Valorisation of steel slag as aggregates for asphalt mixtures

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ABSTRACT: The construction industry is responsible for consuming significant amounts of raw material and causing serious environmental impacts. Natural aggregates are essential to build road pavements and their obtention in the nature causes several negative impacts. Therefore, one way to reduce their impact is to use recycled aggregates. In this work, two hot mix asphalts were studied, one with incorporation of 75% of steel slag as aggregate and another with 100% natural aggregates. Their mechanical performance was evaluated with permanent deformation and water sensitivity tests. The mixture incorporating steel slag showed higher resistance in both tests, proving that it is viable to use this waste material from metallurgical industry as an alternative aggregate for production of asphalt mixtures, reducing the extraction of new materials and saving landfill space.

1 INTRODUCTION

Taking into account the environmental concerns that the Society is facing nowadays, changes are being made to the paradigms on the importance of preserving the natural environment and minimizing the impacts. Thus, the use of recycled material for civil engineering works has increased in recent years.

International environmental regulations are becoming more rigid to preserve natural resources and reduce waste production. In Portugal, the Decree-Law no. 73/2011 (2011) provides the basis for the approval of prevention programs and sets targets for reuse, recycling and other forms of waste recovery, to be achieved by 2020. Given the importance of a strong incentive for recycling to accomplish these goals, but also with the objective of preserving natural resources, this regulation states that at least 5% of recycled materials are to be used in public works contracts.

According to Araújo et al. (2013), a conventional AC14 surf 35/50 mixture comprises about 95% aggregates and 5% bitumen. Thus, given the dominance of the aggregate in the mixture, it can be concluded that recycling of paving materials, in particular, a substitute of the aggregate, can reduce the environmental impact from mining/extraction of that natural resource and that would also lead to a reduction of cost.

One of the wastes that is being studied is the steel slag aggregate (SSA), which is derived from the steel production industry and are the most significant waste generated (more the 60% of waste generation) in this type of industrial process (Chen et al., 2018, Nascimento et al., 2018). It is estimated that Portugal produces about 400×10^3 tons of steel slag from Electric Arc Furnaces (EAF) per year (Ferreira, 2010). Thus, with the amount of waste generated, its valorisation to produce new materials should be seriously considered.

Kim et al. (2018) investigated the mechanical behaviour of Hot Mix Asphalt (HMA) using SSA. In comparison to a conventional mixture, the asphalt mixture produced with SSA showed improved performance on the rutting resistance and a higher dynamic modulus, although, the air void content was higher than that of the conventional mix.

Kara et al. (2004) studied the incorporation of steel slag in HMAs to be applied in base courses (100% SSA), binder courses (70% SSA and 30% limestone aggregate) and surface courses (50% SSA and 50% limestone) and concluded that steel slag can be used as an aggregate in asphaltic mixtures. A similar conclusion was obtained by Nguyen et al. (2018).

Martinho et al. (2018) studied the incorporation of 30% of SSA in Warm Mixture Asphalt (WMA) to decrease the energy consumed in the production process. In that study, it was observed that the Marshall Stability increased for the mixture with SSA incorporation, while the stiffness modulus reduced and fatigue resistance did not change. Thus, the author concluded that this mixture showed satisfactory results when compared to a conventional mixture. Other authors (Masoudi et al., 2017) also concluded that the incorporation of SSA in WMA mixtures is generally recommended.

The steel slag may contain free CaO and MgO. Therefore it can expand and cause problems in the presence of water, decreasing the useful life of the pavement, which may start to show early distresses (Washington State DOT, 2015).

When working with SSA, some authors recommend using a curing process in open storage for a certain time and under humid climatic conditions to remove all free CaO and MgO (Horii et al., 2015, Choi et al., 2007, Chen et al., 2018). Fakhri and Ahmadi (2017) also recommend exposing the SSA to weather agents for six months before using it in pavement applications.

Those studies show that SSA can replace a large amount of new materials, which means, a reduction on the landfill of these type of industrial wastes and the extractions of raw materials. Furthermore, their use can improve some pavement mechanical proprieties and mitigate the environmental impacts caused by the construction works.

In this study, experimental work was carried out to assess the possibility of incorporating high contents of SSA in HMA, based on a series of mechanical tests, e.g., water sensitivity and rutting resistance, in comparison to a conventional HMA produced with natural aggregates.

2 MATERIALS AND METHODS

2.1 *Materials*

As previously mentioned, two types of aggregate were used in this work. A natural granitic aggregate separated in four granular fractions; namely, powder 0/4 mm, 4/10 mm, 10/14 mm, 14/20 mm and a steel slag aggregate (SSA) divided in fractions 0/20 mm and 10/14 mm. The SSA is classified as "waste from steel slag processing" in chapter 10 of the European list of waste (OJEU, 2014), under code 10 02 01. The other materials used were a 35/50 pen bitumen, which is commonly used in Portugal and limestone filler.

The density and water absorption of each aggregate can be observed in Table 1, and the basic properties of bitumen (i.e., penetration and softening point) are presented in Table 2.

Table 1. Physical properties of aggregates used

	Density (EN1097-6)	Water absorption (EN1097-6)
	Mg/m^3	%
Granitic aggregate	2.55	0.91
Steel slag aggregate	3.13	1.40

Table 2. Basic properties of bitumen

	Penetration (EN 1426)	Softening point (EN 1427)
	0.1 mm	ºC
Bitumen 35/50	36.4	47.3

2.2 *Methods*

2.2.1 *Mix design and production of the HMA with granitic and SSA aggregates.*

Two asphalt mixtures were produced using the mentioned aggregates to be applied in a pavement base course. One of the mixtures was produced using 100% natural aggregates and the other using 75% SSA and 25% natural aggregates. According to the national specifications (Estradas Portugal, 2014), the typical mixture used in such applications is an asphalt concrete (AC 20 base 35/50), which is produced with a maximum aggregate size of 20 mm and with a particle size distribution that fulfils a specified grading envelope. In order to determine the optimum binder content, a mix design study was carried out, based on the Marshall method, according to the EN 12697-12 standard.

After producing the asphalt mixtures, testing specimens were compacted using the impact compaction method, specified by EN 12697-30 standard, for cylindrical specimens, and using the roller compactor, according to EN 12697-33, for slab shaped specimens.

2.2.2 *Water sensitivity*

One of the parameters usually used to assess the durability of asphalt mixtures is their water sensitivity. This test allows the determination of the influence of water in the loss of affinity between the aggregate and bitumen, evaluating its mechanical performance through indirect tensile strength (ITS) tests.

For those tests, two groups of specimens are conditioned in different scenarios, one group (wet) is placed in a water bath for a period of 72h at 40ºC, and the other group of specimens is kept dry, at room temperature during the same period. Then, the specimens are tested using a uniaxial testing apparatus, according to EN 12697-12 standard, to obtain the indirect tensile strength of each specimen. The ratio between the average results of the wet group (ITSw) and the dry group (ITSd) is known as the indirect tensile strength ratio (ITSR) and is the primary indicator of the sensitivity of the mixture to the presence of water.

2.2.3 *Resistance to permanent deformation*

Wheel tracking tests (WTT) were used to assess the resistance to permanent deformation (also known as rutting resistance) of the asphalt mixtures, following the procedure described in the EN 12697-22 standard (procedure B, in air). This test was carried out in the laboratory using two slab specimens with the dimensions of $30 \times 30 \times 4$ cm^3, and the test temperature is 60 °C.

The test consists essentially of repetitively passing a wheel on these slabs until 10 000 load cycles have been applied, where the wheel load is 700N, and the frequency is 0.44 Hz. The results considered are the wheel tracking slope (WTS_{air}) between the 5000th and the 10000th cycles, the proportional rut depth (PRD_{air}), and maximum rut depth (RD_{air}) at the end of the test. This test provides information on the stability of the mixture at high service temperatures, which also influences the durability of the material.

3 RESULTS AND DISCUSSION

3.1 *Mix design and production of the mixtures*

The mix design started with the analysis of the aggregates particle size distribution (according to the EN 933-1 standard) to combine the different aggregate fractions to fulfil the specified envelope and estimate the maximum amount of SSA that could be incorporated in the mixture. Thus, mixture 1 (M1) is a conventional mixture, comprising only natural aggregates and bitumen (5%), while mixture 2 (M2) was prepared with 75% SSA, 25% natural aggregates and bitumen (5%). The fulfilment of the grading envelope specified by Estradas Portugal (2014) by both M1 and M2 can be observed in Figure 1. Regarding the determination of the optimum binder content, it was obtained by performing the Marshall mix design method and the results indicated that both mixtures should be produced with a binder content of 5% (by mass of mixture).

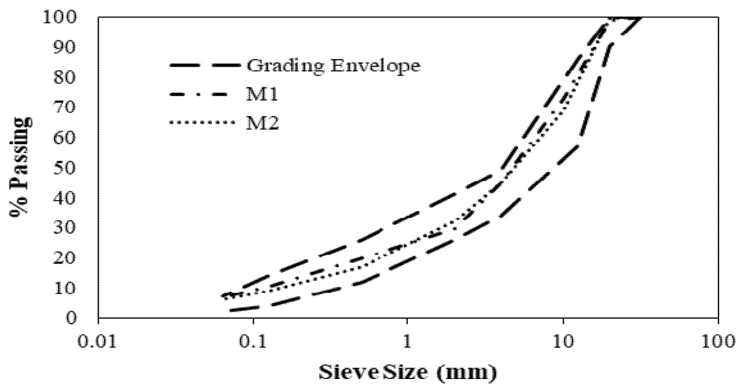

Figure 1. Particle size distribution of HMAs with 100% natural aggregate (M1) and 75% SSA (M2).

3.2 *Water sensitivity*

To study and understand the mechanical behaviour of asphalt mixtures in the presence of water, this is a significant test, since it assesses the performance and durability of the material being studied. The results of ITS and ITSR obtained in this test for both mixtures are presented in Table 3. The relation between the average air voids content of the tested specimens and the ITSR are shown in Figure 2.

Table 3. ITSR results in the water sensitivity test

Mixture	ITS dry	ITS Wet	ITSR
	kPa	kPa	(%)
M1	2936	1993	65
M2	3093	2326	75

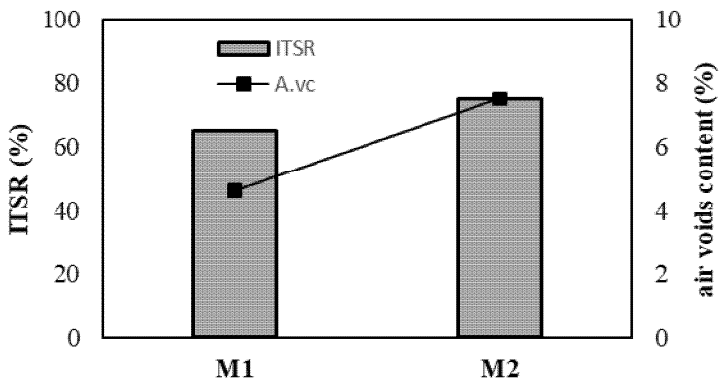

Figure 2. Results of the water sensitivity test: ITSR vs Air voids content.

When analysing the results, it is possible to observe that mixture M2 presents a water sensitivity performance slightly better than M1, as both ITS and ITSR values are higher in mixture M2.

Another important factor that usually compromises the performance of the asphalt mixtures in this test is the air voids content. This parameter is directly influenced by the com-paction of the mixture, the particle size distribution and also the porosity of the aggregates. Since mixture M1 was produced with a natural aggregate that is less porous than the SSA, it presents a lower air voids content (4.6%), in comparison to mixture M2 (7.6%). In conventional asphalt mixtures, a higher air voids content is generally associated with poorer performance in terms of water sensitivity. However, this was not the case in the present study. Mixture M2 showed a higher air void content and also a higher ITSR value, which may be explained by the better adhesion of the bitumen to the SSA aggregates, due to the higher porosity of those aggregates, which makes it more difficult to the water to disturb the bond between the binder and the aggregates.

3.3 *Resistance to permanent deformation*

The resistance to permanent deformation or rut resistance is a significant property of asphalt mixtures, namely when they are applied in locations with high service temperatures. In this study the rut resistance was evaluated by performing WTT tests on both mixtures. The results of that evaluation are presented in Table 4 and Figure 3.

Table 4. Wheel tracking test results

Mixture	WTSair	PRDair	RDair
	(Mm/10^3 cycles)	(%)	(Mm)
M1	0.11	6.34	3.48
M2	0.80	4.95	2.73

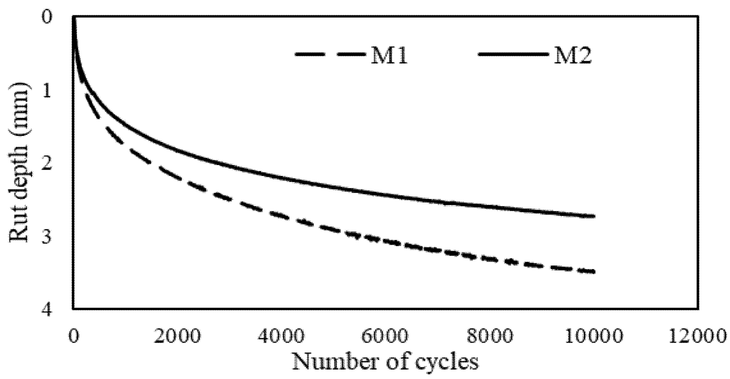

Figure 3. Rut depth evolution during wheel tracking tests.

Analysing the results presented in Table 4 and Figure 3, it can be concluded that M2 is the mixture with the greatest resistance to permanent deformation. The lower rate of permanent deformation obtained for mixture M2 (with SSA) is visible in Figure 3, where the evolution of the rut with the number of cycles is plotted.

It is worth noting that this test was carried out at 60 ºC, which is a high service temperature, since this parameter has a great influence on the deformation. Thus, it can be confirmed that mixture M2 showed a good performance when regarding the resistance to permanent deformation at high service temperatures.

4 CONCLUSIONS

The valorisation of industrial by-products or wastes results in interesting solutions to environmental problems generated by these activities, such as overfilling of landfills and depletion of natural resources. Thus, research studies in these areas are very important in order to make the activity more sustainable and to reduce the environmental impacts caused by the anthropogenic activities.

With the results obtained in this study, it can be concluded that the use of SSA in asphalt mixtures is a viable solution. Regarding the behaviour and mechanical performance of the studied mixtures, namely with respect to water sensitivity and permanent deformation. It was observed that the mixture with 75% SSA outperformed the mixture with 100% natural aggregates. Thus, the use of this type of industrial waste as an aggregate substitute in asphalt mixtures has a great potential. Regarding the other properties evaluated, it was observed that mixture M2 (with SSA) showed air void contents slightly above the limits specified for the type of asphalt mixture produced in this work. Thus, although the mechanical performance was apparently not affected by that parameter, its influence in other properties (e.g., fatigue resistance) should be further evaluated in future works.

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