Technical Paper

ISSN 1996-6814 Int. J. Pavement Res. Technol. 6(4):294-303

Fatigue Performance of Asphalt Concretes made with Steel Slags and Modified Bituminous Binders

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Abstract: This paper describes the results of a research aimed at investigating the fatigue resistance performances, determined by means of the four-point bending test (4PBT), of bituminous mixtures (SMA and traditional ones) for base courses and wearing courses, made with Electric Arc Furnace (EAF) steel slag and bitumen modified with crumb rubber or SBS polymers. The fatigue behaviour was also studied after long-term ageing, in order to check the effectiveness of the crumb rubber modification (by wet process) in reducing the fatigue damage in heavily oxidized mixtures. For both unaged and aged conditions, the asphalt rubber mixes presented better fatigue behaviour than the reference mixtures made with polymer modified bitumen.

DOI:10.6135/ijprt.org.tw/2013.6(4).294

***Key words**: Asphalt concrete, Fatigue life, Modified bitumen, Steel slags.*

Introduction

Fatigue in asphalts, which is the type of damage caused by the repeated transit of vehicles at medium-low temperatures, leads to the development of crackings that may degenerate into the complete fracture of the road pavement. Fatigue resistance is primarily influenced by bitumen content, binder’s rheological properties, as well as by its adhesion to the grains of the lithic skeleton and the compactness of the latter. The paper discusses the results of a laboratory testing concerning the fatigue properties of bituminous mixtures (Stone Mastic Asphalt - SMA, base course and wearing course asphalt concretes), made with Electric Arc Furnace (EAF) steel slag (up to 93% of the weight of the aggregates) and three different bituminous binders, modified with fine crumb rubber or SBS polymers. The purpose was to evaluate the fatigue resistance of the mixtures, by means of the four-point bending test, according to EN 12697-24 Standard, Annex D. Both aged and unaged samples were tested, in order to investigate the ageing effects. The polymer modified mixtures were studied, 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.

Materials

Binders

Three different bitumens were used in the experiment for each mixture: crumb rubber modified bitumen, as well as hard and soft SBS polymer modified bitumen. The fine crumb rubber modified bitumen, as well as the hard and soft polymer modified bitumen, were produced in two different private companies industrial plants. The asphalt rubber derived from the wet process technology [1-10]. In this paper, the presence of asphalt rubber, hard and soft modified polymers in the mixtures is evidenced by the subscript “ar”, “hm”, “sm” next to the mixture acronym. Penetration, softening point, Fraass breaking point, ductility and elastic recovery have been determined for all the binders.

Aggregates

Two granular materials were used in the study: EAF slag and limestone filler. The slags utilized are the main by-product of steel production based on the electric arc furnace (EAF) technology [11-17]. The EAF slags used in the study were supplied by a steel mill in northern Italy, while the limestone filler derived from a quarry in the same area; the steel slags were available in three different fractions: 0/4, 4/8 and 8/14 mm. The chemical composition of the EAF slags have been analyzed with XRF (X-ray fluorescence); their toxicological characteristics were checked in terms of initial concentrations of heavy metals, measured with the ICP-AES methodology (Inductively Coupled Plasma – Atomic Emission Spectrometer), whilst their leaching was determined by the TCLP (Toxic Characteristic Leachability Procedure) given in Appendix A of Standard UNI 10802, following the method in Standard EN 12457-2. The physical-mechanical properties of the steel slags have been investigated in terms of: grading analysis, Los Angeles coefficient, freeze/thaw resistance, equivalent in sand, shape and flakiness index, grain density.

Mixtures

Three mixes were designed: a Stone Mastic Asphalt mix (SMA), a Wearing Course Asphalt concrete (WCA) and a Base course Asphalt Concrete (BAC); the total amount of steel slag was 89%, 92%, 93% for BAC, WCA and SMA respectively (by weight on total aggregate weight). The study of the grading curves was referred to the grading envelopes set by SITEB – Italian Society of Bitumen Technologists [18].

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Note: Submitted January 31, 2013; Revised May 20, 2013; Accepted May 21, 2013.

Methods

Mix Design Procedure

The Marshall procedure (EN 12697-34 Standard) was used for determining the optimal binder content, along with the Indirect Tensile Strength test (EN 12697-23 Standard). The indirect tensile strength was determined using the well-known equation:

$$ITS = \frac{2P_{max}}{\pi dh} \tag{1}$$

where P_{max} represents the breaking load [N] of the specimens under diametral compression, d and h are the average values of the diameter [mm] and height [m] of the specimens, respectively.

The mixes characterised by maximum bulk density, maximum Marshall Stability, a voids content of 4% for SMA, 5% for WAC, 6% for BAC, were considered optimal. The mechanical performances of the mixtures formulated in this way, were further verified by means of the indirect tensile strength at 25°C.

Performance Test Programme

Four-point bending fatigue tests were conducted using the protocol described in Annex D of the European EN 12697-24 Standard, in a regime of stress control, with a wave of sinusoidal loading without rest periods. As reported by Artamendi and Khalid [19], the stress control procedure has to be preferred to the controlled strain testing, in the case of relatively thick layers (as the BAC) and for high stiffness materials (as the SMA and the WAC). The tests were all conducted at a temperature of 20°C, frequency of 10 Hz, and at three stress levels: 1, 1.25 and 1.5 MPa. For each test, in addition to the stress and strain values, the angle phase and energy dissipated at each loading cycle were also monitored, in order to be able to analyze the experimental data with an energy approach. The beam specimens submitted to the bending tests, with dimensions of 400 mm x 50 mm x 60 mm, were cut from 300 mm x 400 mm x 50 mm slabs, prepared using 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 [20], in order to evaluate the effect of seasoning on the fatigue performances of the mixtures and any benefits produced by the bitumen modified with crumb rubber, compared to binders modified with polymers.

Even if the study was primarily focused on the fatigue properties of the mixes, the resistance to moisture damage and to permanent deformation have been also evaluated, in order to complete the full performance characterization of the asphalt concretes investigated; the performance approach has great relevance in order to properly promote the use of industrial by-products, as outlined also by other Authors [21, 22]. Therefore, indirect tensile strength test at 25°C on wet cylindrical samples (Italian Standard CNR 149/92), and Wheel Tracking Tests (WTT, EN 12697-22 Standard, procedure B) at 60°C, have been performed on the nine asphalt concretes optimized in the mix design procedure.

Results and Discussion

Materials Characterization

Table 1 reports the conventional engineering properties of the three bitumens used in the mixes. The elastic recovery data have been certified by the bitumen manufacturer. The crumb rubber modified bitumen, compared to the polymer modified binders, presented improved properties, in terms of penetration (- 24%) and softening temperature (+ 16%), particularly with respect to the soft modified bitumen. The ductility (evaluated by means of an Italian test) resulted adequate for all the binders.

According to Italian Law, EAF slags are *non-hazardous, special non-toxic and non-noxious* refuse. They are a solid material, greyish in colour and with no particular smell; the pH is 10.7. The results in Table 2 show that the slags, in terms of oxides, contain a prevalence of FeO and CaO, as well as SiO_2, and Al_2O_3. The SiO_2/CaO ratio characterizes the EAF slag as a substantially alkaline aggregate and therefore suitable to guarantee the necessary adhesion with the weakly acid bitumen. With regard to the initial concentration of heavy metals (Table 3), the steel slags present higher contents of vanadium, zinc and chromium, the latter predominating over all the other metals; anyhow it is less than 0.9% of the total volume of slags.

The results in Table 3 demonstrate that, for the steel slag, the release of heavy metals by leaching is within the limits of the environmental regulations in force in Italy (Legislative Decree no. 152/2006). Therefore, given that the constituents of the mixtures

Table 1. Bitumen Characterization.

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
Ductility [cm] at 25°C	CNR 44/74	Over 100	Over 100	Over 100
Fraass Breaking Point [°C]	EN 12593	- 15	- 14	- 12
Elastic Recovery [%] at 25°C	EN 13398	> 50	> 50	> 50

Table 2. Chemical Composition of EAF Slags.

Aggregate Type	Oxide Content [%]							
	MgO	Al_2O_3	SiO_2	CaO	TiO_2	Cr_2O_3	MnO	FeO
EAF Slags	3.617	9.138	12.860	29.270	0.347	4.077	5.174	33.370

Table 3. Major Heavy Metal Content of EAF Slags.

Element	Initial Concentration [mg/kg]	TCLP Leaching Concentration	Limit Leaching Concentration - legal Thresholds
Copper (Cu)	188.860	0.0012 mg/L	0.05 mg/L
Cadmium (Cd)	14.491	1.2 µg/L	5 µg/L
Lead (Pb)	58.202	11.7 µg/L	50 µg/L
Zinc (Zn)	749.211	0.0001 mg/L	3 mg/L
Chromium – Total (Cr)	8750.300	5.8 µg/L	50 µg/L
Nickel (Ni)	74.095	0.4 µg/L	10 µg/L
Mercury (Hg)	1.000	0.5 µg/L	1 µg/L
Selenium (Se)	87.274	8.9 µg/L	10 µg/L
Vanadium (V)	503.394	45.1 µg/L	250 µg/L
Arsenic (As)	131.542	4.4 µg/L	50 µg/L
Beryllium (Be)	0.453	0.08 µg/L	10 µg/L
Cobalt (Co)	11.337	0.07 µg/L	250 µg/L

do not present toxicological problems, it was considered unnecessary to proceed with leaching tests on asphalt specimens.

The grading analysis of the steel slags (Fig. 1), performed on the basis of the EN 933-1 Standard, has shown a continuous curve for the 0/4 fraction, while the coarser fractions, namely 4/8 and 8/14 mm, are resulted basically discontinuous; therefore it can be concluded that the particle size distributions of the three fractions, are suitable in order to get a wide spectrum of grading combinations, for both conventional and high performance bituminous mixtures.

The results of Table 4 put in evidence the overall physical-mechanical equivalence of the two coarser fractions of slags (4/8 and 8/14 mm). The fraction 8/14 presents a higher mechanical resistance (low Los Angeles coefficient) and a lower unit weight, in spite of some worse physical requisites related to particles' morphology (Shape Index, Flakening Index). The freeze/thawing resistance resulted excellent, for both the coarser slags. The finest fraction (0/4) was characterized by the highest grain density and water absorption, even if for both the properties, the values recorded for all the fractions are very similar.

A direct test of the volumetric stability of the EAF slags, according to the Standard EN 1744/1 part 15.3, showed an expansion null after the 168 hours suggested in the test protocol.

The steel slags demonstrated an excellent affinity with the bitumen, with no stripping of the grains coated with binder after 24 hours of immersion in water at 25 ℃ (Italian Standard CNR 138/92). This property obviously greatly enhances the durability of the bituminous mixtures.

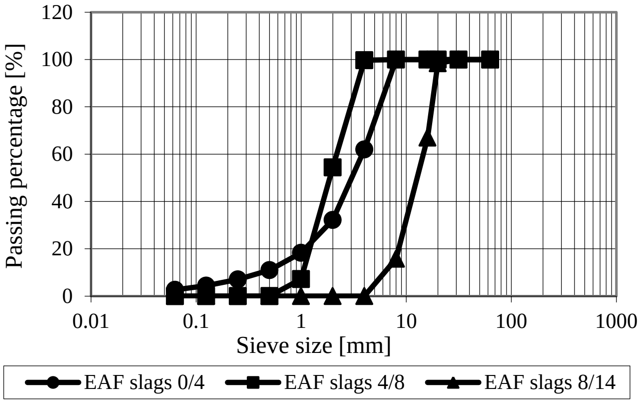

Fig. 1. EAF Slags Grading Curves.

Grading and Composition of the Mixes

Three mixes were produced using, with the appropriate bitumen content, the EAF slags and the limestone filler. For each mixture, the grading curve was defined starting from the individual particle sizes, optimised in accordance with the specific grading envelope included in the SITEB Specifications [18], in order to identify a design grading curve all within the reference grading envelope. Bailey's method, based on grain density, can be alternatively used for the volumetric design of the aggregate skeleton [23]. Table 5 reports the type and the proportions of the aggregate which compose the mixes; the total amount of steel slag was 89%, 92%, 93% for

Table 4. Physical and Mechanical Characteristics of EAF Slags.

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
Flakening 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	3.757	3.719	3.685
Water Absorption [%]	EN 1097-6	0.510	0.307	0.112
Stripping in Water [%]	CNR 138/92	0	0	0

Table 5. Aggregate Type and Composition 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

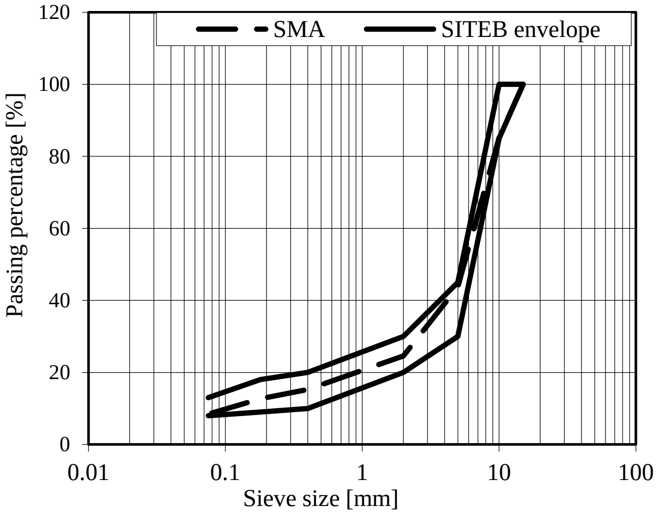

Fig. 2. SMA Design Grading Curve and Reference Envelope.

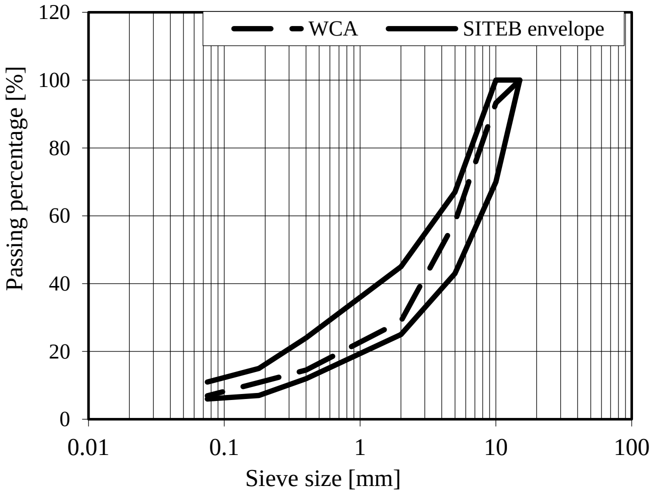

Fig. 3. WCA Design Grading Curve and Reference Envelope.

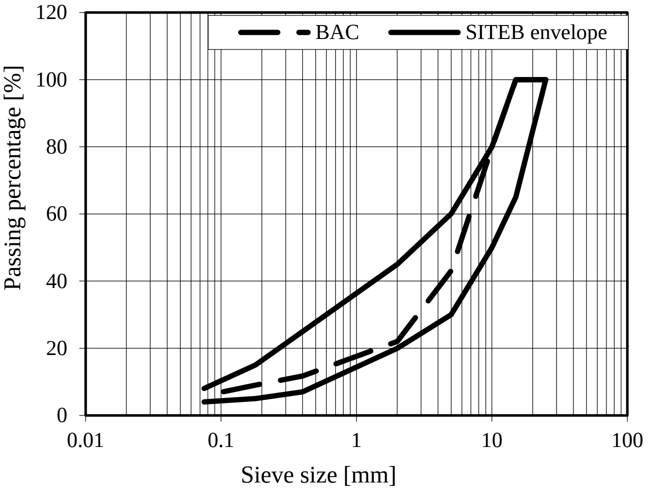

Fig. 4 BAC Design Grading Curve and Reference Envelope.

BAC, WCA and SMA respectively. Fig. 2, Fig. 3, Fig. 4 introduce the grading curves of the asphalt concrete and the respective SITEB reference envelopes, for the SMA, WCA and the BAC respectively. The nominal maximum aggregate size was 15 mm for the SMA and BAC, 10 mm for the WAC.

Optimization of the Mixture

For each of the three types of asphalt concrete (SMA, WCA, BAC) three different groups of mixtures were analysed; a first made with crumb rubber modified bitumen, a second and a third produced with hard and soft SBS polymer modified bitumen, respectively. Each group of mixtures was characterised by the same grading curve, the same type of aggregate and bitumen, but binder contents variable at intervals of 0.5% on the weight of the aggregate, within specific ranges for each of the 3 asphalt concretes (4.0 to 5.5% for BCA, 4.5 to 6% for WCA, 5.5 to 7% for SMA). To support the mix design procedure, four standard Marshall samples were prepared for each mix.

Table 6 reports Optimum Bitumen Content (OBC), Voids in the Mineral Aggregate (VMA), Voids Filled with Bitumen (VFB), bulk density, Marshall Stability (MS), Marshall Quotient (MQ), Indirect Tensile Strength (ITS) values of the bituminous mixtures.

The asphalt rubber mixtures as well as the hard and soft modified ones are marked by the subscript “ar”, “hm”, “sm” next to the mixture acronym.

Table 6. Mix Design Results.

Mixtures	OBC [%]	VMA [%]	VFB [%]	Bulk Density [g/cm^3]	MS [daN]	MQ [daN/mm]	ITS [MPa]
SMA/ar	6.0	23.5	82.9	3.306	1,986	482	2.35
SMA/hm	6.0	23.3	82.8	3.277	1,580	455	2.17
SMA/sm	6.0	23.1	82.7	3.248	1,324	405	2.04
WCA/ar	5.0	21.3	76.5	3.338	2,203	523	1.63
WCA/hm	5.0	21.2	76.4	3.307	1,551	507	1.55
WCA/sm	5.0	21.0	76.2	3.275	1,530	462	1.46
BAC/ar	4.0	19.0	68.5	3.325	1,295	450	1.57
BAC/hm	4.0	18.9	68.3	3.292	1,164	393	1.38
BAC/sm	4.0	18.7	68.0	3.258	1,222	336	1.23

For all the mixes the requisites fixed by the Italian Road Technical Standards [18] were guaranteed, with Marshall Stability and Quotient higher than 1100 daN and 300 daN/mm for BAC, 1200 daN and 350 daN/mm for WCA, 1000 daN and 350 daN/mm for; the additional requisite for the SMA, relative to a minimum ITS value equal to 0.6 MPa, was completely satisfied, thus demonstrating the acceptability of these mixtures for road construction.

Moreover, for SMA mixes a percentage of Voids in the Mineral Aggregate (VMA) higher than 17% [24, 25] and a percentage of Voids Filled with Bitumen (VFB) between 75% and 85% [26] are needed, whilst for WCA and BAC mixes the requirement is a VMA percentage higher than 15% [27]. According to data in Table 6, all the volumetric requisites are verified for the designed mixes.

The mixes with crumb rubber modified bitumen showed better Marshall results as well as ITS values, than the corresponding asphalts with SBS polymer modified binders.

Fatigue Test

Combining the number of cycles of load application that correspond to a 50% reduction in the initial stiffness modulus (N_f), with the stress value (σ), the fatigue curves have been elaborated, [28] in order to evaluate the fatigue performance of each mixture. The regression analysis of the fatigue data was performed using a power law model of the type:

$$\sigma = aN_f^b \qquad (2)$$

where a and b are regression coefficients depending on the type of material. Figs. 5 to 10 present, for the different mixtures, the experimental data and the fatigue curves (FC), while Tables 7 and 8 report the regression coefficients and coefficient of determination R^2. The slope of the fatigue curves, for each type of asphalt concrete, is lower for the asphalt rubber mixtures with respect to the polymer modified mixtures (with one exception, given by the BAC/hm), thus demonstrating the greater fatigue life of the asphalt concretes made with crumb rubber modified bitumen. This general trend is completely confirmed for the aged mixtures.

With reference to a fatigue life of 1,000,000 loading cycles (as indicated in Standard EN 12697–24, Annex D), and using Eq. (2), it was possible to calculate the corresponding stress σ (10^6), that is reported in Tables 7 and 8 for each bituminous mixture; the percentage variations of the stress σ (10^6) of the asphalt rubber concretes, compared to the corresponding polymer modified asphalts (named $\Delta\ \sigma_6$) are also evidenced. In each type of mixture, the hard modified bitumen led to an improved fatigue life compared to the soft, in terms of higher σ_6 values (Table 7); the increase, although quite reduced in the case of the SMA concrete (9%), is 43% and 44% for WCA and BAC, respectively. The increase in fatigue life due to the adoption of crumb rubber modified bitumen proved to be much more substantial, particularly where compared with the soft modified binder, with increases varying up to a maximum of 88%, in relation to the type of concrete; the asphalt rubber mixtures recorded the highest σ_6 values. These experimental results are basically related to the higher ductility, flexibility and resiliency of the asphalt rubber [5, 6, 8, 9], being the rubber and

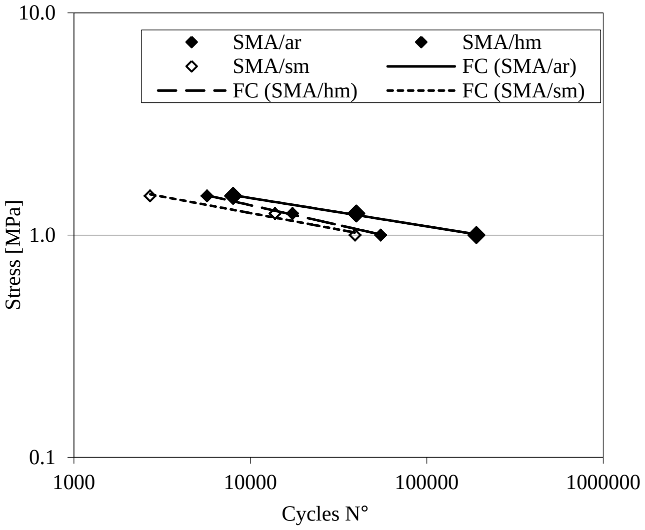

Fig. 5. Fatigue Life N_f Versus Stress; SMA Mixtures.

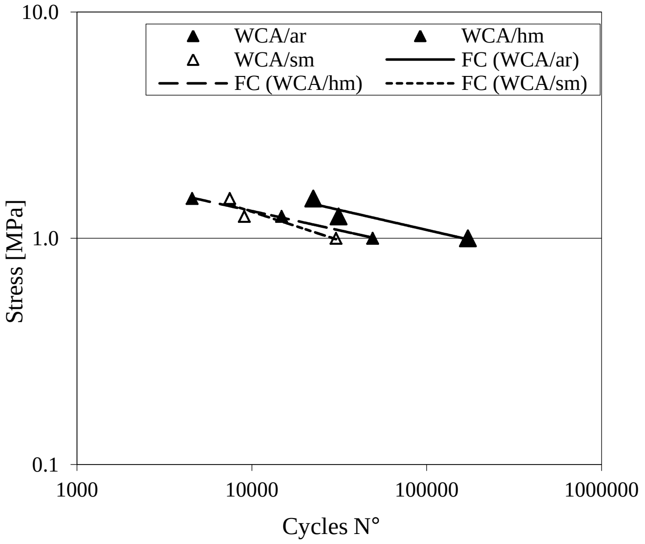

Fig. 6. Fatigue Life N_f Versus Stress; WCA Mixtures.

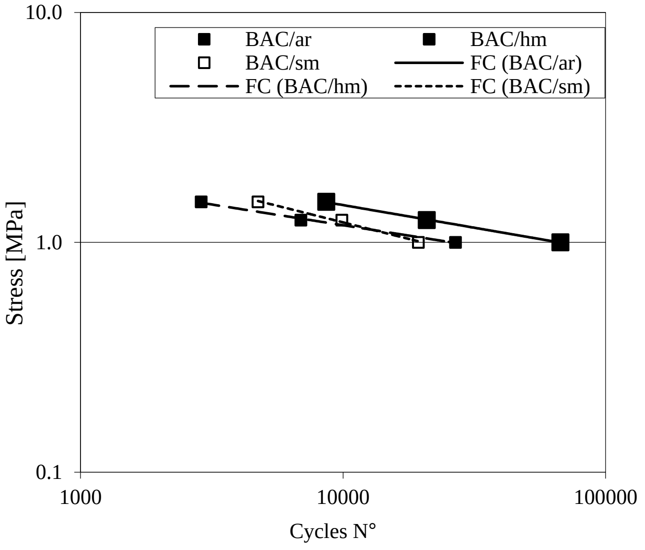

Fig. 7. Fatigue Life N_f Versus Stress; BAC Mixtures.

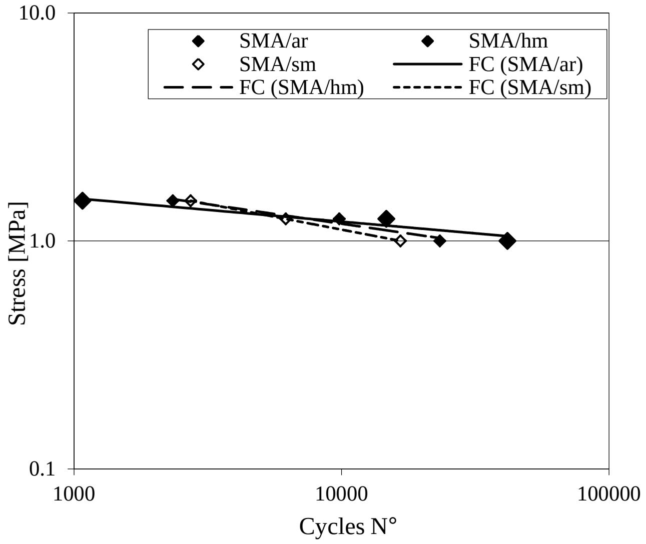

Fig. 8. Fatigue Life N_f Versus Stress; SMA Aged Mixtures.

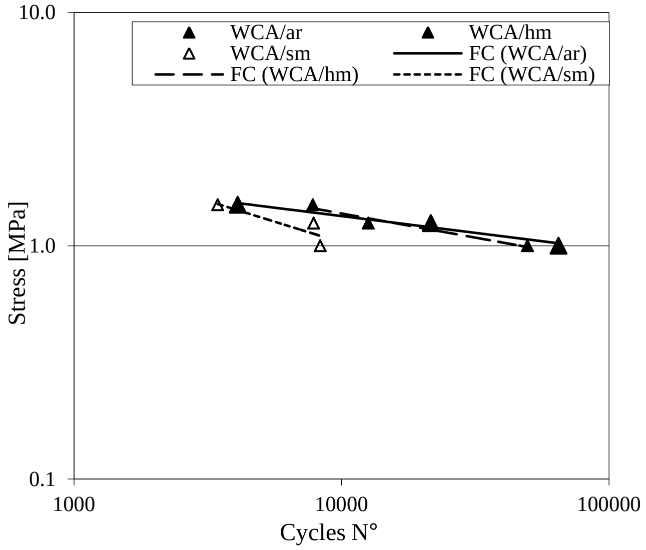

Fig. 9. Fatigue Life N_f Versus Stress; WCA Aged Mixtures.

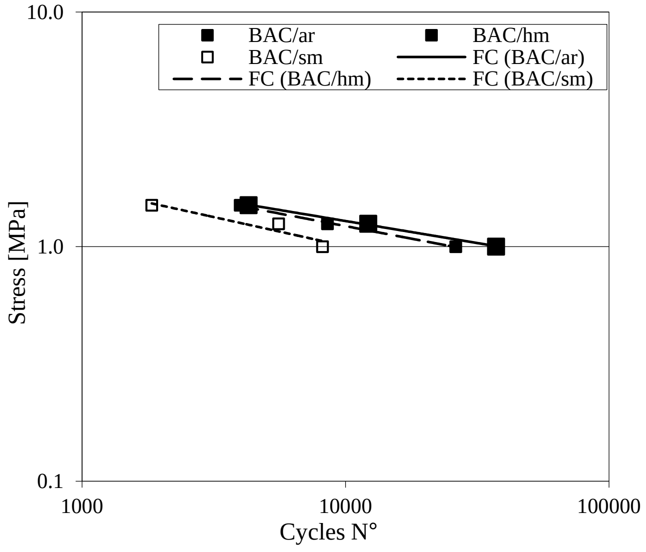

Fig. 10. Fatigue Life N_f Versus Stress; BAC Aged Mixtures.

Table 7. Fatigue Curves - regression Coefficients.

Mixtures	*a* [MPa]	*b* [-]	R^2 [-]	σ_6 [MPa]	$\Delta\ \sigma_6$ [%]
SMA/ar	4.7594	-0.1276	0.9957	0.907	-
SMA/hm	7.0844	-0.1789	0.9976	0.677	34
SMA/sm	4.9188	-0.1482	0.9666	0.619	47
WCA/ar	8.3555	-0.1770	0.9054	0.798	-
WCA/hm	6.3560	-0.1706	0.9972	0.607	31
WCA/sm	13.4200	-0.2526	0.8893	0.424	88
BAC/ar	8.9301	-0.1972	0.9994	0.647	-
BAC/hm	6.2524	-0.1803	0.9957	0.520	24
BAC/sm	17.243	-0.2874	0.9929	0.360	80

Table 8. Fatigue Curves, Aged Mixtures - regression Coefficients.

Mixtures	*a* [MPa]	*b* [-]	R^2 [-]	σ_6 [MPa]	$\Delta\ \sigma_6$ [%]
SMA/ar	3.1371	-0.1029	0.9119	0.788	-
SMA/hm	5.7739	-0.1715	0.9607	0.551	43
SMA/sm	8.8776	-0.2246	0.9999	0.425	85
WCA/ar	5.0424	-0.1438	0.9696	0.729	-
WCA/hm	9.2423	-0.2068	0.9548	0.583	25
WCA/sm	27.3570	-0.3556	0.7490	0.217	236
BAC/ar	7.2417	-0.1877	0.9984	0.602	-
BAC/hm	8.7869	-0.2141	0.9974	0.483	25
BAC/sm	9.8455	-0.2478	0.8942	0.357	69

bitumen combined in a more elastic binder. 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 (Table 8). The SMA and WCA concretes with soft modified bitumen were more affected by ageing (reductions of σ (10^6) of up to 49%), while variations of σ (10^6) of 13% were recorded for the correspondent asphalt rubber mixtures. The hard modified bitumen, compared to the crumb rubber modified one, showed similar effects, in relation to the type of mixture.

Dissipated Energy Analysis

The data gathered in the fatigue tests were also analyzed with Carpenter's energy approach [29, 30], recently also utilized by other Authors [31-33]: the Plateau Value (PV) of the Ratio of Dissipated Energy Change (RDEC) is assumed as a fundamental damage parameter. This approach defines the RDEC as the ratio of the change in dissipated energy between two cycles and the dissipated energy of the first cycle, according to the formula:

$$RDEC = \frac{DE_{n+1} - DE_n}{DE_n} \tag{3}$$

where DE_n and DE_{n+1} represent the dissipated energy produced in load cycle n and $n+1$, respectively.

The RDEC is considered as a reliable indicator of the damage being done to the asphalt concrete from one cycle to another, as a function of how much dissipated energy was involved in the previous cycle [29, 30]. It results to be independent from other types of dissipated energy, due to mechanical work or heat generation and therefore it represents a true indicator of the internal damage developed into the material, during a fatigue test. As discussed by Carpenter et al. [29, 30], the damage curve represented by the evolution of RDEC with the varying of the load cycles, can be

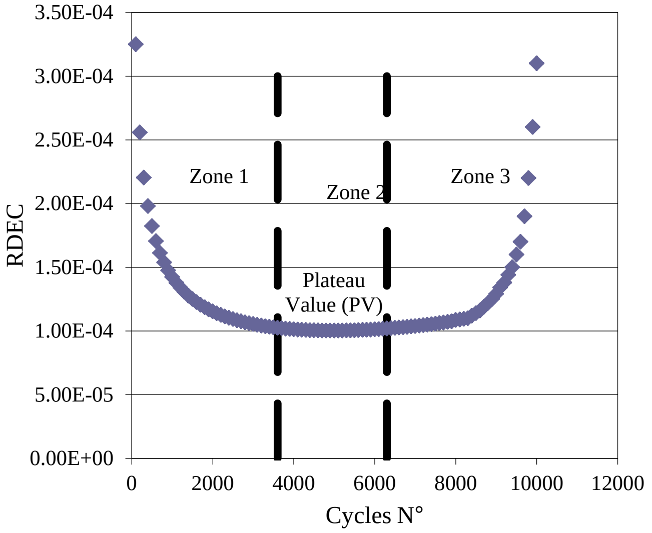

Fig. 11 Determination of PV value for SMA/ar at 1.5 MPa.

divided into three different zones. RDEC decreases with the number of cycles in zone 1, then it is almost constant in zone 2, representing a stage during which there is a constant percent of input energy turned into internal damage. The third zone is characterized by a consistent and rapid increase of the RDEC with the load cycles; it describes the onset of true failure of the mixture. The stage of relevant interest in the Carpenter's approach is zone 2. The approximately constant RDEC value in zone 2 is named *Plateau Value* (PV) of RDEC and it is assumed as a fundamental damage parameter; a lower PV value corresponds to a longer fatigue life of the mixture [29, 30]. Fig. 8 reports an example of the determination of PV value for the asphalt rubber mix type SMA.

Shu et al [31] have already used the PV value in order to compare different bituminous mixtures, containing an increasing amount of RAP material, but with regards to four point bending tests in a regime of strain control and using a single strain level for each asphalt concrete.

In this study, the *damage curves* (PV curves – PVC) have been elaborated, in order to compute the PV value for a 1,000,000 loading cycles (PV_6). Figs. 12 to 17 show the damage curves, determined as a function of N_f (load cycles that correspond to a 50% stiffness reduction) and the PV value, for the unaged and aged mixtures, respectively.

For the analytical interpolation of the damage curves, a power law model was used:

$$PV = aN_f^b \tag{4}$$

where a and b are regression coefficients depending on the type of material. Tables 9 and 10 report the coefficients of regression and determination, as well as the PV value computed using Eq. (4) with reference to a 1,000,000 loading cycles, for the unaged and aged mixtures, respectively. The percentage variations of the PV_6 of the asphalt rubber concretes, compared to the corresponding polymer modified mixtures (named Δ PV_6) have been also reported.

The analysis of the PV_6 values, determined with the energy based approach, allows the different types of mixtures to be compared. The crumb rubber modified mixtures presented lower PV values and

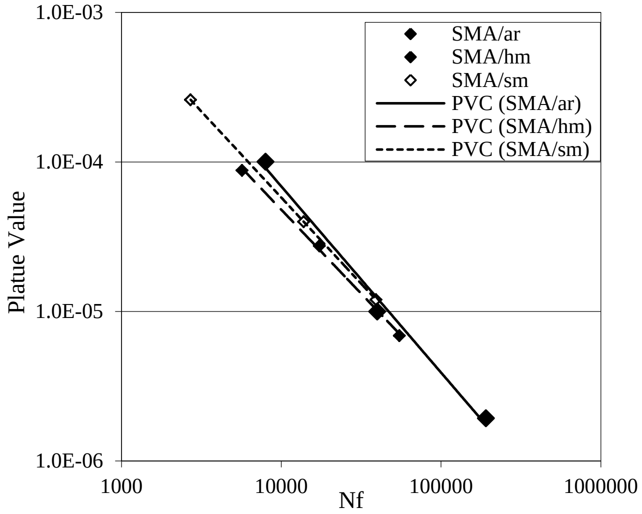

Fig. 12. Plateau Value (PV) Versus Cycles to Failure (N_f); SMA Mixtures.

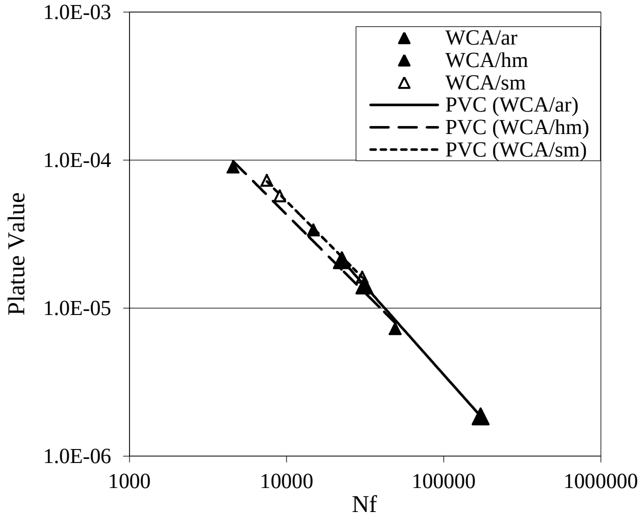

Fig. 13. Plateau Value (PV) Versus Cycles to Failure (N_f); WCA Mixtures.

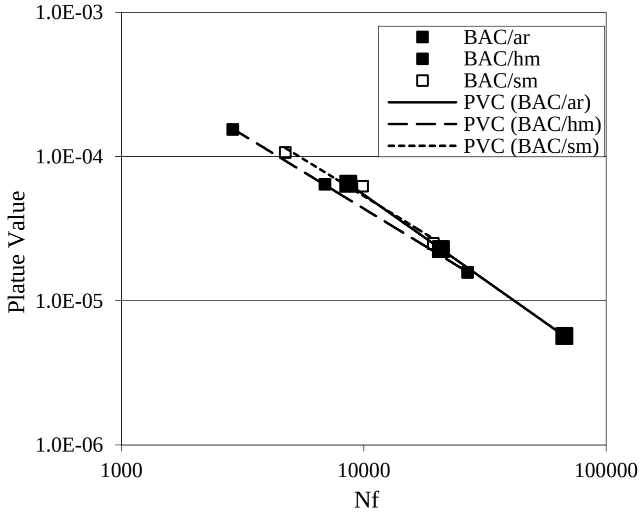

Fig. 14. Plateau Value (PV) Versus Cycles to Failure (N_f); BAC Mixtures.

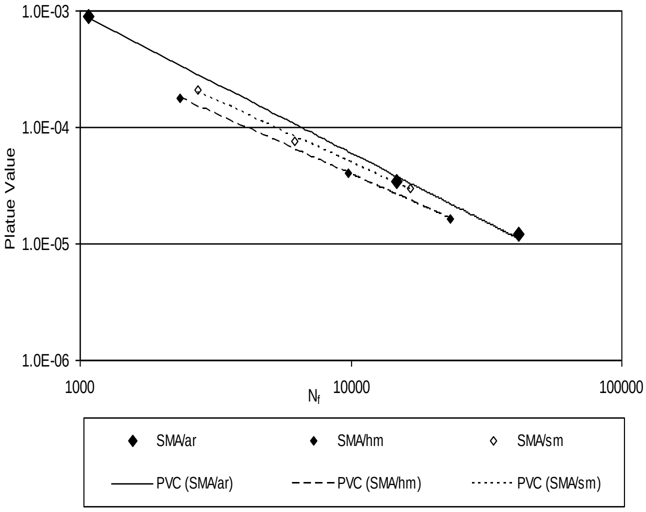

Fig. 15. Plateau Value (PV) Versus Cycles to Failure (N_f); SMA Aged Mixtures.

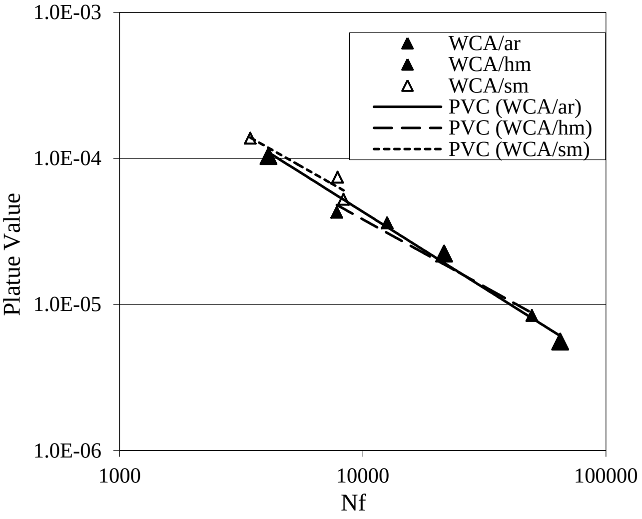

Fig. 16. Plateau Value (PV) Versus Cycles to Failure (N_f); WCA Aged Mixtures.

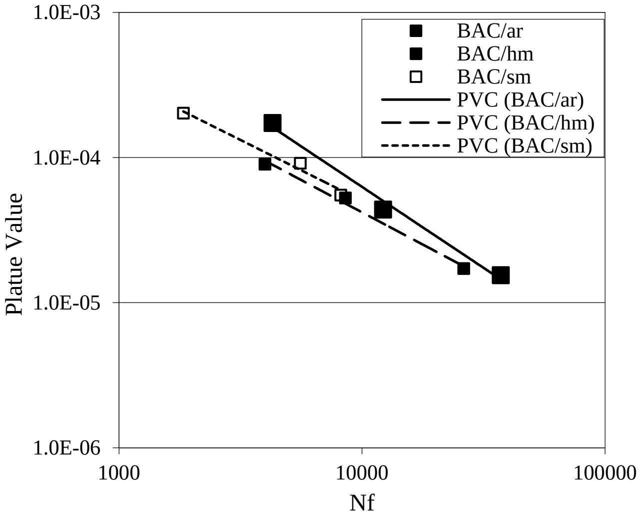

Fig. 17. Plateau Value (PV) Versus Cycles to Failure (N_f); BAC Aged Mixtures.

Table 9. Damage Curves - regression Coefficients.

Mixtures	*a* [MPa]	*b* [-]	R^2 [-]	PV_6 [-]	Δ PV_6 [%]
SMA/ar	6.5741	-1.2453	0.9922	2.218E-07	-
SMA/hm	1.4908	-1.1231	0.9983	2.722E-07	23
SMA/sm	2.3372	-1.1517	0.9999	2.874E-07	30
WCA/ar	3.3702	-1.1955	0.9999	2.263E-07	-
WCA/hm	0.7346	-1.059	0.9852	3.251E-07	44
WCA/sm	0.9831	-1.068	0.9994	3.842E-07	70
BAC/ar	0.3272	-0.958	0.9999	5.845E-07	-
BAC/hm	0.5465	-1.025	0.9999	3.869E-07	66
BAC/sm	2.9839	-1.1847	0.9694	2.326E-07	151

Table 10. Damage Curves, Aged Mixtures - regression Coefficients.

Mixtures	*a* [MPa]	*b* [-]	R^2 [-]	PV_6 [-]	Δ PV_6 [%]
SMA/ar	3.5574	-1.192	0.9978	2.507E-07	-
SMA/hm	0.5478	-1.036	0.9999	3.331E-07	33
SMA/sm	0.9542	-1.071	0.9929	3.578E-07	43
WCA/ar	0.6650	-1.047	0.9923	3.474E-07	-
WCA/hm	0.1849	-0.9211	0.9751	5.500E-07	58
WCA/sm	0.2992	-0.9424	0.9080	6.631E-07	91
BAC/ar	1.8069	-1.115	0.9904	3.689E-07	-
BAC/hm	0.1502	-0.8885	0.9915	7.009E-07	90
BAC/sm	0.1118	-0.8366	0.9788	1.069E-06	190

therefore lower damage, with respect to correspondent polymer modified mixes; the highest Δ PV_6 were always determined for the soft polymer modified asphalts, both for unaged and aged conditions.

However, a relevant difference in the ranking of the mixtures, using the two methodologies, is worth mentioning. The energy based analysis led to rank the BAC mixtures as less resistant to fatigue, whereas the conventional approach identified the WCA mixes as those characterized by the lower fatigue life. As observed by several researchers [29-33], in the standard approach the failure of the sample is empirically based on the 50% stiffness reduction, whereas the energy based analysis can be considered more reliable and effective, since the key parameter considered, the Plateau Value of the Ratio of Dissipated Energy Change, is rationally related to the internal state of damage achieved into the material during the fatigue test.

Resistance to Moisture Damage

The indirect tensile strength test on a first set of specimens, after 7 days of immersion in a thermostatic bath at 25°C, and on a second set of dry specimens, has been determined for each mixture. The damage caused by the immersion in water is expressed by the Tensile Strength Ratio (TSR), according to the formula:

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} \tag{3}$$

where ITS_{wet} and ITS_{dry} represent the indirect tensile strength [MPa] of the specimens treated with 7 days of immersion in a thermostatic bath at 25°C and untreated, respectively. Table 11 presents the ITS_{wet} and the TSR values, for the mixtures studied; the ITS_{dry} values have been already reported in Table 6.

Table 11. Moisture Damage – Indirect Tensile Strength and TSR Values.

Mixtures	SMA/ar	SMA/hm	SMA/sm	WCA/ar	WCA/hm	WCA/sm	BAC/ar	BAC/hm	BAC/sm
ITS_{wet} [MPa]	2.24	1.90	1.73	1.46	1.28	1.17	1.36	1.07	0.94
TSR [%]	95	88	85	90	83	80	87	78	76

Table 12. Permanent Deformation Evaluation Results.

Mixtures	SMA/ar	SMA/hm	SMA/sm	WCA/ar	WCA/hm	WCA/sm	BAC/ar	BAC/hm	BAC/sm
RD [mm]	1.18	2.46	2.55	2.52	2.9	3.01	3.1	4.74	4.85
WTS [mm/1000 Cycles]	0.025	0.058	0.072	0.068	0.084	0.108	0.091	0.150	0.242

Even if the mixtures made with crumb rubber modified bitumen were clearly characterized by the less pronounced moisture susceptibility, it should be stressed that all the asphalts have shown a reasonable resistance to moisture damage; the limit value of the TSR below which a bituminous mixture may present problems of stripping, usually equal to 70% [34], has been overcome by all the asphalts. There is a full agreement in the ranking of the mixes, in terms of both fatigue resistance and moisture damage resistance.

Permanent Deformation Test

Table 12 reports the permanent deformation recorded (Rut Depth - RD) and the Wheel Tracking Slope computed (WTS, evaluated between 5,000 and 10,000 cycles) for the WTT, for each asphalt.

The use of crumb rubber modified bitumen reduces noticeably the permanent deformation, as well as the wheel tracking slope, especially for the SMA and the BAC mixtures. The asphalt concretes characterized by the highest fatigue life, namely the crumb rubber modified mixtures, resulted also the most resistant to the permanent deformation accumulation.

Summary

The four point bending fatigue tests, conducted on bituminous concretes of the SMA, WCA, BAC type (all made with EAF steel slag), at 20°C and 10 Hz in the stress control mode, have demonstrated the superior performance of the crumb rubber modified mixtures when compared with those made with SBS polymer modified binder. The better performance of the modification with crumb rubber is also fully confirmed, for all the types of concrete, by means of Carpenter’s energy based approach.

The effectiveness of the crumb rubber modified bitumen in the increase of fatigue life was also clear for the mixtures in conditions of post-long term ageing.

Moreover, with respect to the corresponding asphalts with SBS polymer modified bitumen, all the mixtures with crumb rubber modified binder showed better performances in terms of permanent deformation and moisture resistance. Therefore, is has been verified a complete congruence, in terms of ranking of the mixes, between the different performance tests used in the investigation, namely fatigue, rutting and moisture damage tests.

In this study a discrepancy emerged between the empirical fatigue evaluation and the energy based analysis, therefore it is recommended to approach very carefully the fatigue characterization based on the 50% stiffness reduction criterion.

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