Comprehensive performance characterization of warm mix asphalt containing steel slags: a laboratory study

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Research and application concerning the use of environmentally friendly materials and technologies in road pavements have reached high relevance mainly due to the increasing public consciousness addressed to environmental protection and preservation. In regard to this, Warm Mix Asphalt (WMA) can be successfully used since it is an asphalt concrete modified with additives that can be compacted at lower temperatures than the traditional Hot Mix Asphalt (HMA). The environmental sustainability of WMA can be further enhanced thanks to the inclusion of recycled/waste materials. Given this background, the present paper illustrates the overall results of a wide research study aimed at verifying the utilization feasibility of steel slags in warm-modified asphalt concretes. This was accomplished by investigating in the laboratory the midrange and high-service temperature properties of warm bituminous binders, as well as mastics and mixtures containing steel slag aggregates. The warm modification was performed using a chemical tensoactive additive; steel slags were produced in a metallurgical plant by electric arc furnace (EAF) treatment. To evaluate the combined effect of manufactured EAF steel slags and warm chemical additive, a comparative analysis was carried out taking into account unmodified binders as well as mastics and mixtures prepared with only natural aggregates. The rheological study on unaged and long-term aged binders and mastics was performed with the dynamic shear rheometer (DSR), whereas cyclic tests on WMA mixes were conducted with the Nottingham Asphalt Tester (NAT). The results mainly showed that materials prepared combining chemical warm technology and EAF steel slag aggregates seem to assure equal or even enhanced performance than the corresponding traditional hot mixed materials, demonstrating promising field applicability.

Keywords: WMA, EAF Steel Slags, Fatigue and rutting resistance, Stiffness

Literature review

Warm Mix Asphalt

Warm Mix Asphalt (WMA) is an asphalt concrete that is characterized by lower production and application temperatures (100–140 °C) than traditional Hot Mix Asphalt (HMA), which requires high production temperatures (> 150 °C).

According to wide literature (D'Angelo et al. 2008; Capitao et al. 2012; Rubio et al. 2012; Kheradmand et al. 2014), WMA can be obtained by using organic (wax), chemical or foaming additives achieving environmental benefits (reduced energy consumption, gas and fume emissions) as well as economic/operational advantages (lower production costs, longer hauling distances and extended construction periods).

However, the amount of additive and the type of WMA technology clearly affect the final properties of WMA, which can vary in a large range (Capitao et al. 2012).

Chemical additives represent the most recent WMA technology usually consisting of a package of products (emulsification agents, surfactants, polymers, additives and adhesion promoters). This additive should be able to allow lower mixing and compaction temperatures thanks to the reduced friction at the interface between bitumen and aggregates without affecting viscosity and performance grade of the binder (Mo et al. 2012; Morea et al. 2012; Xiao et al. 2012; Kheradmand et al. 2014, Pasetto et al. 2015). This could be accomplished thanks to the presence of surfactants which should reduce the surface tension of the asphalt binder acting as an emulsifier and thus increasing lubricity (D'Angelo et al. 2008; Capitao et al. 2012). Several experimental studies seem to confirm that WMAs prepared with such additive are characterized by slightly higher workability than the corresponding HMAs (Hurley and Prowell 2006; Sanchez-Alonso et al. 2011; Mo et al. 2012; Pasetto et al. 2015).

However, reducing mixing and compaction temperatures could also lead to possible drawbacks mainly related to greater moisture susceptibility, coating and bonding problems, reduced interface shear strength and higher rutting potential, (Hurley and Prowell 2006; Capitao et al. 2012; Mo et al. 2012; Morea et al. 2012; Rubio et al. 2012; Zhao et al. 2012; Sanchez-Alonso et al. 2013; Kheradmand et al. 2014; Pasquini et al. 2015).

Steel slags in asphalt mixtures

Slag is a waste product from the pyrometallurgical processing of various ores and can be classified into ferrous and non-ferrous slag. Since hundreds of millions of tonnes of ferrous slag are produced worldwide annually (Piatak et al. 2014), the possible use of such material for construction applications (including road pavements) is of strategic importance in order to convert a waste into a valuable resource, taking also into account that ferrous slag may have a lower potential to negatively impact the environment.

Ferrous slags are created during the recovery of iron from natural ores or recycled materials to produce either iron or steel. Steel slag is a by-product of the steelmaking and steel refining processes. The more common steel slags used in road construction are categorized in basic oxygen furnace (BOF) steel slag and electric arc furnace (EAF) steel slag (Yildirim and Prezzi 2011; Piatak et al. 2014) based on the type of furnace used.

In this research study, the use EAF steel slag has been evaluated. This kind of steel slag is generally characterized by a lower content of free magnesium and calcium oxides than BOF steel slag. Some researchers affirmed that EAF steel slag can be successfully used as high quality aggregate in road pavements thanks to its physical and mechanical properties since it can be classified as a hard, wear-resistant, adhesive and rough material (Emery 1984; Motz and Geiseler 2001; Asi 2007; Yi et al. 2012). Nevertheless, some drawbacks can be also detected due to the use of such material.

First, steel slags have high bulk density leading to higher transportation costs that limit their extensive use in road construction. Furthermore, due to the presence of unstable phases in its mineralogy, steel slags could show volumetric instability with volume increase in the presence of water (Emery 1984; Sofilic et al. 2010; Yildirim and Prezzi 2011) even if it has been shown that the use of steel slag in asphalt mixtures should limit this potential expansion. Moreover, an aging period of steel slag (at least 2-3 months) prior to its use is advisable in order to minimize subsequent volumetric changes due to oxidation (Emery 1984; Wu et al. 2007; Sofilic et al. 2010; Sorlini et al. 2012). As far as environmental issues are concerned, different studies demonstrated that the release of pollutants by leaching, although it cannot be considered negligible, generally meets environmental requirements established in different countries (Emery 1984; Sofilic et al. 2010; Sorlini et al. 2012).

On the other hand, several studies reported improved mechanical properties and durability of asphalt mixtures thanks to the use of steel slag aggregates (Ahmedzade and Sengoz 2009; Pasetto and Baldo 2010; Pasetto and Baldo 2011; Pasetto and Baldo 2012). Accordingly, the first results of the wider research program presented in this paper documented potentialities of increased compactability and rutting resistance of asphalt mixtures thanks to the use of EAF steel slags even if issues related to the correct bonding between bitumens and steel slags emerged due to the low alkalinity of such an aggregate (Pasetto et al. 2015).

Research goals and experimental approach

Based on the increasing interest in preservation and protection of natural and working environments, the main objective of the present research is to evaluate the feasibility of using EAF steel slag in dense graded WMA prepared using a chemical tensoactive additive. In such a mixture, WMA can be used to reduce energy consumption and emission of pollutants whereas the use of steel slags in partial substitution of natural aggregates allows both saving natural resources and re-using industrial waste, enhancing the environmental sustainability of the material.

Since the abovementioned environmental benefits should be achieved also preserving performances usually required by technical specifications, a wide experimental research was carried out in order to assess workability, mechanical properties and durability of WMA prepared with EAF steel slags and chemical tensoactive additives. This paper summarizes the main part of such a research project, also analysing some preliminary results (Pasetto et al. 2015; 2016) thoroughly.

A multi-scale approach aimed at investigating rheological and mechanical behaviour of warm binders, mastics and mixtures at midrange and high-service temperatures in terms of stiffness, fatigue and permanent deformation properties is presented. To accomplish this objective, two bitumens, four mastics and three dense graded mixtures of different nature and composition were studied at unaged and long-term aged conditions through dynamic tests in a wide range of temperatures, obtaining a global picture of the influence of warm technology and EAF steel slag aggregates.

In particular, a plain bitumen (P) and the corresponding warm binder (W) were used to prepare mastics (using limestone – L – and EAF steel slag – S – fillers) and mixtures (using limestone and EAF steel slag aggregates).

Binders and mastics were tested through the use of a dynamic shear rheometer (DSR) by performing oscillatory strain-controlled frequency sweep (FS) and time sweep (TS) tests on long-term aged materials at midrange temperatures as well as multiple stress creep recovery (MSCR) tests on unaged materials at high temperatures in order to evaluate stiffness, fatigue and permanent deformation properties, respectively.

Stiffness modulus as well as fatigue and rutting resistance of hot (HMA) or warm (WMA) mixtures prepared with the studied binders, limestone (_L) and with or without EAF steel slag aggregates (_S) were assessed through dynamic tests on cylindrical specimens prepared by means of a Superpave gyratory compactor. Indirect tensile tests at midrange temperatures were carried out to assess stiffness modulus (ITSM tests) and fatigue resistance (ITF tests) on long-term aged specimens whereas repeated load axial (RLA) tests at high temperatures were used to evaluate the rutting potential of unaged samples.

Based on the previous considerations and acronyms, Table 1 summarizes the experimental approach adopted to characterize the tested materials. More details regarding materials and testing procedures are given in the following.

Table 1. Multi-scale experimental approach.

Material		Condition	Property		
			Stiffness modulus	Fatigue resistance	Rutting resistance
Binders	P	Unaged	-	-	MSCR tests
		Aged	FS tests	TS tests	-
	W	Unaged	-	-	MSCR tests
		Aged	FS tests	TS tests	-
Mastics	PL	Unaged	-	-	MSCR tests
		Aged	FS tests	TS tests	-
	PS	Unaged	-	-	MSCR tests
		Aged	FS tests	TS tests	-
	WL	Unaged	-	-	MSCR tests
		Aged	FS tests	TS tests	-
	WS	Unaged	-	-	MSCR tests
		Aged	FS tests	TS tests	-
Mixtures	HMA_L	Unaged	-	-	RLA tests
		Aged	ITSM tests	ITF tests	-
	WMA_L	Unaged	-	-	RLA tests
		Aged	ITSM tests	ITF tests	-
	WMA_S	Unaged	-	-	RLA tests
		Aged	ITSM tests	ITF tests	-

Materials

Binders and Mastics

The studied warm binder (W) was obtained in the laboratory by modifying a plain binder (P) with a commercial chemical WMA additive (viscous liquid) dosed at 0.5% by weight of the binder according to the recommendations of the producer. This was accomplished by mixing the binder P and the additive at 150 °C using a portable equipment operating at high stirring rates.

The binder P, selected as base reference binder, was a 35/50 penetration grade bitumen, whereas the warm additive can be classified as a water-free liquid product containing surface active agents. The basic properties of the studied binders can be found elsewhere (Pasetto et al., 2015).

Four different mastics at two aging conditions were tested during this research study. The mastics were obtained by combining the above-mentioned plain (P) and warm (W) bitumens with two types of fillers (natural limestone and EAF steel slag) dosed at a constant filler/bitumen volume ratio (27% filler and 73% binder by volume), properly taking into account the higher apparent specific gravity of steel slag with respect to that of mineral limestone aggregate. The studied fillers (particle dimensions < 0.063 mm) were characterized by very different physical and chemical properties (Pasetto et al., 2016) affecting viscoelastic response of mastics. In order to achieve homogeneous materials without filler segregation, mastics were mechanically prepared at 150°C by blending accurately fillers and bitumens.

A lower preparation temperature of warm binder and mastics, simulating real production of WMA (e.g 130 °C), was not adopted due to laboratory constraints.

As anticipated (Table 1), binders and mastics were tested at both unaged and long-term aged conditions, which was simulated through the pressure aging vessel (PAV) procedure, assessing the rutting potential (high-service temperature properties) as well as the stiffness characteristics and the fatigue resistance (midrange-service temperature properties), respectively.

Asphalt Mixtures

Three different dense graded asphalt mixtures were investigated in order to accomplish the objectives of this study. Such mixtures were prepared blending the abovementioned binders (P and W) with crushed limestone aggregates (filler included) and EAF steel slag. Gradations of the different stockpiles of limestone and steel slag are given in Table 2 whereas Table 3 shows the main physical and mechanical properties of aggregates.

Table 2. Limestone and steel slag fraction gradations.

Sieves (mm)	Limestone stockpiles (% passing)					Steel slag stockpiles (%passing)		
	12/20	8/12	4/8	0/4	Filler	8/12	4/8	0/4
31.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
20	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0
14	29.8	100.0	100.0	100.0	100.0	98.3	100.0	100.0
10	1.2	53.4	97.4	100.0	100.0	24.0	99.8	100.0
6.3	0.0	3.8	50.8	100.0	100.0	0.3	68.7	100.0
2	0.0	0.0	0.2	62.7	100.0	0.0	0.6	69.4
0.5	0.0	0.0	0.0	33.5	100.0	0.0	0.0	28.4
0.25	0.0	0.0	0.0	25.5	96.0	0.0	0.0	18.8
0.063	0.0	0.0	0.0	14.8	67.1	0.0	0.0	9.8

Table 3. Basic physical and mechanical properties of limestone and steel slag.

Properties	Standard	Unit	Limestone				Steel slag		
			12/20	8/12	4/8	0/4	8/12	4/8	0/4
Particle density	EN 1097-6	g/cm^3	2.71	2.74	2.75	2.76	3.90	3.89	3.80
Los Angeles coefficient	EN 1097-2	%	-	16.0	-	-	12.4	-	-
Shape index	EN 933-4	%	10.5	7.5	12.8	-	4.2	7.8	-
Flakiness index	EN 933-3	%	13.8	11.8	10.5	-	4.5	8.3	-
Sand equivalent	EN 933-8	%	-	-	-	78	-	-	92

Two warm mixes (WMA_L and WMA_S), one of which containing EAF steel slag in partial substitution of limestone aggregates(WMA_S), were prepared by properly combining the abovementioned aggregates and bitumens (P or W). A corresponding traditional hot mix asphalt prepared with binder P and containing only limestone (HMA_L) was also taken into account as reference material. In order to reduce the variables to be accounted for during the comparison of the mixes, all the materials were characterized by the same (volumetric) gradation and bitumen content (complying with typical technical specifications for wearing courses) by selecting the proportions of the different fractions of limestone and steel slag reported in Table 4.

Table 4. Mixture composition: dosages (by weight) of the different fractions.

Mixtures	Limestone dosages (%)					Steel slag dosages (%)		
	12/20	8/12	4/8	0/4	Filler	8/12	4/8	0/4
HMA_L & WMA_L	5	15	37	38	5	-	-	-
WMA_S	5	7	20	23	5	10	15	15

In particular, a dosage of steel slag equal to 40% by the weight of total aggregates (corresponding to 32% by volume) was selected in case of the WMA_S mixture. This allowed practically the same volumetric proportions in the aggregate skeleton of the mixtures without an excessive increase of transportation costs due to the use of aggregates with high bulk density. To maintain the same volumetric composition, also the binder content was selected taking into account the different apparent specific gravity of the aggregates used. Thus, all the mixtures were prepared by using a bitumen content of about 15% by volume of the aggregate (that corresponds, by weight of aggregates, to 5.5% in the case of HMA_L and WMA_L and 4.9% in the case of the isovolumetric WMA_S containing aggregates having higher particle densities).

The design gradations in terms of volumetric passing together with the corresponding binder contents are reported in Table 5. In order to simulate real scale applications, HMA_L was produced at 150 °C and compacted at 140 °C whereas WMA_L and WMA_S were mixed and compacted at 130 °C and 110 °C, respectively. 150 mm diameter cylindrical specimens were prepared through 100 gyrations of a Superpave gyratory compactor assuming a target of 3% air void content. After compaction, 65 mm height cylindrical specimens were obtained by sawing to carry out subsequent stiffness, fatigue and rutting tests.

Table 5. Design mixture gradations and binder contents.

Sieves (mm)	HMA_L & WMA_L mixtures	WMA_S mixture
	% volumetric passing	% volumetric passing
20	100.0	100.0
14	96.5	95.9
10	87.1	84.0
6.3	62.4	63.8
2	28.9	30.5
0.5	17.7	17.8
0.25	14.5	14.4
0.063	9.0	8.8
Binder content (% by volume)	14.8	14.9

Testing methods

Stiffness Characteristics

At binder-mastic scale, the mechanical properties of tested materials at midrange service temperatures was studied through a dynamic shear rheometer (DSR). In particular, the linear viscoelastic behaviour of binders and mastics was assessed through the construction of master curves of the complex shear modulus G* applying the time-temperature superposition principle. This was accomplished by performing strain-controlled frequency sweeps at different temperatures and test frequencies, ranging from 16°C to 58°C and from 0.1 to 100 rad/s, respectively. Tests were performed applying a strain level within the previously checked linear viscoelastic domain. In order to fit DSR test results constructing the master curves at the reference temperature of 34 °C, the well-known model of Eq. 1 (Bahia et al. 2001) was selected. In this model, the Williams–Landel–Ferry (WLF) formulation (Williams et al. 1955) for the temperature-dependent shift factors was used for the superposition of the isotherms at different temperatures.

$$G^*(f') = G_e + \frac{G_g - G_e}{\left[1+\left(f_c/f'\right)^k\right]^{m_e/k}} \tag{1}$$

Further details can be found in Pasetto et al. 2016.

To assess stiffness characteristics at mixture scale, non-destructive indirect tensile stiffness modulus (ITSM) tests were carried out at 20 °C through a dynamic equipment in accordance with EN 12697-26/Annex C. After a conditioning period of at least four hours at the test temperature, eight cylindrical specimens were tested for each mixture in strain-controlled mode, applying five load pulses. The load pulses are applied by a suitable load actuator while the corresponding horizontal deformation is measured through two linear variable displacement transducers (LVDT) mounted opposite one another in a rigid frame clamped to the specimen. A rise time (time for applying the load from zero to peak load) of 124 ms and a target peak horizontal deformation of 5 µm were selected according to the standard specifications. The Poisson’s ratio was assumed to be 0.35.

Fatigue Resistance

As far as midrange service temperature behaviour of binders and mastics concerns, fatigue resistance at long-term aged conditions was also assessed by using the DSR equipment. In particular, strain-controlled repeated loading time sweeps were carried out at 20 °C test temperature and 10 Hz loading frequency by using 8 mm parallel plate geometry with 2 mm gap. Three replicates were performed for each tested materials after a thermal conditioning of 30 minutes. Due to laboratory and material constraints, tests were carried out adopting only one common strain level (1.0%) for all materials. According to wide literature concerning strain-controlled fatigue tests, a conventional failure criterion was arbitrarily established corresponding to the number of cycles at which a 50% reduction in initial complex modulus occurred.

Repeated indirect tensile fatigue (ITF) tests were carried out through a dynamic equipment according to the British standard BS DD ABF in order to assess the fatigue resistance of asphalt mixtures. Such a test consisted of applying load pulses with a repetition period of 1.5 s in stress-controlled mode along the vertical diameter of the test specimens. Tests were performed at 20°C fixing a rise time of 124 ms and applying five different indirect tensile stress levels (from 300 kPa to 500 kPa). The number of cycles corresponding to the complete fracture of specimens was assumed as fatigue failure criterion. Then, fatigue curves were obtained in a bi-logarithmic plane by regression analysis of the fatigue data using a power law. Experimental data were plotted in terms of initial horizontal tensile strain as a function of the number of cycles to failure.

Rutting Potential

The rutting potential (high temperature mechanical properties) of unaged binders and mastics was evaluated through multiple stress creep recovery (MSCR) tests carried out through the DSR according to EN 16659 that demonstrates its suitability for both plain and polymer modified bitumens. 10 creep-recovery cycles, each one lasting 10 s (1 s creep loading time and 9 s recovery unloading time), were performed at 58, 64, 70 and 76 °C applying 0.1 and 3.2 kPa (plus 10 kPa only for mastics) stress levels. Average values of two replicates for each material and testing condition were used to assess the rutting potential of studied materials in terms of the non-recoverable creep compliance J_{nr} and the ratio between J_{nr} and total compliance J_{tot}. In particular, J_{nr} is the ratio between residual (plastic) strain at the end of each cycle (post-recovery phase) and the corresponding applied creep stress, whereas J_{nr}/J_{tot} represents the compliance at load removal (at the end of the creep phase). Further details can be found in Pasetto et al. 2016.

Performance-related rutting tests were carried out on hot and warm asphalt mixtures using a dynamic test equipment. According to EN 12697-25/Method A, repeated load axial (RLA) tests with confinement were executed at 40 °C on three replicates for each tested materials after four hours conditioning period. To achieve the confinement, 150 mm diameter cylindrical specimens were subjected to a cyclic axial block-pulse pressure using an upper loading platen having a smaller diameter (100 mm). In this way, the “ring” of the material not directly subjected to the axial load simulates a confining action reproducing field conditions. 3600 square loading pulses with a frequency of 0.5 Hz (1 s loading time and 1 s rest period) and a stress level of 100 kPa were applied according to the standard procedure. The evolution of the cumulative axial strain as a function of the number of loading cycles typically shows a first phase with a decreasing creep rate (i.e. slope of the curve) and a second phase with a quasi-constant creep rate. According to the European standard, the rutting potential of the tested mixtures was estimated not only through the cumulative axial strain at the end of the test but also in terms of creep rate of the quasi-linear part of the curve. Such a steady state was located over the final 2400 loading cycles. Further details can be found in Pasetto et al. 2015.

Results and Discussions

Stiffness Properties

Based on the results of frequency sweep tests, master curves of complex modulus G* at the reference temperature of 34 °C were constructed to assess the viscoelastic behaviour of binders and mastics at midrange service temperatures (Pasetto et al., 2016). Referring to the model of Eq. (1), also in the case of mastics, G_g and G_e values tended to typical bitumen values of 10^9 and 0 Pa, respectively.

G* master curves are reported in Figure 1 where real shifted data are not represented for the sake of readability. According to other studies (Xiao et al. 2012, Morea et al. 2012), the effect of the warm chemical additive appeared quasi-negligible in the case of bitumens (Figure 1a). Similar results were found for limestone mastic (Figure 1b) whereas a certain physical-chemical frequency-dependent interaction between the components occurred when steel slag filler was used (Figure 1c).

On the contrary, a clear stiffness increase due to filler addition was detected (Figure 2), particularly in the case of steel slag mastics, according to wide literature (Buttlar et al. 1999, Bahia et al. 2010, Cardone et al. 2015). This fact can be justified not only with the stronger filler-filler particle interaction in case of steel slag material, but also with the higher Rigden voids of such a filler (Pasetto et al. 2016) that led to higher stiffening effect, according to Harris and Stuart (1995).

As far as stiffness properties of studied mixtures are concerned, Table 6 shows the average results of the stiffness modulus analysis along with the corresponding standard deviations. It can be observed that warm mixes were characterized by a stiffness rather lower than that of the control material. Likely, this apparent discordance with the abovementioned binder results was only due to the less oxidative hardening of the warm bitumen in asphalt mixtures because of the lower production temperatures adopted (Capitao et al. 2012, Sanchez-Alonso et al. 2011). However, a stiffness reduction contribution due to the use of the chemical additive could also occur according to Sanchez-Alonso et al. (2011). In any case, it is worth noting that the absolute stiffness value of warm mixes still remained adequate.

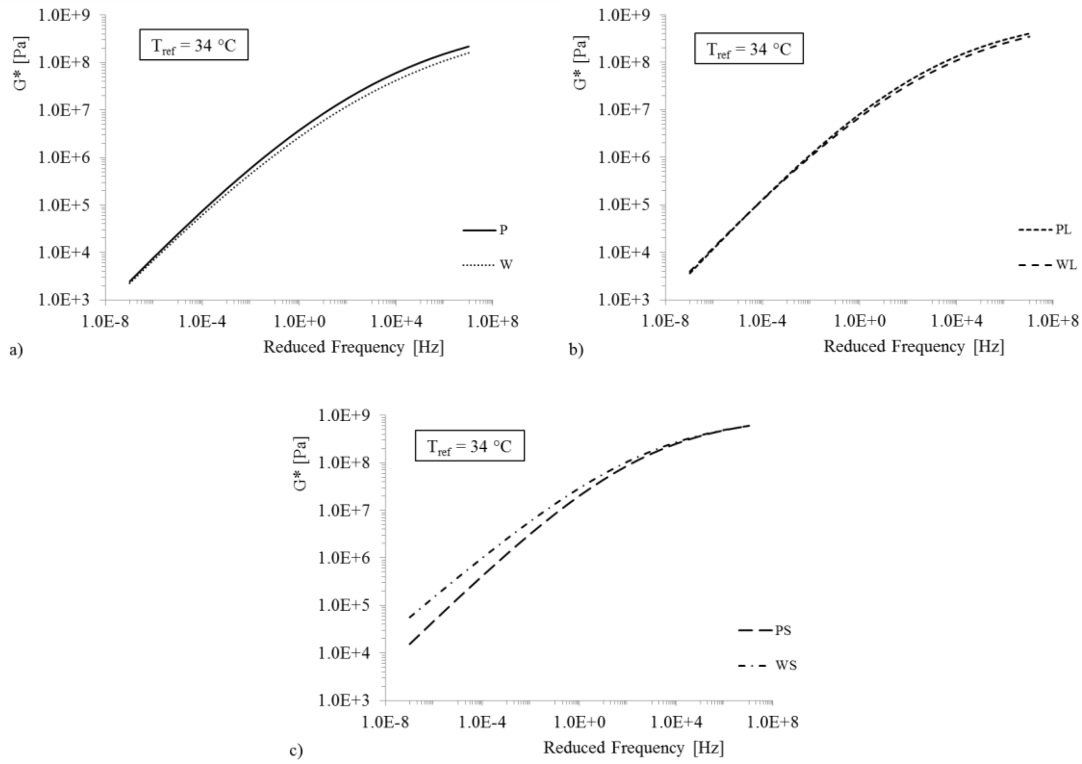

Figure 1. G* master curves: effect of the warm additive on bitumen (a), limestone mastic (b) and steel slag mastic (c).

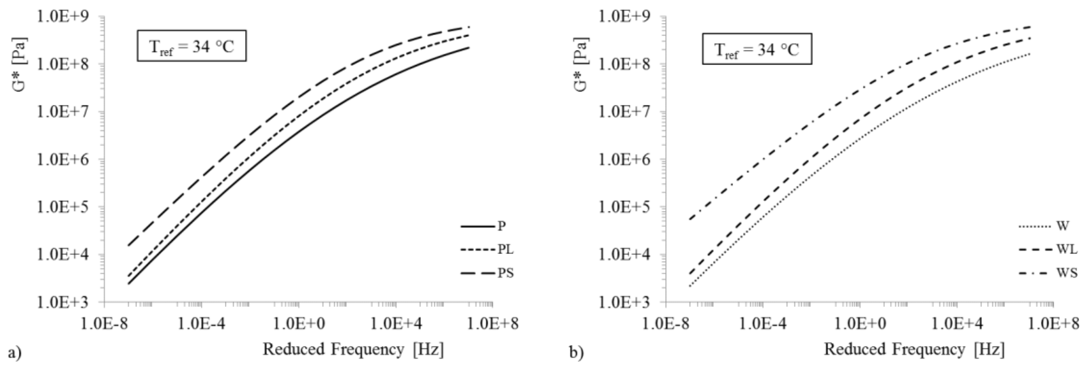

Figure 2. G* master curves: effect of the filler on plain (a) and warm (b) binders.

Table 6. Indirect tensile stiffness modulus (ITSM) test results (T = 20 °C).

Mixture	Mean ITSM (MPa)	Standard deviation (MPa)
HMA_L	6812	379
WMA_L	4615	390
WMA_S	4885	469

Otherwise, according to the results obtained with the mastics, the inclusion of EAF steel slag hard aggregates led to a slight increase in stiffness, similarly to what found by other researchers (Emery 1984; Motz and Geiseler 2001; Ahmedzade and Sengoz 2009; Pasetto and Baldo 2010; Pasetto and Baldo 2011; Pasetto and Baldo 2012; Yi et al. 2012; Ameri et al. 2013).

Fatigue resistance

Fatigue test results obtained for bitumens and mastics are summarized in Table 7 in terms of number of cycles corresponding to 50% reduction in initial complex modulus G*. For completeness, initial complex moduli as well as the adopted strain level for the repeated loading time sweep tests are also reported.

The presence of the warm additive led to a higher fatigue resistance of binder and mastics, regardless of the type of filler used. Moreover, the addition of both natural and manufactured fillers significantly stiffened the binder, in particular when EAF steel slag mastic is considered. This is likely due not only to a volume-filling reinforcement mechanism, but also to physico-chemical interactions between bitumen and filler particles, since different behaviours also occurred in presence of the warm chemical additive. However, this stiffening effect clearly induced a significant decrease in strain-controlled fatigue resistance, according to previous studies (Liao 2007, Liao et al. 2013, Bahia et al. 2010, Frigio et al. 2015).

Table 7. Binders and mastics fatigue test results (T = 20 °C, f = 10 Hz).

Material	Applied strain (%)	Initial complex modulus (MPa)	Cycles to failure -
P	1.0	42.1	3576000
W	1.0	34.7	4825500
PL	1.0	95.3	87000
WL	1.0	62.7	247500
PS	1.0	110.9	60000
WS	1.0	66.7	159000

As anticipated, mixtures were also investigated against fatigue by carrying out stress-controlled dynamic tests in indirect tensile configuration. Figure 3 reports the fatigue curves constructed on the basis of the obtained experimental data in terms of initial strain level (strain of the undamaged specimens, i.e. the ratio between applied stress and initial stiffness modulus) versus the corresponding number of cycles to failure.

Confirming results of bitumens and mastics, experimental findings showed that the warm mixtures (WMA_L and WMA_S) guaranteed higher fatigue resistance than the control one (HMA_L), prepared at usual temperatures using limestone aggregates and plain bitumen. Moreover, the fatigue performance of the mixture containing steel slags (WMA_S) was lower than that of the corresponding material prepared with mineral aggregates (WMA_L), probably related to the higher stiffening effect provided by the finer part of slag aggregate leading to higher brittleness.

These considerations seem confirmed by the strain level corresponding to a fatigue life of 10^6 loading cycles (ε_6) which can be calculated from the fatigue curves, according to EN 12697-24. ε_6 equal to 67 μstrain was obtained for the control mixture HMA_L whereas the warm mixes WMA_L and WMA_S achieved a higher ε_6 value of 83 μstrain and 69 μstrain, respectively.

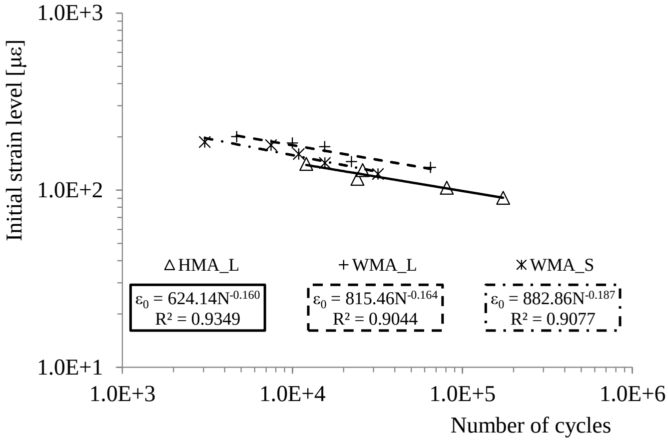

Figure 3. Asphalt mixtures fatigue test results (T = 20 °C).

Consistent results obtained for binders, mastics and mixtures confirm the key role of asphaltic component in the fatigue behaviour of bituminous mixtures.

Permanent Deformation Behaviour

The permanent deformation resistance of binders and mastics was assessed by MSCR tests carried out through the DSR equipment (Pasetto et al. 2016). Since similar considerations can be drawn based on the findings achieved at the different investigated stress levels, Figure 4 shows, as an example, the results obtained at 0.1 kPa.

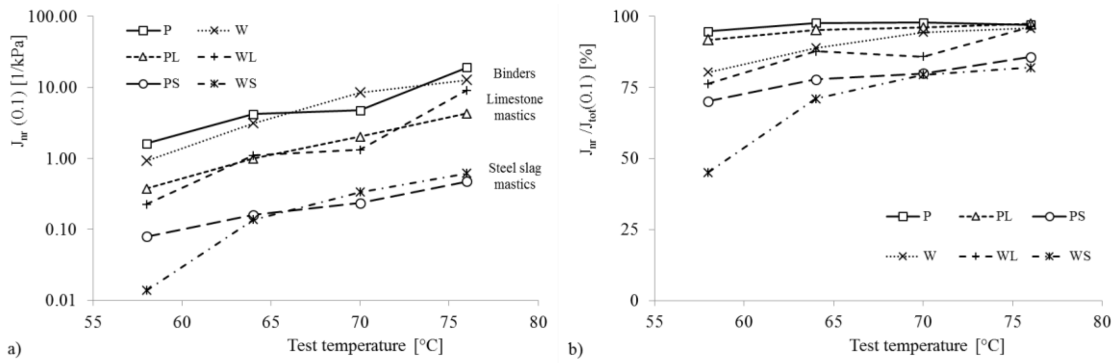

Figure 4. J_{nr} (a) and J_{nr}/J_{tot} (b) of binders and mastics at 0.1 kPa stress level.

Experimental data are represented in terms of non-recoverable creep compliance J_{nr} and ratio between J_{nr} and total compliance J_{tot}, i.e. the compliance at load removal (at the end of the creep phase), as a function of test temperature. It is worth noting that J_{nr}/J_{tot} can range from 0 to 100% for materials varying the behaviour from purely elastic (complete recovery of the accumulated strain) to purely viscous (any recovery of the accumulated strain), respectively.

Similar non-recoverable creep compliance (except for the positive effect at lower test temperature in the case of steel slag mastics) and higher resilient properties (lower J_{nr}/J_{tot}) due to the addition of the warm additive was detected. Thus, it is possible to assert that the studied warm additive was able to improve the rheological behaviour (elastic response) of selected binders and mixtures against permanent deformations. This fact is in accordance with previous studies (Morea et al. 2012, Xiao et al. 2012, Zhao et al. 2012) which demonstrated that the rutting resistance of binders prepared by adding such a chemical additive was not compromised (sometimes even improved).

According to previous studies (Liao et al. 2013, Bahia et al. 2010), MSCR test results clearly showed also the enhanced permanent deformation resistance of mastics as a consequence of the filler stiffening effect (lower J_{nr}) as well as specific physico-chemical interaction between fillers and bitumens (lower J_{nr}/J_{tot}). In this sense, the steel slag mastics demonstrated noticeable anti-rutting properties, especially when prepared with the warm binder, whereas a slight performance increase was observed in the case of limestone mastics.

As far as rutting potential of the corresponding asphalt mixtures concerns (Pasetto et al. 2015), the experimental results reported in Figure 5 (along with the error bars reporting maximum and minimum experimental data) generally show similar performance of the studied mixtures, which exhibited virtually no deformation at the end of the test (< 0.6%). It is possible to assert that neither the addition of the warm additive nor the use of EAF steel slag aggregates seemed to provide lower rutting resistance with respect to the control HMA, notwithstanding the rather reduced stiffness of such mixtures due to the less oxidative hardening of the warm bitumen occurred during specimen preparation. Since several authors (Morea et al. 2012, Mo et al. 2012, Sanchez-Alonso et al. 2013, Zhao et al. 2012) found worse rutting performance due to lower mixing and compaction temperatures, higher permanent deformation resistance could be hypothesized in case of equivalent preparation procedures, according to the results obtained on binders and mastics and to what found by Hurley and Prowell (2006).

Finally, the alleged performance decrease of WMA containing EAF steel slags, deducible from the slightly higher final strain and creep rate than the WMA_L control mixture, seems in accordance with Ameri et al. (2013) who showed a higher rutting potential of mixtures containing a fine fraction of EAF steel slag.

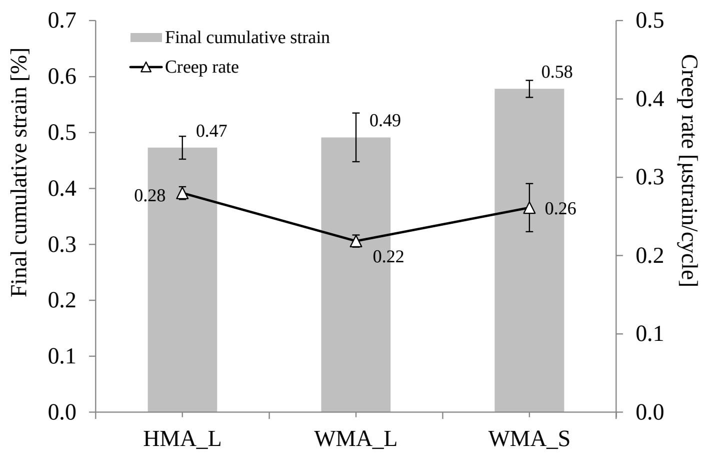

Figure 5. Repeated load axial (RLA) test results (T = 40 °C).

Conclusions

The feasibility of using electric arc furnace steel slag aggregates in warm mix asphalt mixtures has been investigated in this comprehensive study assessing midrange and high-service temperature mechanical properties (stiffness characteristics as well as fatigue and permanent deformation resistance) of bitumens, mastics and corresponding dense graded mixtures. A chemical tensoactive additive was selected as warm modifier.

The main conclusions of such research can be summarized as follows highlighting the influence of the warm technology and the slag aggregates, respectively:

- the presence of the warm chemical additive seemed to affect the elastic response of binders and mastics, improving their fatigue and permanent deformation resistance without a clear effect on stiffness properties. Accordingly, warm-mix asphalt mixtures, prepared at lower temperatures, were characterized by a reduced stiffness due to less oxidative hardening of bitumens; nevertheless, this led to extended fatigue life without affecting rutting behaviour;
- a distinct stiffening effect (mechanical filling reinforcement and physico-chemical interactions) was provided by EAF steel slag filler, enhancing stiffness and permanent deformation properties but reducing fatigue resistance of mastics. Similarly, the influence of lower mixing and compaction temperatures of the warm mixtures on stiffness, fatigue and rutting behaviour mainly hid the contribution (positive or negative) due to the presence of EAF steel slag aggregates. In particular, the potential higher stiffness and rutting resistance of steel slag mixtures are limited whereas the possible lower fatigue resistance is positively counterbalanced.

Overall, the studied warm-modified materials containing steel slag seemed able to assure equal or even enhanced mechanical response in the laboratory than the control hot materials. This can be ascribed to the effective interaction between the selected warm technology and artificial aggregates. However, further specific studies addressing low temperature behaviour and moisture resistance should be carried out as well as field validation should be promoted. Moreover, similar studies changing the warm chemical additive should be performed to generalize the obtained findings.

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