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Sustainable solutions for road pavements: A multi-scale characterization of warm mix asphalts containing steel slags

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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. Warm Mix Asphalt (WMA) is a valid option in this regard. In fact, WMA is a cleaner asphalt concrete that can be prepared and compacted at lower temperatures than the traditional Hot Mix Asphalt (HMA). Moreover, the inclusion of recycled/waste materials in WMA can further enhance its environmental sustainability. 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 tensioactive 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. Binders, mastics and mixtures were studied in terms of stiffness, fatigue and permanent deformation resistance by carrying out dynamic tests on unaged and long-term aged samples. The results showed that cleaner 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. In particular, the influence of lower mixing and compaction temperatures of the warm mixtures on stiffness, fatigue and rutting behaviour seemed to hide the contribution (positive or negative) due to the presence of EAF steel slag aggregates. In fact, the potential higher stiffness and rutting resistance of steel slag mixtures were limited whereas the possible lower fatigue resistance was positively counterbalanced.

1. Literature background

1.1. Warm Mix Asphalt

Warm Mix Asphalt (WMA) is an 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). Thus, the use of WMA can be really considered a cleaner practice since considerable reduction of energy consumption and gas and fume emissions can be achieved. In this sense, Blankendaal et al. (2014) calculated, through a life cycle assessment (LCA), a 33% lower environmental impact when a WMA is used instead of the corresponding HMA. In particular, a LCA simulation carried out by Rodriguez-Alloza et al. (2015) predicted that WMA technology is able to reduce greenhouse gas (GHG) emissions by 20%. Similarly, Sol-Sanchez et al. (2016) measured a decrease of CO_2 and NO_x during the monitoring of a real plant production of WMA and corresponding HMA aimed at the construction of a specific trial section. They also reported a reduction of energy consumption of about 35% during the in-plant production of WMA compared with HMA (17% reduction taking into account the whole manufacturing process of raw materials and mixtures). Almeida-Costa and Benta (2016) estimated similar results (9÷18%

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energy reduction) in terms of heat energy required to produce a given volume of HMA and corresponding WMA, taking into account different warm technologies.

It is worldwide recognized that organic waxes, chemical additives or foaming technologies are today used to obtain WMA (Capitao et al., 2012; D'Angelo et al., 2008; Kheradmand et al., 2014; Rubio et al., 2012) leading to very different final properties of the corresponding asphalt mixtures (Capitao et al., 2012).

Warm chemical tensioactive additives are currently gaining popularity. The surfactants included in such products should reduce the friction between aggregates and bitumen (characterized by lower surface tension) guaranteeing the same workability of HMA at lower temperatures (Capitao et al., 2012; D'Angelo et al., 2008; Kheradmand et al., 2014; Mo et al., 2012; Morea et al., 2012; Xiao 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; Mo et al., 2012; Oliveira et al., 2013; Pasetto et al., 2015; Sanchez-Alonso et al., 2011; Sol-Sanchez et al., 2016).

However, reducing mixing and compaction temperatures could also lead to possible drawbacks that mostly depend on the warm technology used. Authors generally report issues related to greater moisture susceptibility, coating and bonding problems, reduced interface shear strength and higher rutting potential (Capitao et al., 2012; Hurley and Prowell, 2006; Kheradmand et al., 2014; Mo et al., 2012; Morea et al., 2012; Pasquini et al., 2015; Rubio et al., 2012; Sanchez-Alonso et al., 2013; Zhao et al., 2012). In particular, the higher rutting potential, essentially due to a reduced hardening of the bitumen during mixing, transportation and compaction at lower temperatures, is generally counterbalanced efficaciously when organic waxes are used as warm additive. Otherwise, a specific aggregate gradation can be adopted to enhance the rutting resistance of the mixture. The possible reduction of shear strength at the interface between the warm upper layer and the underneath cold asphalt surface can be limited by accurate construction operations (e.g. preparation of dry, regular and clean laying surface; use of high-properties asphalt materials as tack coat, etc.). Finally, issues related to a prospective lower adhesion between warm aggregates and binders should be tackled by adopting adhesion promoters (such additives are generally included within chemical warm products).

1.2. 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. 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 and it is classified based on the type of furnace used.

The inclusion of recycled/waste materials, such as steel slags, can further enhance the environmental valence of WMA by converting a waste (slag) into a valuable resource (Ferreira et al., 2016). Thus, construction applications using steel slags (pavements included) noticeably contribute to a cleaner environment taking into account that hundreds of millions of tonnes of ferrous slag are produced worldwide annually (Piatak et al., 2014) and that reused ferrous slag may have a lower potential to negatively impact the environment. In this sense, LCA carried out by Mladenovic et al. (2015) demonstrated that the use of steel slag aggregates in asphalt mixtures can lead to lower environmental impact, even if such a positive effect decreases when the delivery distance increases due to the high particle density of slags. A 10% reduction of carbon footprint was also reported by Ferreira et al. (2016) who developed a similar LCA modelling. Similarly, a specific LCA analysis based on a real case study revealed a reduced environmental impact thanks to the introduction of recycled/marginal aggregates (reclaimed asphalt and steel slag) into asphalt mixtures (Pasetto et al., 2017).

In this research study, the use electric arc furnace (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 basic oxygen furnace (BOF) steel slag. Some researchers (Asi, 2007; Emery, 1984; Motz and Geiseler, 2001; Yi et al., 2012) affirmed that EAF steel slag can be successfully used as high quality aggregate in road pavements, thanks to its physical and mechanical properties (hardness, toughness, adhesiveness and roughness). Improved structural and durability performance of mixtures including steel slag aggregates were evidenced by recent studies (Ahmedzade and Sengoz, 2009; Oluwasola et al., 2016; Pasetto and Baldo, 2010, 2011, 2012; Sayadi and Hesami, 2017). 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).

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 their 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; Sofilic et al., 2010; Sorlini et al., 2012; Wu et al., 2007). 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).

2. Research goals and experimental approach

Based on the increasing interest in preservation and protection of natural and working environments, this research aimed at assessing the possibility of producing innovative cleaner pavement materials, such as WMA (reduced air pollutants and energy consumption) including steel slag (saved natural resources and re-used industrial waste). To accomplish this objective, a warm chemical warm-additive and EAF steel slags were selected to prepare the studied WMA mixture.

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 tensioactive 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 (Table 1). To accomplish this objective, two bitumens, four mastics and three