The influence of processed steel slag on the performance of a bituminous mixture

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ABSTRACT: The use of recycled materials in pavements gains a wider acceptance for a more sustainable construction and rehabilitation of the transport infrastructures. An example is the incorporation of steel slag in bituminous mixtures. This paper refers to the evaluation of fatigue properties for a bituminous mixture – AC 20 base 35/50 – that include processed steel slag aggregate (SSA) in their composition. Two types of this bituminous mixture were considered: a hot asphalt mixture, incorporating 20% of SSA, and a warm asphalt mixture, with the additive Sasobit and incorporating 30 % of SSA. To compare the performance of SSA bituminous mixtures to the equivalent traditional bituminous mixture, materials were evaluated in the laboratory by fatigue tests. Repeated flexural loading on the four-point bending beam apparatus was conducted on samples to compare how the SSA affects fatigue cracking. Laboratory tests were performed according to the standard EN 12697-24. Test results are presented and they indicated, in general, that the incorporation of SSA has not impaired the fatigue behavior of the bituminous mixture. This preliminary conclusion, to be confirmed in further research, suggests that the application in pavement layers of the SSA bituminous mixture considered in this study is still possible in terms of road bearing capacity, beyond the benefit of promoting the recycle of an industrial waste.

KEY WORDS: Road pavements, Steel slag, Bituminous mixtures, Fatigue, Stiffness.

1 INTRODUCTION

The economical and environmental benefits that arise from the use of recycled materials in road construction and maintenance justify that major efforts should be made in order to have a better understanding of the behavior of these non-usual materials. So, further research is encouraged to achieve this knowledge and to contribute for a more realistic establishment of the reference values for the parameters used in the design and quality control based on the materials performance. This is the case of the use of processed steel slag aggregate (SSA), an industrial by-product, in the composition of the bituminous mixtures.

The SSA is an artificial aggregate obtained from the production process of steel and laminates. Intensive researches are being conducted in order to promote the utilization of this industrial by-product in transportation infrastructures and geotechnical constructions. This is the case of Portugal, where the two steel mills in operation have produced 300,000 tonnes of black steel slag annually in recent years. Gomes Correia et al. (2009) describe an experimental program developed recently in order to study the viability of this industrial waste for unbound granular layers purposes. In the case of bound layers, other studies are being carried out in order to study the re-use of SSA in bituminous mixtures, either in hot asphalt mixtures (Neves et al. 2011a and 2011b) or in warm asphalt mixtures (Martinho et al. (2012). Preliminary test results presented by the authors take into consideration the Marshall resistance and the affinity between aggregate and bitumen.

This paper is the main objective to present a further study concerning the influence of SSA on the performance of two bituminous mixtures. This performance was based on the resistance to fatigue, addressed by the four-point bending test on prismatic shaped specimens according the standard EN 12697-24 (CEN, 2004). The composition of all the tested bituminous mixtures was determined by the Marshall Method.

The results presented concern the stiffness modulus and the fatigue lines obtained in the fatigue tests performed at 20ºC. The discussion of the results pointed out that the influence of SSA in the resistance to fatigue of the bituminous mixtures, affording even the improvement of this property in one of the mixtures. Conclusions encourage further studies related to other performance tests, e.g. permanent deformation, and other bituminous mixtures.

2 FATIGUE STUDY

2.1 Materials

The study of the resistance to fatigue was performed on a bituminous mixture AC 20 base 35/50 with the incorporation of SSA, and using two types of materials:

- A hot mixture asphalt (AC1), incorporating 20% of SSA.
- A warm mixture asphalt (AC2), incorporating 30% of SSA.

Processed steel slag used in this experimental work is produced by the Portuguese steel industry that processes the steel slag in order to produce aggregates of various grain sizes. The 0/16 fraction, with CE marking by EN 13242 (aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction), was used in this study (Figure 1). Table 1 presents the main geometrical, physical and mechanical properties (Neves et al. 2011a). SSA exhibit high values concerning particle densities and water absorption, and reasonable geometrical properties and resistance to fragmentation.

The chemical and expansion properties of SSA, in general, are strongly depending on the technology used in the manufacturing of steel. Iron and oxides of calcium, magnesium and aluminum are the majority constituents of the SSA. Research studies have confirmed that SSA could be considered an inert material (Gomes Correia et al. 2009).

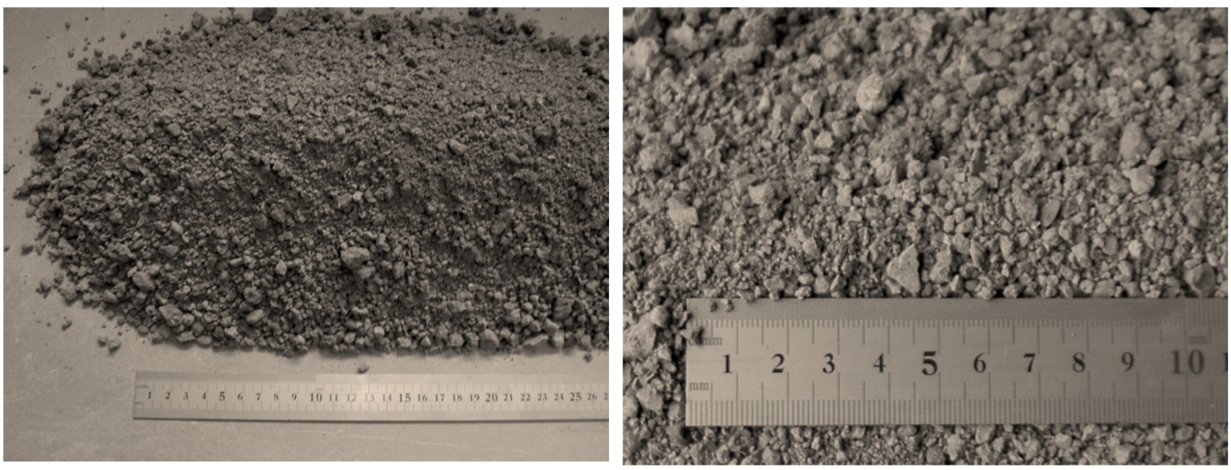

Figure 1: Processed steel slag (SSA).

Table 1: SSA properties.

Properties	Unit	Values
Flakiness index (NP EN 933-4)	%	1
Shape index (NP EN 933-3)	%	2
Sand equivalent (NP EN 933-8)	%	78
Methylene blue value (NP EN 933-9)	g/kg	0.2
Apparent particle density (NP EN 1097-6)	Mg/m^3	3.84
Particle density on an oven-dried basis (NP EN 1097-6)	Mg/m^3	3.63
Particle density on a saturated and surface-dried basis (NP EN 1097-6)	Mg/m^3	3.69
Water absorption (NP EN 1097-6)	%	1.7
Resistance to fragmentation Los Angeles (NP EN 1097-2)	---	25

The bituminous mixtures were obtained by the composition of 0/4, 4/10 and 10/20 fractions of aggregates produced from the crushing of limestone, including filler material.

An ordinary bitumen with a penetration value (25ºC) belonging the class 35/50 was used to produce the bituminous mixtures.

2.2 Bituminous mixtures

In both materials – AC1 and AC2 – the correspondent bituminous mixture composed exclusively by natural aggregates (no incorporation of SSA) was always considered, constituting an important reference to obtain conclusions. It means that, globally, four bituminous mixtures were studied:

- Hot asphalt mixture AC 20 base 35/50 without SSA (0%) (AC1_0)
- Hot asphalt mixture AC 20 base 35/50 incorporating 20% of SSA (AC1_20)
- Warm asphalt mixture AC 20 base 35/50 without SSA (0%) (AC2_0)
- Warm asphalt mixture AC 20 base 35/50 incorporating 30% of SSA (AC2_30)

The composition of the bituminous mixtures, in terms of the optimal percentage of bitumen the proportion of each fraction of aggregates (0/4, 4/10, 10/20 and filer), was obtained by the volumetric and Marshall properties. In the case of AC1_20 bituminous mixture (20% of SSA), the composition has resulted from a previous study performed in order to achieve an optimization of the quantity of the SSA in this type of bituminous material, based on Marshall and affinity between aggregate and bitumen tests (Neves et al. 2011a, 2011b).

As already referred, the SSA was used with the grade 0/16.

Warm asphalt mixtures – AC2_0 and AC2_30 – are also constituted by the solid organic additive designated by Sasobit, responsible for the significantly reduction of the viscosity of the base bitumen at mixing and compaction temperatures. These bituminous mixtures are composed with 4% of this additive (Martinho et al. 2012).

Figure 2 presents the global grading curves of the mix of aggregates for the bituminous mixtures. It could be observed that the grain size distributions are very similar, excepting AC2_30 mixture.

Marshall specimens were compacted using the impact compactor by applying 75 blows to each side. Marshall tests were performed according the standard EN 12697-34 (CEN, 2004). Density, volumetric and Marshall results are presented in Figure 3: stability, flow, quotient, bulk density, porosity and voids in mixed aggregates (VMA). Despite a scattering of values and some uncommon behaviors in certain percentages of bitumen, in general, it could be observed that bituminous materials with SSA exhibit a similar behavior to the corresponding reference material. However, the presence of the SSA has incremented significantly the stability and the flow of the mixtures. Bulk density is also higher for the bituminous mixture with SSA (AC1_20 and AC2_30), as expected because of the higher density values for SSA (Table 1). It is also observed that hot asphalt mixture (AC1_0) and warm asphalt mixture (AC2_0) doesn't exhibit always the same behavior.

Based on an overall analysis of results (Figure 3), the final composition of the bituminous mixtures was defined as it is summarized in the Table 2: aggregates and bitumen.

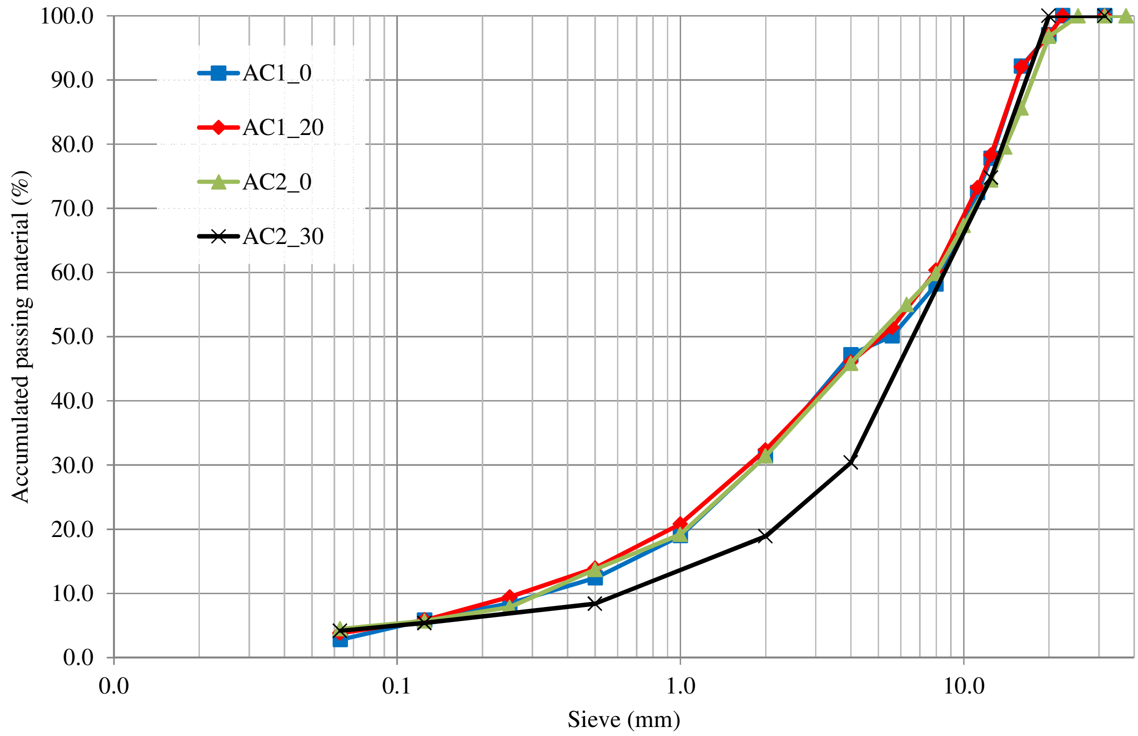

Figure 2: Grading curves of the bituminous mixtures.

Table 2: Bituminous mixtures composition.

Bituminous mixtures		Aggregates (%)					Bitumen (%)
Description	Designation	SSA	0/4	4/10	10/20	Filler	
Hot Asphalt Mixture	AC1_0	0	45	22	30	3	4.7
	AC1_20	20	30	20	25	5	4.7
Warm Asphalt Mixture	AC2_0	0	48	20	32	0	4.5
	AC2_30	30	35	0	30	5	4.5

2.3 Fatigue test conditions

Different procedures to determine resistance to fatigue are available according the standard EN 12697-24 (CEN, 2004). In Portugal, four-point bending test is in general the most common procedure used to obtain fatigue lines of bituminous mixtures. Fatigue tests were based on the normative Annex D of the EN 12697-24 (CEN, 2004). Four-point bending tests were performed on prismatic shaped specimens resulting from sawing of slabs compacted by a small cylinder compactor. Tests were conducted at a 20ºC temperature (Freire et al. 2006). For all the materials, a total of 18 specimens were tested. Figure 4 shows two prismatic specimens of AC1 mixture, where it is marked a SSA particle observed in the mixture. In

Figure 5, it is shown the device used in this research and a detail of a specimen clamped in position at the four points of the frame.

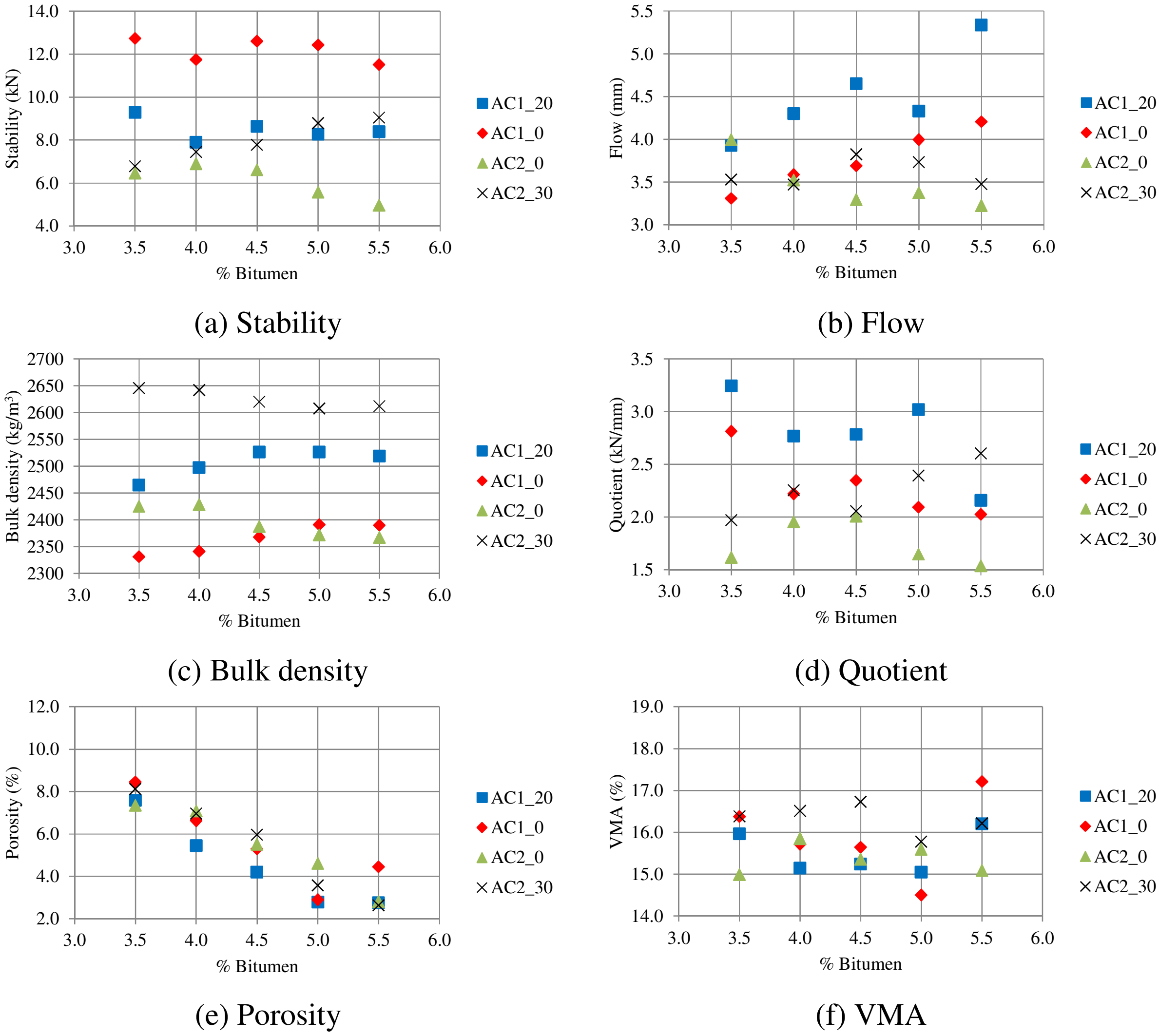

Figure 3: Marshall results.

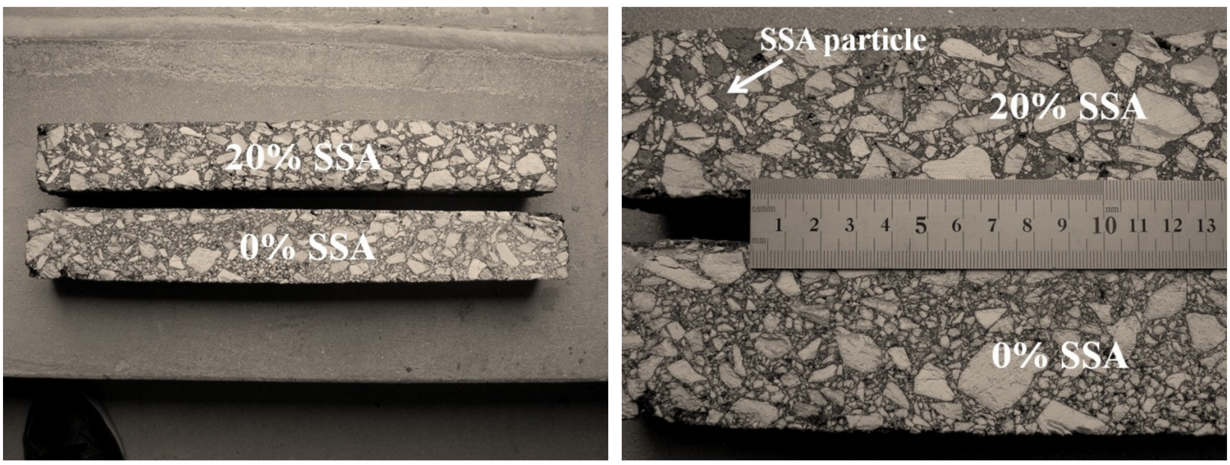

Figure 4: Prismatic shaped specimens.

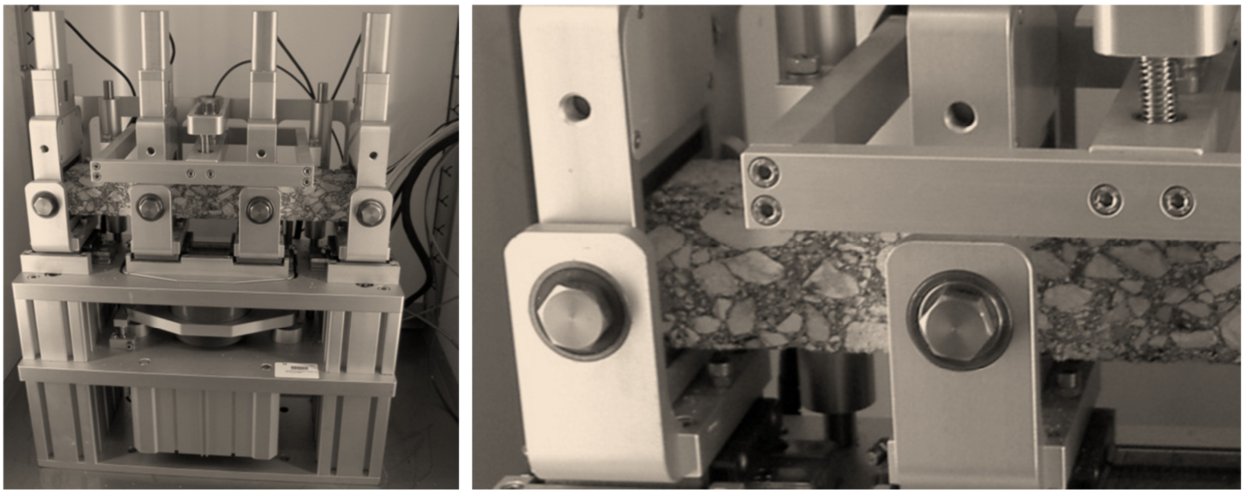

Figure 5: Four point bending device.

In order to study the stiffness modulus, previous tests were performed for a strain of 50 µm/m with a sinusoidal form and a range of nominal frequencies of 1, 3, 5, 10, 20 and 30 Hz and subsequently again at 1 Hz. At each frequency, a number of 100 repetitions was applied.

The fatigue tests were carried out, in general, using three levels of controlled strains: 150, 250 and 400 µm/m. These strains were applied with a sinusoidal waveform signal characterized by amplitude of the strain value and frequency of 10 Hz. As criteria of failure, it was adopted the number of load applications when the stiffness modulus decreased to half its initial value. For each level of strain, a set of 6 specimens were tested.

3 RESULTS AND DISCUSSION

As referred, the results from the laboratory fatigue tests conducted in the conditions described above concern stiffness modulus and fatigue lines at 20ºC.

Table 3 summarizes stiffness modulus results (average values for all test specimens) for frequencies 1, 3, 5, 10, 20 and 30 Hz. In the case of 1 Hz, the values indicated correspond only to the first frequency applied. In general, it could be observed, as expected, that the stiffness modulus is a function of the test frequency and it increases with the increasing of the frequency. In general, the results are very similar but for the AC2 material, the presence of the SSA has influenced the results: slightly lower moduli occurred for the same bituminous mixtures with SSA (AC2_30) tested at the same frequency.

Table 3: Stiffness modulus at 20ºC.

Frequency (Hz)	Stiffness modulus (MPa)			
	AC1_0	AC1_20	AC2_0	AC2_30
1	4272	4037	2567	1863
3	5506	5712	3703	2764
5	6149	6629	4355	3308
10	7247	7891	5273	4011
20	8335	9321	6291	4804
30	8890	10191	6971	5460

Resistance to fatigue of bituminous mixtures is represented by fatigue lines that consist in relationships between the applied strains and the number of load cycles to achieve the criteria of failure. Figure 6 represented the fatigue lines for all the bituminous mixtures, where it could be concluded directly that fatigue behavior is very similar for all the materials. In the particular case of the AC1 material, it could be said that he presence of the SSA has resulted in a slightly improvement of the resistance to fatigue, but not very significant.

Figure 6 also presents the law equations and the coefficient of correlation which are considered reasonable values for all the fatigue laws.

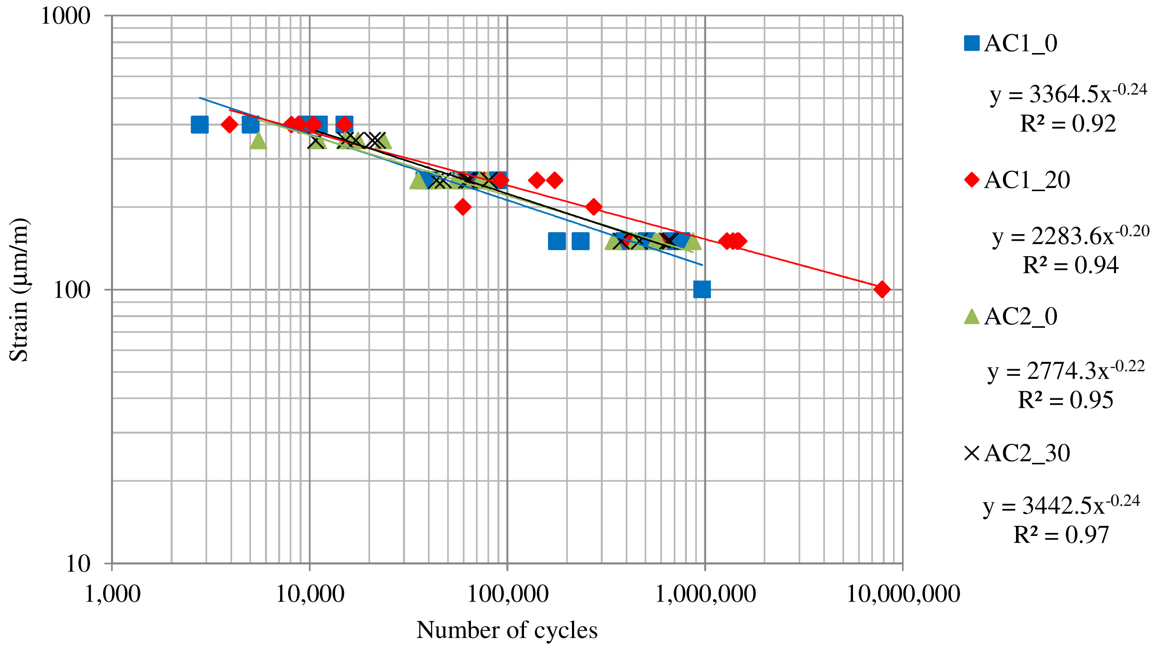

Figure 6: Fatigue lines at 20ºC.

Table 4 contains the strain values interpolated by the fatigue lines at hundred thousand (ε_5), one million (ε_6) and 10 million (ε_7) number of cycles. Fatigue lines shown in Figure 6 and the strains given in Table 4 confirm, in general, that the presence of the SSA has not influenced the resistance to fatigue, i.e. resistance to fatigue was not impaired. Obviously, this behavior should be confirmed in other materials and test conditions (e.g. temperature).

Table 4: Strains at hundred thousand (ε_5), one million (ε_6) and 10 million (ε_7) number of cycles.

Strains (µm/m)	Bituminous mixtures			
	AC1_0	AC1_20	AC2_0	AC2_30
ε_5	212	239	220	225
ε_6	122	152	133	130
ε_7	70	97	80	75

4 CONCLUSIONS AND RECOMMENDATIONS

The experimental research presented in this paper, in order to study the influence of processed steel slag on the performance of a AC 20 base 35/50 bituminous mixture, has consisted, firstly, in Marshall tests to achieve the final composition of the materials and, secondly, in resistance to fatigue tests to obtain stiffness modulus and fatigue lines, that could be useful for design purposes of bituminous layers where the resistance to fatigue is an important criterion of failure.

The main following conclusions concerning the influence of the presence of SSA in the bituminous mixtures can be taken:

- The stability has increased in Marshall tests, but the correspondent increase of the flow could not be desirable.
- Bulk density of bituminous mixtures strongly increases.
- The stiffness modulus obtained in the pre-tests of fatigue, for the range of frequencies applied (1 to 30 Hz) is similar.
- The resistance to fatigue was not significantly changed and, at least, was not impaired.

The behavior of the bituminous mixtures observed in Marshall tests for the case of SSA included in the material was not clear in some cases. This was a difficulty in order to establish the optimum bitumen content.

In conclusion, the preliminary results presented in this paper encourage the continuation of the investigation concerning the performance of bituminous mixtures with the incorporation of SSA.

In addition to a further development of the work presented in this article, extended to more test specimens and conditions, the research concerning the influence of processed steel slag on the performance of bituminous mixtures should also involve, as already referred, other performance tests, e.g. permanent deformation, and others bituminous mixtures. Taking into account the chemical properties of SSA, it should be important to study the behaviour of the materials during their life cycle. Aging study could be recommended for this purpose.

It is also very important to study the performance of these materials in pilot scale or field trials. A better understanding of the influence of SSA in the life-cycle of the bituminous mixtures could be achieved, when the materials are applied in structural layers of the pavement submitted to traffic and climatic real conditions.

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