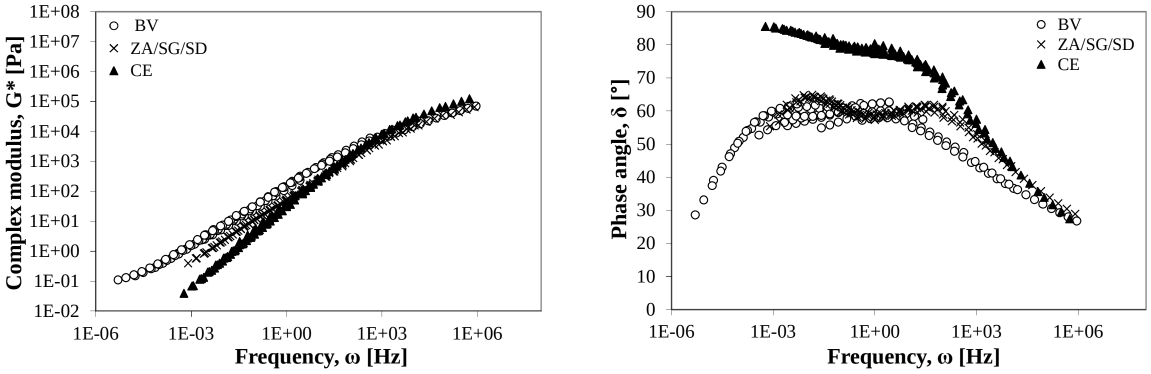


Figure 3. Complex modulus and phase angle master curves of asphalt rubber binders

Significant variations were recorded when comparing different binders since they were prepared by employing different base bitumens and crumb rubber products supplied by different plants. While binders BV, TB and ZA/SG/SD were produced with the standard “wet” technology, with approximately 18% crumb rubber (as declared by the producer), binder CE derived from a hybrid process in which binder ZA/SG/SD was diluted with an additional neat bitumen. Consequently, its crumb rubber content was of the order of 7%, more similar to a “terminal blend” product than to a regular “asphalt rubber”.

It can be observed that rheological behaviour of standard asphalt rubber binders (BV, TB and ZA/SG/SD) 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. Moreover, viscosity decreases as a function of temperature, with values at 175℃ which are comprised within the acceptance range indicated by ASTM standard D6114 (1,500÷5,000 cP). As expected, binder CE exhibited a lower viscosity and higher phase angle values over the entire investigated ranges.

Identification of job-mix formulae

Recipes of the bituminous mixtures considered in the investigation are shown in Table 4. Corresponding aggregate size distributions are given in Figure 4, where they are compared with reference acceptance intervals which were used for mix design purposes.

Table 4. Recipes of bituminous mixtures

Mixture BV	P [%]
Fraction 0/5	30
Fraction 5/10	16
Fraction 10/15	54
Asphalt rubber	8.3

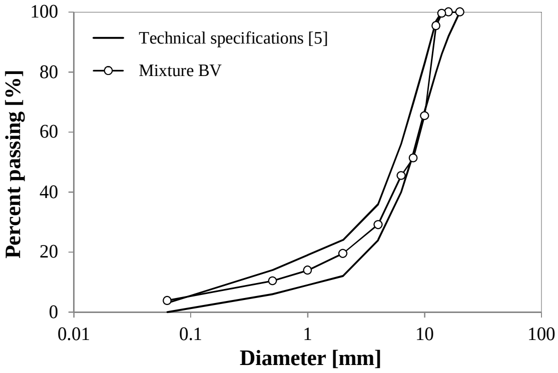
Mixture TB	P [%]
Fraction 0/5	30
Fraction 5/10	16
Fraction 10/15	54
Asphalt rubber	6.8

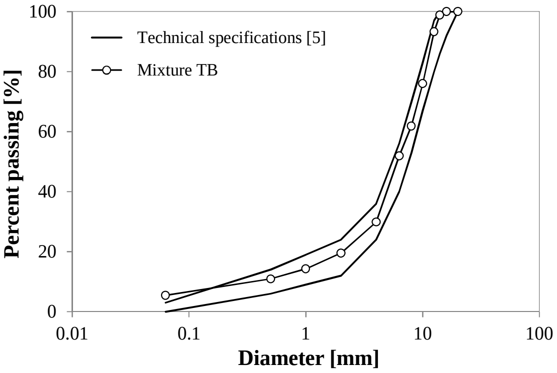
Mixture ZA	P [%]
Fraction 0/5	25
Fraction 3/8	20
Fraction 5/15	55
Asphalt rubber	8.5

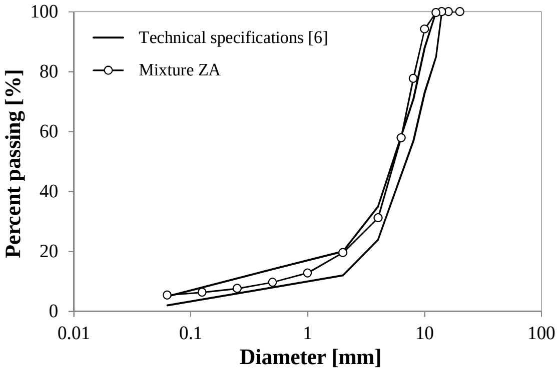
Mixture CE	P [%]
Fraction SC	22.5
Fraction SB	22.5
Fraction 3/6	5
Fraction 5/12	50
Asphalt rubber	5.6

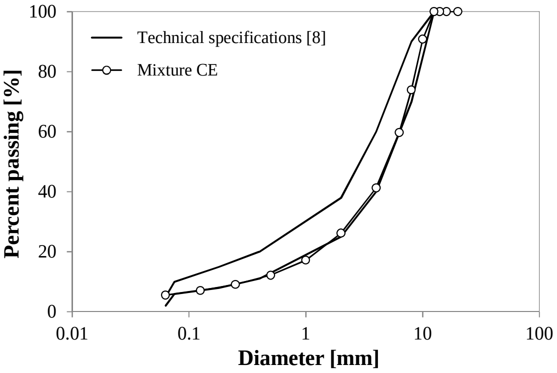
Mixture SG	P [%]
Fraction 0/4	24
Fraction 4/8	30.4
Fraction 8/12	30.4
Fraction 12/22	11.4
Filler	3.8
Asphalt rubber	7.5

Mixture SD	P [%]
Fraction 0/4	42
Fraction 4/8	35.5
Fraction 8/12	16.7
Filler	5.8
Asphalt rubber	5.5









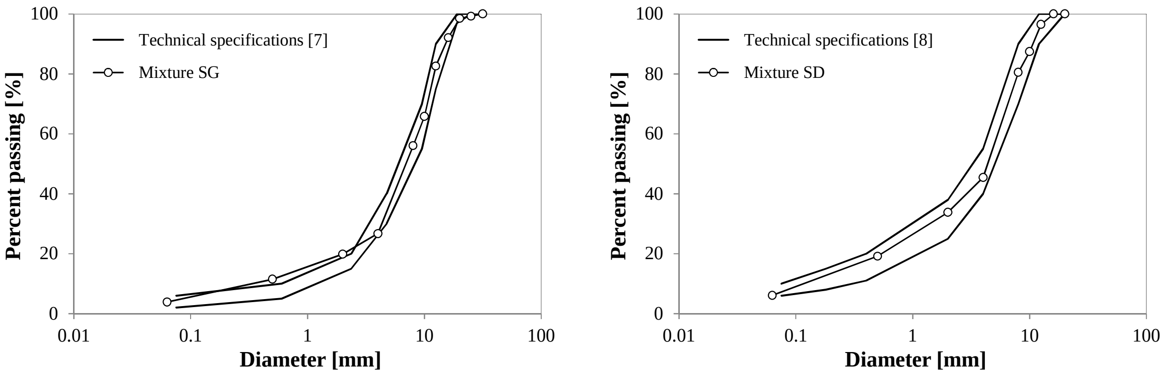


Figure 4. Aggregate size distributions of bituminous mixtures

Volumetric tests

Results of volumetric tests performed on loose and laboratory-compacted specimens are listed in Table 5, which shows average values of density (ρ), theoretical maximum density (TMD), percent air voids (%v), voids in the mineral aggregate (VMA) and voids filled with bitumen (VFB).

Table 5. Volumetric properties of laboratory-compacted specimens

	BV		**TB**	**ZA**		**CE**		**SG**	**SD**
	M	G	M	M	G	M	G	G	G
%B [%]	8.3	8.3	6.8	8.5	8.5	5.6	5.6	7.5	5.5
ρ [g/cm^3]	2.351	2.343	2.316	2.348	2.428	2.235	2.256	2.447	2.427
TMD [g/cm^3]	2.472	2.472	2.487	2.540	2.540	2.491	2.491	2.508	2.563
%v [%]	4.9	5.2	6.9	7.5	4.4	10.3	9.4	2.4	5.3
VMA [%]	22.6	22.9	21.4	25.5	22.9	21.9	21.1	19.1	17.7
VFB [%]	78.4	77.2	68.1	70.4	80.8	53.0	55.4	87.3	70.0

- A significant variability of volumetric properties was recorded due to the combined effects of aggregates types (Table 1), particle size distributions (Figure 4), binder viscosity during mixing and compaction (Figure 2) and binder content

Simple QA/QC mechanical tests

Results of the simple QA/QC mechanical tests performed on laboratory-compacted specimens are listed in Table 6, which shows average values of Marshall stability (S), Marshall flow (f), indirect tensile strength (ITS), Marshall stability ratio (SR_{15days}) and indirect tensile strength ratio ($ITSR_{7days}$).

Table 6. Simple QA/QC mechanical properties of laboratory-compacted specimens

	BV		**TB**	**ZA**	**CE**
	M	G	M	M	M
S [kN]	8.5	-	7.4	7.7	8.3
f [mm]	4.1	-	4.0	5.1	1.9
ITS [N/mm^2]	-	1.19	-	-	-
SR_{15days} [%]	96.1	-	106.6	-	-
$ITSR_{7days}$ [%]	-	103.9	-	-	-

Results of Marshall and ITS tests were coherent with those obtained for similar materials in previous studies performed on mixtures containing asphalt rubber binders. However, it was confirmed that the minimum Marshall stability requirement often indicated by Technical Specifications (equal to 8 kN) may be slightly too stringent for standard gap-graded mixtures. With respect to water sensitivity, the two investigated mixtures exhibited stability and ITS ratios which were always above 96%, thus indicating that the presence of thick binder coatings in the mixtures ensures a good resistance to water aggression.

Wheel-tracking tests

Results of wheel-tracking tests, represented in terms of proportional rut depth (P_i) as a function of applied loading cycles (N), are given in Table 7 and Figure 5. Experimental data were fitted to power law equations as indicated below:

$$P_i = P_{100} \cdot \left(\frac{N}{100} \right)^{\beta} \quad (4)$$

where P_{100} and β are regression constants, which depend upon material characteristics and test conditions. P_{100}, which corresponds to proportional rut depth after 100 loading cycles, gives an idea of the early response of the mixture under repeated loading, while β is related to the rate of strain accumulation which is exhibited throughout the test up to 30,000 loadings.

Table 7. Wheel-tracking test results and model parameters

	T	%v	Number of loading cycles (N)						Model parameters	
	[°C]	[%]	100	300	1000	3000	10000	30000	P_{100}	β
BV	60	6.9^{**}	2.2	3.0	2.9	3.1	3.9	4.4	2.48	0.094
TB	60	6.5^{*}	4.4	4.6	5.9	6.5	6.9	8.0	4.29	0.111
TB	60	8.1^{*}	1.7	2.3	2.6	2.9	3.6	4.4	1.87	0.143
ZA	40	8.2^{**}	2.4	3.7	4.4	5.4	6.2	7.3	3.18	0.147
ZA	60	7.8^{**}	2.4	3.4	4.1	4.7	5.1	5.9	3.08	0.115
CE	40	12.7^{**}	0.7	0.9	1.2	1.7	2.3	3.2	0.63	0.283
CE	60	12.9^{**}	1.2	1.8	2.6	3.1	3.8	4.7	1.54	0.198
SG	60	6.1^{**}	-	1.4	3.8	5.0	5.5	11.4	1.17	0.390
SD	60	8.7^{**}	-	1.2	1.5	3.0	3.7	4.3	0.84	0.307

* Measured voids content

** Calculated (geometrical) voids content

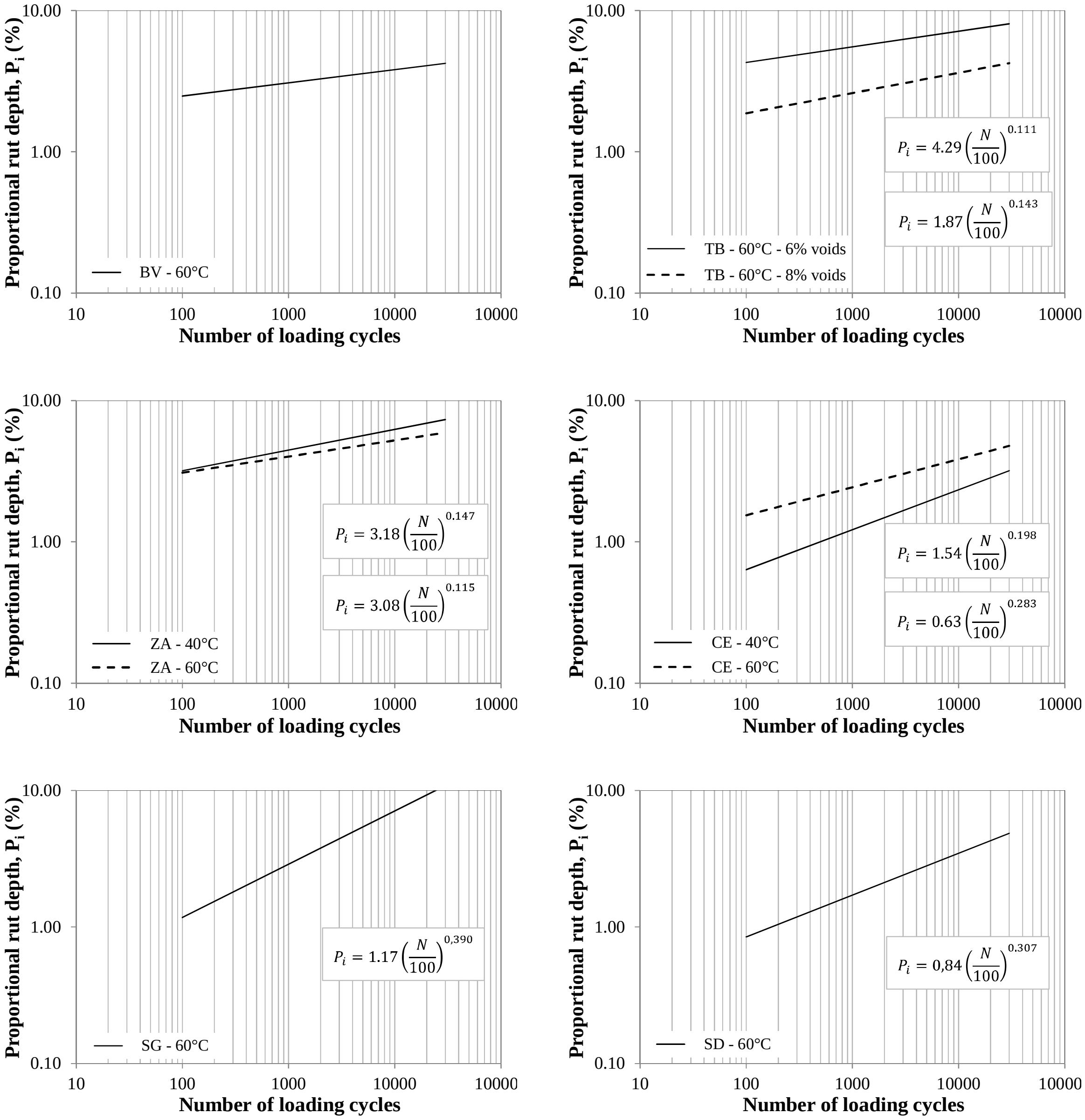


Figure 5. Wheel-tracking test results

It can be observed that mixtures are indeed very sensitive to changes in compaction and aggregate structure, both in terms of rutting rate and final permanent deformation value. Effects due to variable slab thickness, which were not analyzed in detail in the study, may also be responsible for the different behaviour of mixtures (all slabs had an initial thickness of 4 cm, with the exception of the 3 cm thick slabs prepared with mixture BV).

The best response in terms of rutting response was recorded for gap-graded mixture BV, which exhibited the lowest β value (0.094), while the worst response was shown by the SG and SD mixtures which, although different in terms of particle size distribution, contained aggregates of the same origin.

Semi-circular bending tests

Results of SCB tests, synthesized in Table 8 and in Figure 6, were expressed in different forms depending upon the adopted testing protocol.

In the case of mixtures BV and TB, tested with three different notch depths, fracture energy (G_{f0}) was calculated at 0 mm notch depth as the ratio between energy dissipated to total collapse and initial ligament cross-section, while ductility ratio (DR_0) was computed for the same reference condition as the ratio between energy at collapse and energy at peak load. Plots of energy at peak load (U) divided by specimen thickness (b) were also analysed since the slope of interpolating lines can be used for the calculation of the so-called J-integral (J_c), which provides an overall quantification of fracture resistance.
As required by the corresponding EN standard, results of all the other tests (performed on mixtures ZA and CE) were expressed in terms of strain at maximum force (ε_{max}) and fracture toughness (K_{Ic}) which is function of geometrical characteristics and stress at failure of the specimen.

Table 8. SCB test results

	%v [%]	G_{f0} [N/m]	DR_0 [-]	J_c kJ/m^2	ε_{max} [%]	K_{Ic} [N/mm$^{3/2}$]
BV	5.0	1373.77	1.88	0.92	-	-
TB	6.0	1163.85	1.49	0.98	-	-
TB	8.0	898.21	1.99	0.78	-	-
ZA	7.0	-	-	-	2.68	1.4
CE	10.5	-	-	-	1.60	2.7

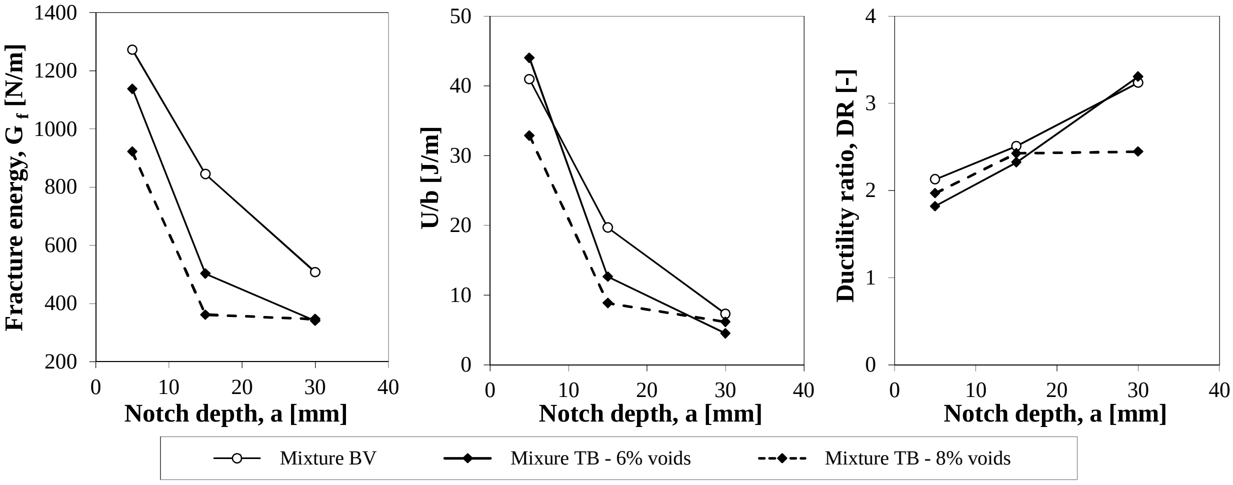


Figure 6. SCB test results

Leaching tests

Results of the analyses performed on eluates retrieved from laboratory leaching tests are given in Tables 9 and 10. Whenever possible, results 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].

Table 9. Results of leaching tests - Volatile organic compounds (VOCs) (in µg/kg) and Polycyclic aromatic hydrocarbons (PAHs) (in µg/kg)

	BV	**ZA**	**CE**
Benzene	2.32	7.89	14.92
Toluene	3.86	2.73	1.61
Ethylbenzene	<0.10	<0.10	<0.10
p-Xylene	2.67	3.30	3.26
Styrene	1.19	<0.10	<0.10
Bromobenzene	1.85	7.01	5.86
1,3,5-Trimethylbenzene	8.95	0.52	0.21
1,2,4-Trimethylbenzene	18.45	7.01	7.15
p-Isopropiltoluene	0.36	2.11	1.81
Butylbenzene,	0.37	20.01	7.88
1,3,5-Trichlorobenzene	1.49	0.10	0.10
1,2,4-Trichlorobenzene	2.69	0.72	1.66
total VOCs	44.16	51.42	44.46

	BV	**ZA**	**CE**
Naphthalene	4.78	6.72	1.36
Acenaphthylene	0.15	3.77	3.93
1-bromoaphthalene	2.24	5.42	11.00
Acenaphthene	0.24	6.12	2.52
Fluorene	0.24	4.34	3.49
Phenanthrene	0.72	9.12	8.81
Anthracene	0.23	5.19	6.68
Fluoranthene	0.38	5.48	14.08
Pyrene	0.62	5.32	4.80
Triphenylene	<0.10	3.38	2.08
Benzo[a]anthracene	<0.10	4.96	6.63
Benzo[b]fluoranthene	4.64	5.48	7.81
Benzo[a]pyrene	1.63	5.24	8.27
Indeno[1,2,3-cd]pirene	<0.10	<0.10	<0.10
Dibenzo[a,h]antracene	<0.10	<0.10	<0.10
Benzo[ghi]perylene	2.83	9.20	<0.10
total PAHs	18.68	79.74	81.48

Table 10. Results of leaching tests - Anions, metals, COD and electrochemical properties

	BV	ZA	CE	Limit
Nitrate [mg/l]	< 0.1	0.40	0.42	50
Fluoride [mg/l]	< 0.1	< 0.1	< 0.1	1.5
Sulphate [mg/l]	1.24	1.19	1.16	250
Chloride [mg/l]	0.54	0.15	< 0.1	100
Ba [μg/l]	18.40	0.65	0.36	1000
Cu [μg/l]	18.60	1.52	1.50	50
Zn [μg/l]	11.00	9.85	16.30	3000
Co [μg/l]	< 0.60	< 0.70	< 0.70	250
Ni [μg/l]	3.48	< 1.5	< 1.5	10
As [μg/l]	< 5.3	< 5.3	< 5.3	50
Cd [μg/l]	< 0.25	< 0.25	< 0.25	5
Cr [μg/l]	1.04	< 0.71	< 0.71	50
Pb [μg/l]	< 4.20	< 4.20	< 4.20	50
Al [μg/l]	< 0.28	15.90	24.90	
Fe [μg/l]	1.45	5.47	7.52	
Mn [μg/l]	8.88	5.32	1.43	
COD [mg/l]	9.30	< 5	< 5	30
pH	7.95	9.55	9.79	5.5-12
CE [μS/cm]	8	24	29	

While the VOC content of the leaching solutions obtained for the three bituminous mixtures was found to be almost constant, significant differences were observed in the case of PAH content. In particular, this may be due to the different binder composition (both in terms of base bitumen and crumb rubber type).
Even though no acceptance limits are provided for VOC and PAH, the low value of COD (Table 12) suggests that the mixtures can be considered “inert” even from the viewpoint of total organic substances.

It was observed that experimental results all comply to Italian regulations [11], even in the case of metals such as zinc and iron, which are present in significant amounts in crumb rubber [12]. However, it is hypothesized that they are not dissolved in water due to the fact that they are fixed in the rubber matrix and further encapsulated in bitumen.

Potential gaseous emission tests

Results of the analyses performed on gaseous emissions sampled during laboratory tests are given in Table 11. Organic compounds listed therein are those which are toxic among all substances potentially detectable by means of gas-chromatographic techniques.

Table 11. Results of PGE tests - Volatile organic compounds (VOCs) (in μg/m^3) and Polycyclic aromatic hydrocarbons (PAHs) (in μg/m^3)

	BV	ZA	CE
Benzene	14.52	2.45	14.06
Toluene	11.09	20.52	27.08
Ethylbenzene	2.27	5.26	7.08
p-Xylene	2.57	2.72	1.88
Styrene	< 0.10	1.38	0.22
Bromobenzene	1.31	1.58	2.85
1,3,5-Trimethylbenzene	54.91	75.63	6.23
1,2,4-Trimethylbenzene	35.31	13.47	3.97
p-Isopropiltoluene	15.77	1.85	6.19
Butylbenzene,	5.92	2.32	1.14
1,3,5-Trichlorobenzene	< 0.10	< 0.10	< 0.10
1,2,4-Trichlorobenzene	< 0.10	< 0.10	< 0.10
total VOCs	143.67	127.19	70.70

	BV	ZA	CE
Naphthalene	2.51	2.08	2.51
Acenaphthylene	0.73	<0.10	<0.10
1-bromoaphthalene	8.36	4.56	13.50
Acenaphthene	1.09	<0.10	<0.10
Fluorene	1.14	2.33	13.91
Phenanthrene	0.61	0.12	0.12
Anthracene	0.14	<0.10	<0.10
Fluoranthene	0.31	0.18	0.14
Pyrene	0.28	0.38	0.77
Triphenylene	<0.10	<0.10	<0.10
Benzo[a]anthracene	<0.10	<0.10	<0.10
Benzo[b]fluoranthene	1.53	2.83	1.83
Benzo[a]pyrene	5.68	11.29	4.92
Indeno[1,2,3-cd]pirene	<0.10	<0.10	<0.10
Dibenzo[a,h]antracene	<0.10	<0.10	<0.10
Benzo[ghi]perylene	<0.10	<0.10	<0.10
total PAHs	22.39	23.77	37.69

The American Conference of Governmental Industrial Hygienists (ACGIH) [13] 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 [14] refer to a maximum concentration of total hydrocarbons in emissions equal to 10 mg/m^3. Data collected from laboratory tests 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.

CONCLUSIONS

Experimental data collected from tests carried out on reference bituminous mixtures containing asphalt rubber binders 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. In particular, 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 investigate the effects of compaction level, loading conditions and temperature for a better assessment of potential field performance. In any case, data obtained during the construction of full-scale test sections will provide further technical information which will be available in the future for the design and construction of other asphalt rubber wearing course layers.

REFERENCES

[1] Asphalt Institute (2009). *Asphalt binder testing: technician's manual for specification testing*. Lexington, KY.
[2] Anderson, D.A., Christensen, D.W., Bahia, H.U., Dongre, R., Sharma, M.G., Antle, C.E. & Button, J. (1994). *Binder characterization and evaluation*. Vol. 3, SHRP A-369, Strategic Highway Research Program, Washington, D.C.
[3] Marasteanu, M.O. & Anderson, D.A. (1999). Improved model for bitumen rheological characterization. *Eurobitume Workshop - Performance Related Properties of Bituminous Binders*, Luxembourg, May 1999.
[4] Williams, M.L., Landel, R.F. & Ferry, J.D. (1955). The temperature dependence of relaxation mechanisms in amorphous polymers and other glass-forming liquid. *J. of the American Chemical Society*, 77, 3701-3707.
[5] CIRS (2009). *Bituminous mixtures of the Asphalt Rubber type*. Final Report. Centro Interuniversitario di Ricerca Stradale ed Autostradale, Ancona, Italy.
[6] Asphalt Rubber Italia (2012). *Technical specifications. Asphalt rubber bituminous mixtures (“wet” method)*.
[7] Arizona department of transportation (ADOT) (2007). *Development of mix design procedures for gap-graded asphalt-rubber asphalt concrete*. Phoenix, AZ.
[8] CIRS (2001). *Performance-related technical specifications*. Ministry of infrastructures and transport, Rome, Italy.
[9] Santagata, E., Zanetti, M.C. (2012). *Technologies for the use in road pavements of crumb rubber products deriving from end-of-life-tyres*, Technical Report, ECOPNEUS, Milan, Italy.
[10] Lindberg, H. K., Väänänen, V., Järventaus, H., Suhonen, S., Nygren, J., Hämeilä et al. (2008). Genotoxic effects of fumes from asphalt modified with waste plastic and tall oil pitch. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, 653 (1-2), 82-90.
[11] D.L. 152. (2006). Norme in materia ambientale. *Decreto Legislativo n. 152*, 3 aprile 2006.
[12] Zanetti, M.C., Fiore, S., Ruffino, B. & Santagata, E. (2011). End of life tyres: crumb rubber physical and chemical characterization for reuse in paving applications. *Sardinia 2011. Thirteenth International Waste Management and Landfill Symposium*, S. Margherita di Pula, Italy, October 2011.
[13] ACGIH. (2001). TLV and BEI 2001. American Conference of Governmental Industrial Hygienists, Cincinnati, OH.
[14] German Bitumen Forum. *Progress report 2006*.

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