FATIGUE BEHAVIOUR AND STIFFNESS PROPERTIES OF ASPHALT RUBBER MIXTURES MADE WITH STEEL SLAGS

Marco Pasetto[1], *Nicola Baldo*[2]
[1]*University of Padua, Structural and Transport Engineering Dept., Padua, Italy*
[2]*University of Udine, Chemistry Physics and Environment Dept., Udine, Italy*

ABSTRACT

The use of crumb rubber modified bitumen, produced with the wet technology, represents an effective option in order to reduce waste tires and, at the same time, to improve the fundamental engineering properties of asphalt mixtures, for road flexible pavements.
This paper presents the results of a laboratory analysis, aimed to verify the stiffness properties and the fatigue resistance of bituminous mixtures (Stone Mastic Asphalt, wearing course and base course bituminous concretes) characterized by a steel slag content above the 89% in weight and by three different typologies of bitumen (crumb rubber modified, hard and soft polymer modified bitumen). The mixtures have been optimized by means of the Marshall test and the Indirect Tensile Strength test, then evaluated in terms of stiffness modulus (at various temperatures and frequencies) as well as of fatigue life, using the 4 Point Bending Test (4 PBT). The investigation has been performed on both aged and unaged samples, in order to keep in to account the influence given by the oxidative ageing phenomenon. With respect to the mixtures with polymer modified bitumen, the asphalt rubber concretes have presented an increased fatigue life, both before and after the ageing conditioning.

Keywords: fatigue resistance, asphalt rubber, steel slags, stiffness, ageing

1. INTRODUCTION

This paper describes the results of a research studying the fatigue resistance performances of bituminous concretes for base courses and wearing courses (traditional and SMA type), made with steel slags and bitumen modified with crumb rubber or SBS polymers. The fatigue behaviour was also investigated in conditions of long-term ageing, in order to evaluate the effectiveness of the modification with crumb rubber using the wet process in reducing the fatigue damage in heavily oxidized mixtures. The experimental data, obtained from four point bending tests (4PBT), were interpreted both with the classical methodology based on a 50% reduction of the initial stiffness and with Pronk's energy approach [1].

2. MATERIALS AND MIX DESIGN

Two granular materials were used in the study: EAF slags and limestone filler. The slags utilized are the main by-product of steel production based on the electric arc furnace (EAF) technology [2-4]; they were made available in 3 particle sizes: 0/4, 4/8, 8/14 mm. Table 1 reports the physico-mechanical properties of the steel slags, plus the test protocols adopted. The volumetric stability of the EAF slags used in the investigation was tested according to the Standard EN 1744/1 part 15.3; no expansion (0%) was checked after 168 hours requested by the test protocol. The porosity of the slag grains, evaluated following the prescriptions of the Italian Standard CNR 65/78, was lower than 5%; a relatively diffused micro-porosity was confirmed by visual examination of the surfaces of the steel slags particles.

Table 1 : Physical and mechanical characteristics of EAF slags

Physical ÷ Mechanical properties	Standard	EAF slags 0/4 mm	EAF slags 4/8 mm	EAF slags 8/14 mm
Los Angeles coefficient [%]	EN 1097-2	-	16	14
Equivalent in sand [%]	EN 933-8	86	-	-
Shape Index [%]	EN 933-4	-	1.9	2.9
Flakiness Index [%]	EN 933-3	-	4.2	6.4
Freeze/thawing [%]	EN 1367-1	-	0.1	0.1
Fine content [%]	EN 933-1	2.7	0.0	0.0
Grain density [Mg/m^3]	EN 1097-6	4.017	3.979	3.919
Water absorption [%]	EN 1097-6	0.510	0.307	0.112

Three mixes were designed: a Stone Mastic Asphalt mix (SMA), a Wearing Course Asphalt concrete (WCA) and a Base Course Asphalt Concrete (BAC). The grading curves were elaborated and computed starting from the individual particle sizes of the steel grains, optimised in accordance with the grading envelopes included in SITEB – Italian Society of Bitumen Technologists [5]. Table 2 reports the grading composition of the bituminous mixtures and proportions of the components, while the grading curves of the mixes are presented in Table 3 and Figure 1; the total amount of steel slag was 89%, 92%, 93% for BAC, WCA and SMA respectively. The effects related to the use of EAF steel slags, as a substitute of conventional limestone aggregates, in the design of asphalt concretes, have been already investigated by the authors in previous researches [2, 3, 4]; therefore, in the present study, the attention was primarily focused on the influence of the different binders on the mixes. For this reason, three different bitumens were used in the experiments for each of the mixtures: fine crumb rubber modified bitumen, as well as hard and soft SBS polymer modified. All the bitumens were produced in industrial plants of different private companies. Table 4 reports the main results of the bitumen characterization. The polymer modified mixtures were investigated, in order to allow a direct comparison with the corresponding asphalt rubber mixtures, characterized by the same skeleton matrix, but made following the wet process technology [6]. The Marshall procedure was used for determining the optimal binder content, along with the indirect tensile strength test. For each of the BAC, WCA and SMA bituminous concretes, different mixtures were analyzed, where, having defined and fixed the grading composition and type of bitumen, the amounts of binder were varied at intervals of 0.5% on the weight of the aggregate (in the range 4.0 – 5.0% for BAC, 4.5-5.5% for WCA, 5.5-6.5% for SMA). The mixes characterised by maximum bulk density, maximum Marshall Stability, a voids content of 4% and maximum indirect tensile strength at 25 °C, were considered optimal. The target voids content has been set according to the main Italian technical specifications [5] and the most relevant mix design procedures outlined by international researchers [7, 8]. Table 5 reports Optimum Bitumen Content (OBC), bulk density, Marshall Stability (MS), Marshall Quotient (MQ), Indirect Tensile Strength (ITS) at 25°C and Stiffness Modulus (Sm) by 4PBT at 20°C and 10 Hz, of the bituminous mixtures. The stiffness has been evaluated for both aged and unaged specimens, for each mixture. The asphalt rubber mixtures and those hard and soft modified are indicated by the letters "ar", "hm", "sm" next to the mixture acronym. For all the mixes the requisites fixed by the Italian Standards were guaranteed, with MS, MQ, ITS values higher than the minimum thresholds, thus demonstrating that these mixtures are acceptable for road construction. The optimal bitumen content of the mixes resulted within the range that is typically requested for the preparation of asphalt concretes made with limestone, thus demonstrating that the use of the EAF, even in the finest particle sizes of 0/4 mm class , did not entail the problems, reported in the literature [9], of an excessive absorption of bitumen by the fine fractions of steel slags of the BOF type.

Table 2 : **Aggregate type and particle size distribution of the mixtures**

Mix composition	Fraction [mm]	Quantity [%]		
		SMA	WCA	BAC
EAF steel slag	0/4	45	70	50
	4/8	22	12	13
	8/14	22	10	30
Filler (additive)	-	11	8	7

Table 3 : **Design grading curve of the mixtures; numerical data**

Sieves size [mm]	Design grading curve [%]		
	SMA	WCA	BAC
20	100.0	100.0	100.0
15	99.9	99.9	99.9
10	85.2	93.3	79.8
5	43.8	58.2	43.0
2	24.6	28.9	22.0
0.4	15.3	14.5	11.7
0.18	12.7	10.8	9.0
0.075	8.5	6.9	5.9

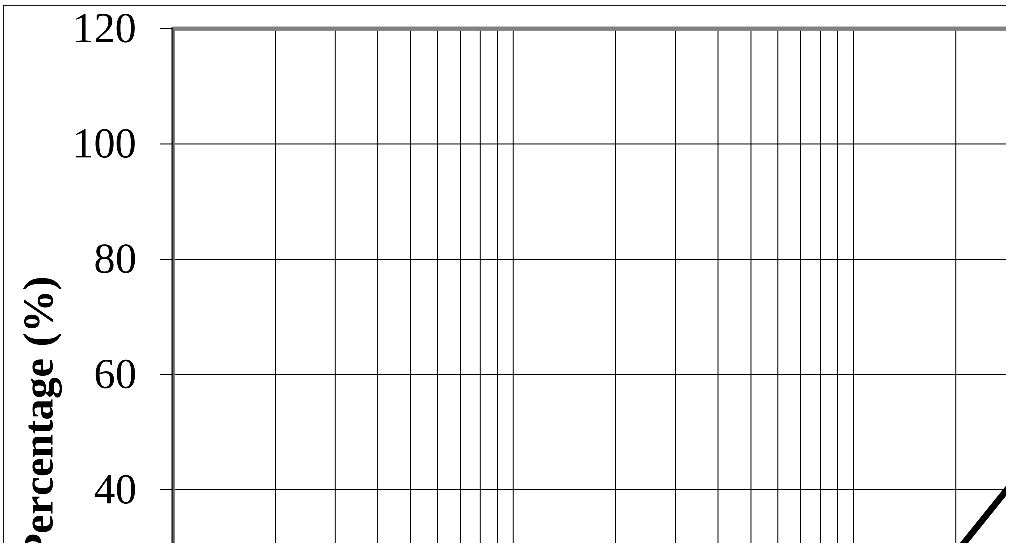

Figure 1 : **Design grading curve of the mixtures**

Table 4 : **Bitumen characterisation**

Properties	Standard	Crumb rubber modified bitumen	Hard polymer modified bitumen	Soft polymer modified bitumen
Penetration (mm/10), 100g, 5 s at 25°C	EN 1426	45	52	59
Softening point (°C), R&B method	EN 1427	82	77	71
Fraass breaking point (°C)	EN 12593	- 15	- 14	- 12

Table 5 : **Physical and mechanical characteristics of the bituminous mixtures**

Mixture	OBC [%]	Bulk density [kg/m^3]	MS [daN]	MQ [daN/mm]	ITS [MPa]	Sm [MPa]	Sm aged samples [MPa]
SMA/ar	6.0	3150	1986	482	1.46	5438	5978
SMA/hm	6.0	3130	1580	455	1.29	5386	6415
SMA/sm	6.0	3080	1324	405	1.13	4405	5366
WCA/ar	5.0	3110	2203	523	1.29	6102	8145
WCA/hm	5.0	3100	1551	507	1.16	6573	8738
WCA/sm	5.0	3060	1530	462	1.00	6349	7384
BAC/ar	4.0	3030	1295	450	0.94	6779	7779
BAC/hm	4.0	2930	1164	393	0.86	6798	7853
BAC/sm	4.0	2910	1222	336	0.78	4992	6582

2. FATIGUE CHARACTERIZATION

The four-point bending fatigue tests were conducted using the protocol described in Annex D of the European EN 12697-24 Standard as reference, in a regime of strain control, with a wave of sinusoidal loading without rest periods. The tests were all conducted at a temperature of 20 °C and frequency of 10 Hz, in a range of strain of between 200 and 500 μm/m. In addition to the data of stress and strain, the phase angle and dissipated energy (both cumulative, and relative to each loading cycle) were determined for each fatigue test.
The beam specimens necessary for conducting the fatigue tests, with dimensions of 400 mm x 50 mm x 60 mm, were cut from 300 mm x 400 mm x 50 mm slabs produced by a laboratory compacting roller, in accordance with the EN 12697-33 Standard.
Some of the beam specimens were then exposed to accelerated long-term ageing, by means of conditioning in an oven at 85 °C for 5 days, in order to evaluate the effect of ageing on the fatigue performances of the mixtures and any benefits produced by the bitumen modified with crumb rubber, compared to binders modified with polymers.

2.1 Fatigue characterization based on the stiffness reduction approach

Figures 2 and 3 present the fatigue curves in the standard format, which links the initial strain ε_0 (evaluated at the 100-th cycle) to the number of cycles N_f that correspond to a 50% reduction in the initial stiffness modulus (that is “failure”), for the unaged and aged mixtures, respectively.
The regression analysis of the fatigue data was performed using a power law model of the type:

$$\varepsilon_0 = aN_f^{\,b} \tag{1}$$

where *a* and *b* are regression coefficients depending on the type of material. Tables 6 and 7 report the regression coefficients and the coefficient of determination R^2.
With reference to a fatigue resistance of 1,000,000 loading cycles (as indicated in Standard EN 12697 – 24, Annex D), and using Eqn. (1), it was possible to calculate the corresponding tensile strain ε (10^6), which was always higher for the asphalt rubber mixtures, with respect to the correspondent polymer modified mixtures; in particular the highest value, 372 μm/m, was obtained for SMA/ar (Table 6).

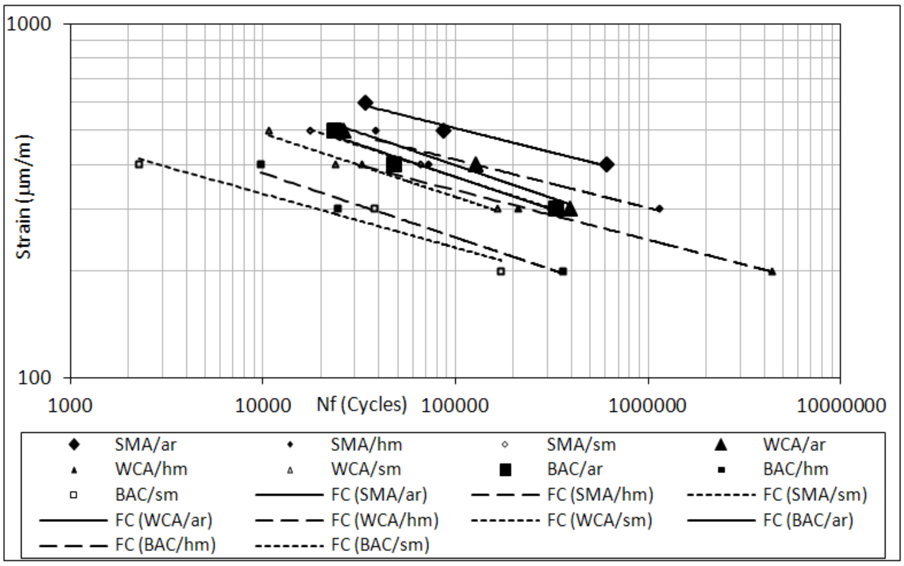

Figure 2 : Fatigue life N_f vs. initial strain; unaged mixtures

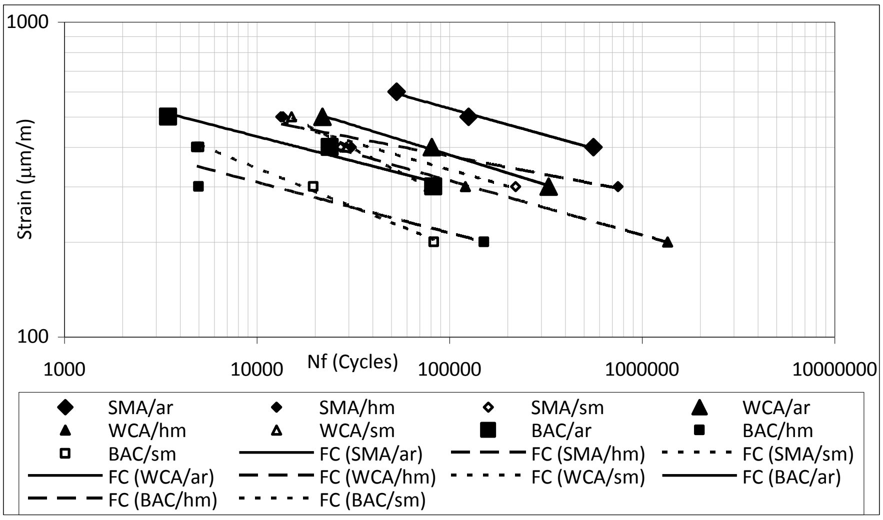

Figure 3 : Fatigue life N_f vs. initial strain; aged mixtures

Table 6 : Fatigue curves – unaged mixtures, regression coefficients (N_f approach)

Mixture	a [µm/m]	b [-]	ε (10^6) [µm/m]	R^2 [-]
SMA/ar	2435.4	-0.1364	372	0.9792
SMA/hm	1979.6	-0.1362	302	0.9263
SMA/sm	2854.5	-0.1778	244	0.9995
WCA/ar	3381.7	-0.1859	259	0.9719
WCA/hm	1702.3	-0.1403	246	0.9985
WCA/sm	2573.0	-0.1801	214	0.9732
BAC/ar	3048.4	-0.1835	243	0.9652
BAC/hm	2032.5	-0.1825	164	0.9687
BAC/sm	1349.4	-0.1527	163	0.9294

In each type of mixture, the hard modified bitumen led to an improved fatigue life compared to the soft; the increase, although minimal in the case of the BAC concrete, is 24% and 15% for SMA and WCA, respectively. The increase in fatigue life due to the adoption of crumb rubber modified bitumen is much more substantial, in particular compared with the soft modified binder, with increases varying up to a maximum of 52%, in relation to the type of concrete.
A comparison of the data in Tables 5, 6 and 7 allows the increase in stiffness to be evaluated linked to the ageing of the concretes, which is followed by a reduction in the fatigue life.
The concretes with soft modified bitumen were more affected by ageing (reductions of ε (10^6) of up to 36%), while variations of ε (10^6) of less than 13% were recorded for the asphalt rubber mixtures. The hard modified bitumen, compared to that modified with crumb rubber, showed similar effects, if slightly worse, in relation to the type of mixture.

Table 7 : Fatigue curves, aged mixtures - regression coefficients (N_f approach)

Mixture	a [µm/m]	b [-]	ε (10^6) [µm/m]	R^2 [-]
SMA/ar	3743.5	-0.17	358	09911
SMA/hm	1432.4	-0.117	284	0.9378
SMA/sm	2476.2	-0.173	227	0.9562
WCA/ar	3334.9	-0.189	245	0.9971
WCA/hm	2275.8	-0.172	211	0.9995
WCA/sm	9757.0	-0.309	137	0.9983
BAC/ar	1843.6	-0.157	211	0.9610
BAC/hm	1363.3	-0.161	147	0.8347
BAC/sm	3345.1	-0.247	110	0.9933

2.2 Fatigue characterization based on the energy ratio approach

The data gathered in the fatigue tests were also analyzed with Pronk's energy approach [1], recently also utilized by Artamendi and Khalid [10], in which a fundamental role is assumed by the energy ratio Rn, calculated as the ratio between the cumulative energy dissipated up to the n-th cycle and that dissipated in the n-th cycle, according to Eqn. (2):

$$R_n = \frac{\pi \sum_{i=0}^{n} \sigma_i \varepsilon_i sen\phi_i}{\pi \sigma_n \varepsilon_n sen\phi_n} \tag{2}$$

where σ, ε, ϕ, *i* and *n* represent the stress, strain, phase angle, generic i-th cycle and n-th cycle, respectively. The criterion of failure in this approach is the formation of macro-cracks in correspondence to the number of cycles N_1, so Rn assumes a non-linear trend. Basically N_1 represents the number of cycles for which cracks are considered to initiate; it has also been defined as the coalescence of micro-cracks to form a sharp crack, which then propagates; therefore N_1 represents the transition point between micro-crack formation and the propagation of macroscopic crack [10]. It has to be clarified that, even if in controlled strain mode N_1 is defined as the number of cycles at which Rn deviates from a straight line, in controlled stress mode it is associated to the peak value or Rn [10], therefore the definition of failure depends on the modes of loading. Figure 4 reports an example of the determination of N_1 for the asphalt rubber mix type BAC.

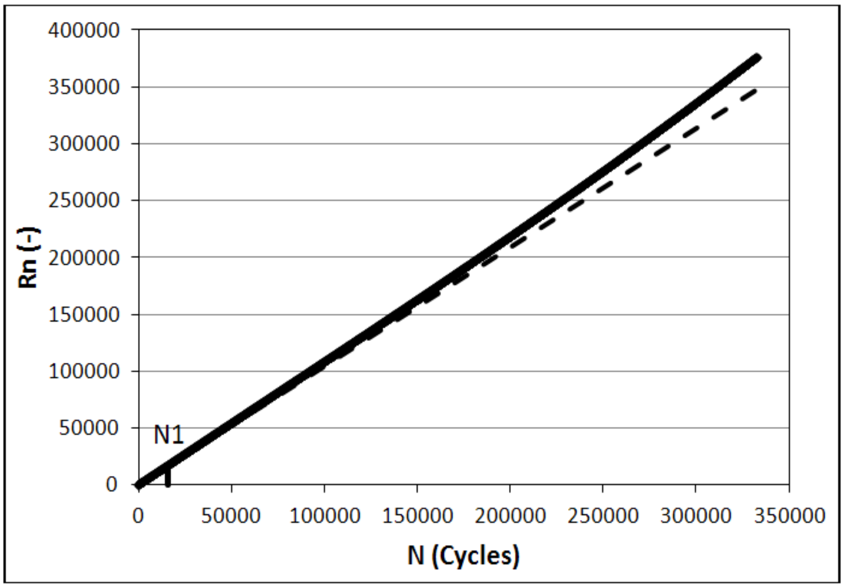

Figure 4 : Determination of failure N_1 for mix BAC/ar at 300 μm/m

In the analysis of the evolution of Rn with the varying of the number of cycles, the exact identification of N_1, although precisely defined in theory, results as being significantly influenced by the subjectivity of the researcher.
Figures 5 and 6 show the fatigue curves elaborated as a function of N_1 and the value of initial strain, for the unaged and aged mixtures, respectively.

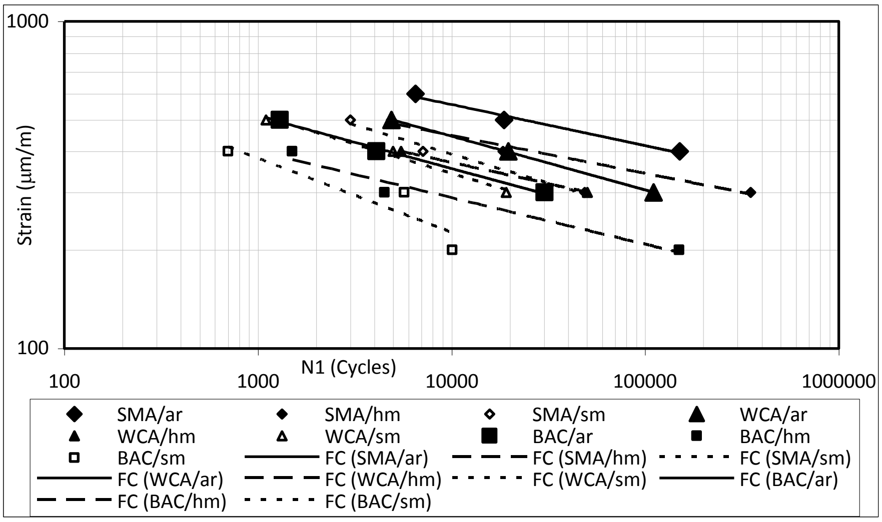

Figure 5 : Fatigue life N_1 vs. initial strain; unaged mixtures

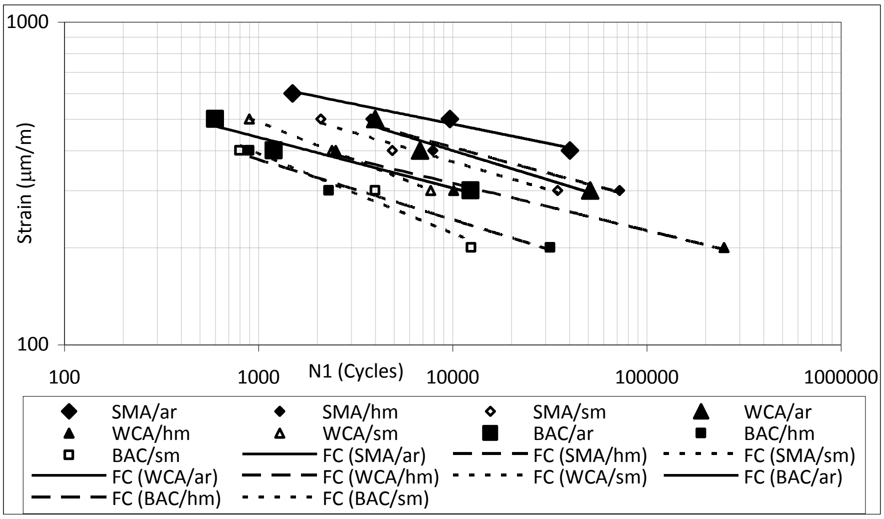

Figure 6 : Fatigue life N_1 versus initial strain; aged mixtures

For the analytical interpolation, a power function was again used, analogous to Eqn. (1), substituting N_1 for N_f. Tables 8 and 9 report the coefficients of regression and determination, as well as the value of ε (10^6), for the unaged and aged mixtures, respectively.

Table 8 : Fatigue curves, unaged mixtures - regression coefficients (N_1 approach)

Mixture	a [µm/m]	b [-]	ε (10^6) [µm/m]	R^2 [-]
SMA/ar	1776.8	-0.126	312	0.9835
SMA/hm	1302.6	-0.116	262	0.9800
SMA/sm	2014.0	-0.178	172	0.9794
WCA/ar	2019.2	-0.164	209	0.9999
WCA/hm	1225.3	-0.130	203	0.9999
WCA/sm	1765.0	-0.178	151	0.9886
BAC/ar	1555.0	-0.160	171	0.9934
BAC/hm	1067.1	-0.142	150	0.9623
BAC/sm	1824.7	-0.227	79	0.8364

The analysis of the values of ε (10^6), determined with Pronk's approach, allows the different types of mixtures to be discriminated in an analogous way to the standard fatigue characterization, also with regard to the aged concretes.
The better performance of the modification with crumb rubber is therefore fully confirmed for all three types of concrete. Nonetheless, the energy analysis can be considered more reliable, in that the criterion of failure used allows the fatigue performances of the bituminous concretes to be compared in the same damage conditions.

Table 9 : Fatigue curves, aged mixtures - regression coefficients (N_1 approach)

Mixture	a [µm/m]	b [-]	ε (10^6) [µm/m]	R^2 [-]
SMA/ar	1483.6	-0.122	275	0.9817
SMA/hm	1834.8	-0.163	193	0.9565
SMA/sm	1863.7	-0.176	164	0.9771
WCA/ar	2182.6	-0.184	172	0.9377
WCA/hm	1213.2	-0.146	161	0.9842
WCA/sm	2537.6	-0.238	95	0.9995
BAC/ar	1299.8	-0.157	149	0.9478
BAC/hm	1348.9	-0.186	103	0.9717
BAC/sm	2158	-0.247	71	0.9620

The energy interpretation leads to an estimate of values of ε (10^6), which is from around 10% to more than 100% lower than that determined with the criterion of reduction of the stiffness, depending on the type of concrete.

3. CONCLUSIONS

The fatigue tests, conducted on bituminous concretes of the SMA, WCA, BAC type (all made with EAF steel slags), have demonstrated the clearly better performance of the asphalt rubber mixtures compared with those of similar type but made with SBS polymer modified bitumen.
The effectiveness of the crumb rubber modified bitumen in the increase of fatigue life was also clear for the mixtures in conditions of post-ageing.
The interpretation of the data from the 4PBT tests on strain control, according to the criteria N_f and N_1, led to a similar comparative evaluation of the mixtures from the qualitative point of view; nonetheless, with the energy approach, a more precautionary estimate was obtained of the fatigue life of the concretes.
Among the different types of mixtures, the one for base courses (BAC) showed the greatest benefits from the use of the crumb rubber modified bitumen; with reference to the energy analysis, the increase in fatigue life in terms of ε (10^6), with respect to the same mixture with the soft SBS modified bitumen, was more than 100%, in both aged and unaged conditions.

REFERENCES

[1] Comparison of 2 and 4 point fatigue tests and healing in 4 point dynamic test based on the dissipated energy concept, Pronk, A. C., Proceedings of the 8th International Conference on Asphalt Pavement, pp. 987–994, Seattle, 1997.
[2] Experimental Evaluation of High Performance Base course and Road Base Asphalt Concrete with Electric Arc Furnace Steel Slags, Pasetto, M. and Baldo, N., J. Hazard. Mater., n. 181, p. 938–948, 2010.
[3] Mix design and Performance Analysis of Asphalt Concretes with Electric Arc Furnace Slag, Pasetto, M. and Baldo, N., Constr. Build. Mater., Vol. 25, n. 8, p. 3458-3468, 2011.
[4] Performance comparative analysis of stone mastic asphalt with electric arc furnace steel slag: a laboratory evaluation, Pasetto, M. and Baldo, N., Mater. Struct., in press, DOI: 10.1617/s11527-011-9773-2, 2011.
[5] Capitolato d'appalto per pavimentazioni stradali con bitume modificato, SITEB, Roma, 2000 [in Italian].
[6] Performance evaluation of asphalt rubber mixtures, Pasetto, M. and Baldo, N., Proceedings of the 5th International Conference on Road & Airfield Pavement Technology, cd-rom, Seul, 2005.
[7] Stone matrix asphalt – properties related to mixture design, Brown, E.R., Mallick, R.B., National Center for Asphalt Technology, Report No. 97-3, Auburn, 1997.
[7] Evaluation of steel slag coarse aggregate in hot mix asphalt concrete, Ahmedzade, P. and Sengoz, B., J. Hazard. Mater., 2009. N. 165 (1), p. 300-305, 2009.
[9] Utilization of municipal solid waste incineration ash in stone mastic asphalt mixture: Pavement performance and environmental impact, Xue, Y., Hou, H., Zhu, S. and Zha, J., Constr. Build. Mater., n. 23, p. 989–996, 2009.
[10] Characterization of fatigue damage for paving asphaltic materials, Artamendi, I. and Khalid, H., Fatigue Fract. Engng. Mater. Struct., n. 28, p. 1113-1118, 2005.