STEEL SLAG AS VALUABLE AGGREGATE IN ECO–FRIENDLY MIXTURES FOR ASPHALT PAVEMENTS

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ABSTRACT

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 this sense, the possible use of steel slags for construction applications (including road pavements) has a strategic importance 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. The environmental sustainability of asphalt mixtures prepared with steel slags can be further enhanced adopting the so-called Warm Mix Asphalt (WMA) technology. In fact, WMA is an asphalt concrete modified with additives that can be produced and applied at lower temperatures than the traditional Hot Mix Asphalt (HMA), thus reducing energy consumption, gas and fume emissions. Given this background, the paper illustrates a part of a wide research study aimed at verifying the utilization feasibility of steel slags in warm asphalt concretes. In particular, midrange and high-service temperature properties as well as water susceptibility of warm mixtures containing steel slags were assessed in the laboratory. The warm modification was performed using a chemical tensoactive additive, whereas slags were taken from a metallurgical plant equipped with an electric arc furnace (EAF). A WMA prepared with only natural aggregates was also studied for comparison purpose. The performance characterization was carried out through both static and cyclic laboratory tests. The results mainly showed that asphalt mixtures prepared combining chemical warm technology and EAF steel slag aggregates demonstrate promising field applicability.

INTRODUCTION

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 this sense, the possible use of steel slags for construction applications (including road pavements) has a 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. Slag is a waste product derived from the metallurgical manufacturing processes that results in a quite variable composition depending on the original ferrous/non-ferrous ores and the production technique from which is generated. In particular, Electric Arc Furnace (EAF) slag is widely diffused in several countries throughout the world, with million tons produced every year (Motz and Geiseler, 2001; Jullien et al, 2010; Piatak et al, 2014). It is generated from iron melted scrap impurities, during steel production processes inside the electric arc furnace and is generally characterized by a lower content of free magnesium and calcium oxides than other steel slag types. EAF large availability and physical-mechanical properties (high roughness, shape, hardness and specific weight) make it suitable to be used as aggregate in civil constructions and often utilized in road pavements (Emery, 1984; Asi, 2007; Yildirim and Prezzi, 2011; Yi et al, 2012; Piatak et al, 2014). In this sense, several literature studies reported improved mechanical properties and durability of asphalt mixtures thanks to the use of EAF steel slag aggregates (Pasetto and Baldo, 2010; Pasetto and Baldo, 2011; Pasetto and Baldo, 2012; Oluwasola et al, 2016; Sayadi and Hesami, 2017). Indeed, some drawbacks have been also reported due to the use of such material in road pavements. As an example, steel slag could manifest volumetric instability and volume increase with water because of the presence of unstable phases in its mineralogy (Emery, 1984; Sofilic et al, 2010; Yildirim and Prezzi, 2011) (even if it has been demonstrated that the use of steel slag in asphalt mixtures could limit the potential expansion). Thus, an aging period (at least 2-3 months) prior to its use is advisable to minimize subsequent volumetric changes due to oxidation (Wu et al, 2007; Sorlini et al, 2012). Furthermore, different studies demonstrated that the release of pollutants by leaching is not negligible (Sofilic et al, 2010; Sorlini et al, 2012) (however, it generally meets environmental requirements established in different countries). Otherwise, the environmental sustainability of asphalt mixture can be further enhanced thanks to the combination of recycled/waste materials and the warm technology. Moreover, chemical warm modification could be a successful way to enhance the chemical affinity between bitumen and steel slag (low bitumen-EAF compatibility was evinced in a previous study by Pasetto et al, 2015). Warm Mix Asphalt (WMA) is a cleaner asphalt concrete characterized by lower production and application temperatures (100–140 °C) than traditional Hot Mix Asphalt (HMA), which requires high production temperatures (>150 °C). Although reduced 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 (Mo et al, 2012; Morea et al, 2012; Zhao et al, 2012; Sanchez-Alonso et al, 2013; Pasquini et al, 2015), WMA represents a consolidate literature topic and a quite diffused technology. According to wide literature part (D’Angelo et al, 2008; Capitao et al, 2012; Rubio et al, 2012; Kheradmand et al, 2014), warm mix asphalt can be obtained by using organic (wax), chemical or foaming additives achieving relevant environmental benefits (reduced energy consumption, gas and fume emissions) and/or some economic/operational advantages (lower production costs, longer hauling distances and extended construction periods). Chemical additives represent the most recent WMA technology usually consisting of a package of products (emulsification agents, surfactants, polymers, additives and adhesion promoters). These additives 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; 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). Several experimental studies seem to confirm that chemically additived warm mix asphalts are characterized by slightly higher workability than the corresponding HMAs (Hurley and Prowell, 2006; Sanchez-Alonso et al, 2011; Oliveira et al, 2013; Pasetto et al, 2015; Sol-Sanchez et al, 2016). Given this background, the paper herein deals with an experimental characterization aimed at assessing performance of warm mix asphalt containing EAF steel slags in comparison with a limestone aggregate WMA, particularly in terms of stiffness, fatigue resistance, rutting potential and moisture susceptibility.

MATERIALS AND TEST METHODS

Materials

Asphalt mixtures were obtained in the laboratory utilizing a warm binder achieved modifying a traditional plain binder (35/50 penetration grade) with a commercial viscous liquid chemical additive (dosed at 0.5 % by weight of the binder, according to the producer recommendations). Bitumen and additive were blended with a portable equipment operating at high stirring rates at temperature of 150 °C. Basic properties of the studied binders can be found elsewhere (Pasetto et al, 2016). Two types of dense graded asphalt mixtures were prepared combining the warm binder with crushed limestone aggregates (mix hereafter coded WLM) and EAF steel slags (mix hereafter named WSM). WLM was produced with total utilization of limestone aggregate whereas WSM included also steel slags (40 % EAF steel slag by total weight of aggregate). Steel slags filler was excluded since it is known that higher specific weight of slag could negatively affect material's transportation costs (Washington State DOT, 2015). Main physical and mechanical properties of utilized aggregates are shown in Table 1 whereas chemical composition of limestone and EAF steel slag are given in Table 2.

Table 1. Basic physical and mechanical properties of limestone and EAF slag

Property	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/cm3	2.71	2.74	2.75	2.76	3.90	3.89	3.80
Los Angeles coeff.	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	%	-	-	-	78.0	-	-	92.0

With the purpose to ensure similar coating of mixes and reduce the variables accounted during the laboratory comparison, materials were prepared taking into account the different specific gravities of aggregates and maintaining constant the volumetric proportion within gradations and bitumen contents. Thus, WLM mix was previously designed with a skeleton fulfilling typical technical specifications for wearing courses and a bitumen content of 5.5 % (resulted after a preliminar mix design). Then, WSM was mixed using an equal bitumen content of about 15 % by volume, which corresponds to a 4.9 % content by weight of aggregates. Table 3 presents the used fractions gradations for WLM and WSM mixtures.

Table 2. Chemical compositions of studied aggregates

Oxide content, %	Filler type	
	Limestone	Steel Slag
MgO	2.50	3.65
Al_2O_3	1.00	9.30
SiO_2	3.34	13.02
CaO	52.71	29.60
TiO_2	-	0.35
Cr_2O_3	-	4.03
MnO	-	5.09
FeO	0.39	32.84

Table 3. Design volumetric mixture gradations and binder contents

Sieve, mm	Passing, % (volumetric)	
	WLM	WSM
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, % (volumetric)	14.8	14.9

Compactions were carried out through 100 gyrations of a Superpave gyratory compactor, assuming a target of 3 % air void content and producing 150-mm diameter cylindrical specimens. Later, specimens for laboratory tests (with approximate heights of 65 mm) were realized sawing the compacted samples.

Test methods

As anticipated, experimental characterization was planned to assess materials performance in terms of stiffness, fatigue resistance and rutting potential, particularly with the purpose to identify the contribution of steel slag in warm asphalt mixes. Moisture susceptibility was then evaluated through indirect tensile strength ratio. The assessment of stiffness characteristics was achieved by non-destructive Indirect Tensile Stiffness Modulus (ITSM) tests performed at the temperature of 20 °C through a dynamic equipment (according 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 WLM and WSM mixtures, applying five load pulses in strain-controlled mode. A suitable load actuator applied the load pulses while the corresponding horizontal deformation was measured through two linear variable displacement transducers mounted opposite one another in a rigid frame clamped to the specimen. A rise time (time for applying the load from zero to load peak) of 124 ms and a target peak horizontal deformation of 5 µm were selected according to standard. The Poisson’s ratio was assumed equal to 0.35. Fatigue resistances were evaluated with repeated Indirect Tensile Fatigue (ITF) tests through a dynamic equipment (according to the British standard BS DD ABF), applying cyclic load pulses with a repetition period of 1.5 s in stress-controlled mode along the vertical diameter of the specimens. ITF tests were executed at 20 °C with a rise time of 124 ms, with the application of five different stress levels from 300 kPa to 500 kPa, in order to construct the fatigue curves (by regression analysis of data, using a power law). Five repetitions for each mixture were executed, assuming as fatigue failure criterion the number of cycles corresponding to the complete fracture of specimens. Experimental data were finally arranged in bi-logarithmic plot reporting the initial horizontal tensile strains as a function of the number of cycles to failure and thus obtaining the fatigue lines. Confined Repeated Load Axial (RLA) tests were carried out to evaluate rutting potential of materials (EN 12697-25/Method A). Three replicates for each mix were executed at 40 °C after a conditioning period of at least four hours at the selected temperature. Confinement was reproduced loading the 150-mm diameter cylindrical specimens with an upper plate having a diameter of 100 mm (the "ring" of the material not directly loaded simulated the confining action replicating field conditions). 3600 cyclical loading pulses with a block-pulse 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. Complying the European standard, rutting potential was estimated 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. Finally, moisture susceptibility of mixtures was estimated with the calculation of indirect tensile strength ratio – ITSR (EN12697-23) which represented the parameter decrease of wet conditioned samples with respect to un-conditioned dry ones. Dry and wet ITS tests were executed at 25 °C. Conditioning procedure was performed according to ASTM D4867/D standard: cylindrical specimens were exposed to a single freeze-thawing cycle constituted by a first phase of cooling (-18.0 ± 2.0 °C for at least 15 hours) and a second phase of soaking in water bath at the temperature of 60.0 ± 1.0 °C for 24 hours.

RESULTS AND DISCUSSION

Concerning mixture stiffness, modulus results are presented in Table 4 along with the corresponding standard deviations. It can be observed that the inclusion of EAF steel slag hard aggregates led to a positive slight increase in stiffness modulus, similarly to that found by other researchers (Motz and Geiseler, 2001; Pasetto and Baldo, 2011; Pasetto and Baldo, 2012; Yi et al, 2012; Ameri et al, 2013). Moreover, stiffness values resulted satisfactory with respect to typical technical specifications. In addition, it has to be remembered that WSM mix was prepared without specific mix-design (utilizing that of WLM in order to avoid the introduction of supplementary variables). Thus, specific mix-design for EAF mixture could suggest further improvements in stiffness with respect to that of the control one.

Table 4. Indirect tensile stiffness test results at 20 °C

Mixture	Mean ITSM, MPa	Std. dev., MPa
WLM	4865	390
WSM	5161	469

Figure 1 reports the fatigue curves constructed on the basis of the obtained experimental data carrying out stress-controlled dynamic tests in indirect tensile configuration. It is plotted 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. According with literature (Goli et al, 2017), performance of the steel slag mixtures (WSM) were found to be slightly lower than that of the corresponding material prepared with mineral aggregates (WLM), probably because of the higher stiffening effect provided by the finer part of slag aggregate (i.e. 0/4 mm) that led to higher brittleness of the bituminous mortar. These findings 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 (EN 12697-24). A ε_6 value equal to 69 µstrain was obtained for the WSMs, whereas warm mixes WLM achieved a higher ε_6 value (83 µstrain).

Rutting potential results are shown in Figure 2. Generally, it is possible to assert that, despite the addition of EAF steel slag aggregates, all mixtures exhibited virtually no deformation (<0.6 %) at the end of the test (i.e. the test was partially unable to cause substantial damage to differentiate mixture performance). However, WSM exhibited slightly greater permanent deformations (higher final strain and creep rate) than those of WLM. This seems to be in accordance with other researches that reported higher rutting potential in the case of EAF steel slag presence in asphalt mixtures (Ameri et al, 2017). Otherwise, as previously anticipated, a specific mix-design could eventually suggest further improvements in warm mix performance.

With respect to the moisture susceptibility of mixes, Figure 3 exposes ITSR (ratio between indirect tensile strength before and after samples conditioning through a wet freeze-thawing cycle). It is interesting to note the comparable dry ITS value between the tested mixtures, but also the slight decrease in durability for EAF steel slag one (lower ITSR). This can be ascribed to the above cited low chemical bitumen-slag affinity, due to the lower alkalinity (i.e. CaO/SiO_2 ratio) of slag responsible of weaker adhesion, cohesion and bonding strength (Pasetto et al, 2015). Otherwise, ITSR values always resulted satisfactory, since literature reported that tensile strength ratios less than 70 % indicate moisture susceptible mixtures, whereas ITS ratios greater than 70 % denote substantial resistance to moisture damage (Kennedy and Anangos, 1984).

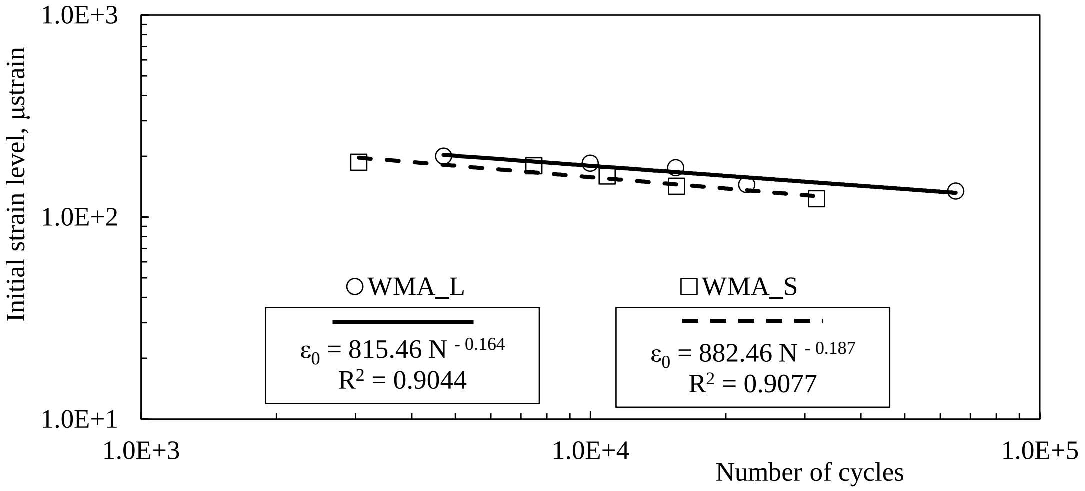

Figure 1. Fatigue curves at 20 °C

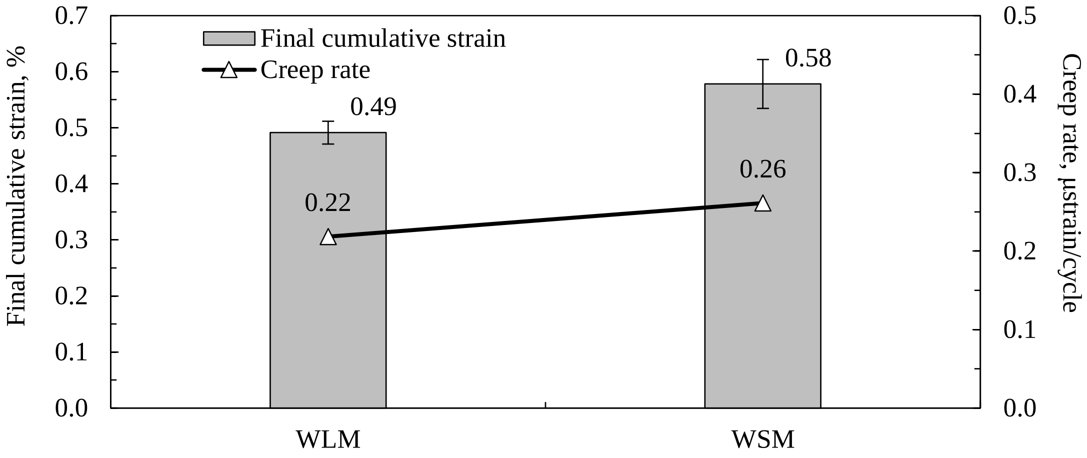

Figure 2. Rutting potential at 40 °C

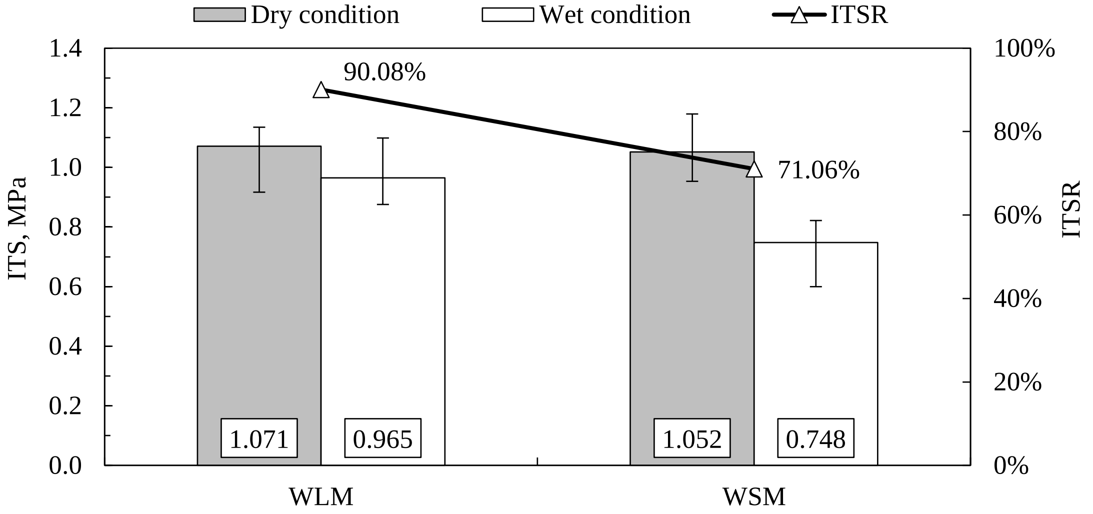

Figure 3. Moisture susceptibility – Indirect tensile strength ratios at 25 °C

CONCLUSIONS

The present paper concerns the feasibility of utilizing electric arc furnace steel slag aggregates in chemical modified warm asphalt mixtures. The main conclusions of such research can be summarized as follows:

- EAF steel slag aggregates lead to a positive increase in stiffness modulus of WMA, probably because of its higher physical-mechanical properties (high hardness, roughness and angularity);
- fatigue resistance of WMA mixture with slags is slightly lower than that of the corresponding material prepared with mineral aggregates (WLM), probably because of the higher stiffening effect provided by the finer part of slag aggregate (i.e. 0/4 mm) that led to higher brittleness of the bituminous mortar;
- despite a slightly increase in rutting potential, the EAF steel slag addition in WMA guarantees negligible final permanent deformations and creep rate;
- slightly higher moisture sensitivity for EAF-WMA mixture was evinced. This can be probably ascribed to low chemical bitumen-slag affinity, due to the lower alkalinity of slag responsible of weaker adhesion, cohesion and bonding strength. Otherwise, moisture ratios always result satisfactory.

Overall, performance of warm mixtures resulted satisfactory with respect to typical technical prescriptions. In addition, specific mix-design for chemically additived mixes with steel slags (not performed to avoid the introduction of supplementary variables) could suggest further performance improvements with respect to the limestone control ones. Based on these promising findings, further specific studies for the execution of dynamic tests at laboratory scale, as well as field testing and validation, should be promoted.

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