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Evaluation of the use of steel slag in micro surfacing

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ABSTRACT
Micro surfacing (MS) is a type of bituminous coating frequently applied in the surface of pavement structures in order to prevent the occurrence of common distress and/or as a maintenance procedure. Micro surfacing has successfully been used in some states of Brazil as well as in many countries all over the world. Local aggregates used for micro surfacing composition are in some cases scarce and/or expensive. Therefore, the main objective of the present research is to verify the technical, financial and environmental viability of using steel slag aggregate (SSA) in micro surfacing applications. To reach the main objective, a procedure was developed in four steps. In the first step it was made the characterization of conventional (granitic) and alternative aggregates (steel slag) and polymer-modified emulsified asphalt. In the second step, mix design, surface abrasion resistance and setting time tests were performed. In the third step, the micro surfacing mechanical performance was analyzed using a laboratory traffic simulator to observe accumulated permanent deformation; surface wear; micro texture and macro texture. In the fourth step, a comparative study of costs concerning micro surfacing application using conventional mineral aggregate (MS-MA) and alternative aggregates (MS-SSA) were performed. The laboratory procedure results indicated that the steel slag studied has the potential to be used in micro surfacing applications with more rutting resistance and better durability. The cost analysis showed for medium transport distances bigger than 60 km, the MS-SSA will be cheaper than MS-MA solution.

1. INTRODUTION

Micro surfacing (MS) is one of the techniques applied to pavement preventive maintenance, with good results when used in heavy traffic highways. The MS is considered an evolution of the slurry seal (SS), but with differences in the specifications of the asphalt emulsion type, of the aggregates, the use of sand is not allowed in MS applications for example, and the durability is better than SS (FHWA, 1994).

According to Hein *et al.* (2003) and from the association of asphalt emulsion manufacturers (AEMA), the MS can be employed as an alternative to hot asphalt mixture to correct pavement rutting. However, according to Ceratti and Reis (2011), it is possible to correct rutting problems with depths up to 40mm. It has also been mentioned that in this case the time of the traffic release is about 3 hours.

Several MS studies have been developed concerning fundamental aspects of mix design, implementation and application of effective benchmarking and comparison to other maintenance techniques. The studies of Santo and Reis (1999), Vale (2003), Vale and Suzuki (2004), Reis (2005), ABEDA (2010), Castro (2011) and Ceratti and Reis (2011) can be highlighted in Brazil. Regarding the international literature, the studies on MS are well established, among which it can be mentioned FHWA (1994), Hick *et al.* (1999), Austroads (2003), Hein *et al.* (2003), Bae and Stoffels (2007), CALTRANS (2009), Broughton *et al*. (2012), Ulhman (2010), NCHRP (2010), ISSA A-143 (2010), Apparoa *et al*. (2013), and Ji *et al*. (2013).

The MS is composed of 90-95% of aggregates. In the way to propose sustainable alternative to pavement preventive maintenance, there is availability of several residues that can be better investigated to be used in the paving area in order to promote the environmental preservation. According to Loiola (2009), certain types of alternative aggregates have been applied to paving. One of the materials with potential to be employed in substitution of mineral aggregates is the steel slag aggregate (SSA).

Although the use of SSA has already been carried out in the pavement community since the 1990s as granular material for base and subbase and as aggregate for asphalt layer applications, studies that analyze the behavior of SSA in MS applications are still incipient in Brazil. SSA is a product that has been gaining prominence in the pavement area, since its use has been well researched for road purposes. However, as cited by Rohde (2002) SSA has in the presence of oxides such as CaO and MgO in its composition. These oxides have an expansive feature due to chemical reactions. Care should be taken to check whether the SSA is already cured before being applied to road works. According to Teixeira *et al*. (2019) the SSA expansive effects could be minimized too when combined with other asphalt mixture components.

Over the years, several studies were developed with the aim of making feasible the use of SSA in road works. In Brazil, the first use of this by-product in the paving in 1986, in the state of Espírito Santo, where the SSA was used over a stretch of more than 100 km (Silva e Mendonça, 2001). Other authors that studied the use of SSA in granular layers were Rohde (2002), Parente *et al*. (2003), Santos Neto (2007), Cavalcante *et al.* (2010) and Pires *et al*. (2019). In addition, DNIT (2008) also studied SSA as an aggregate in base and sub-base layers. The use of SSA in hot-machined asphalt mixtures was also investigated and the results showed that it has the potential to replace the conventional aggregate in such blends as can be seen in Castelo Branco (2004), Pedrosa (2010), Silva (2010) Tavares (2012) and Teixeira *et al*. (2019).

In Brazil, the use of SSA for thinner coating type Surface Treatment (ST) is more recent, dating from 2007 and started by Loiola (2009) and Pereira (2013). The results showed that the SSA also had a satisfactory performance and an experimental pavement section was built as reported by Rocha (2011). It is important to study new materials such as SSA concerning bituminous wearing course applications since local aggregates used are in some cases scarce and/or expensive. In the case of ST, the required characteristics are sometimes difficult to obtain in the local aggregates, for example the Los Angeles abrasion test resistance is sometimes over the limit (40 %).

Vasconcelos (2013) evaluated the behavior of double surface treatment (DST) and cape seal, having performed a comparison using SSA and conventional aggregates. However, the use of SSA in MS has been insufficiently researched, so studies should be more developed in this area. In this paper, the main objective is to verify the technical, financial and environmental viability of using SSA in MS applications.

2. MATERIALS AND METHODS

For the experimental program execution, a mineral aggregate (MA) considered of excellent behavior for application in MS and a SSA were collected. The procedure was divided into the following steps: characterization of materials; MS mix design; evaluation of the coating behavior with the use of an LCPC (laboratory central des ponts et chaussées) type laboratory traffic simulator and financial analysis of the studied aggregates.

The characterization tests carried out, including those specific for the steel aggregates were: Particle size distribution (DNER-ME 083/98); Shape index (DNER-ME 086/94); Los Angeles Abrasion (DNER-ME 035/98); Methylene blue (NBR 14949/2003); Sand equivalent (DNER – ME 054/94). To complement the SSA characterization, the environmental tests of solubilization (NBR 10006/2004) and leaching (NBR 10005/2004), as well as the evaluation of its expansion (DNIT - ME 113/2009) were necessary.

a) Metal disk (mold) b) Aggregates homogenization c) Water addition

d) Emulsion addition e) Performing the mixture f) Mold filling

g) Surface regularization h) Mold removal i) Cured specimen

Figure 1. WTAT specimen molding procedure (adapted from Castro, 2011)

The asphalt emulsion used in the study was CCS-1P (Cationic Controlled Setting Polymer Modified) and it was characterized by the following tests: Saybolt Furol Viscosity (NBR 14491/2000); Sedimentation (DNER - ME 006/2000); Screening (NBR 14393/99); Particle charge (NBR 6567/2000); Residue by evaporation (NBR 14376/2007); Determination of pH

(NBR 6299/99); Penetration (DNER - ME 003/99); Elastic recovery (DNER - ME382/99) and Softening point (NBR 6560/2008).

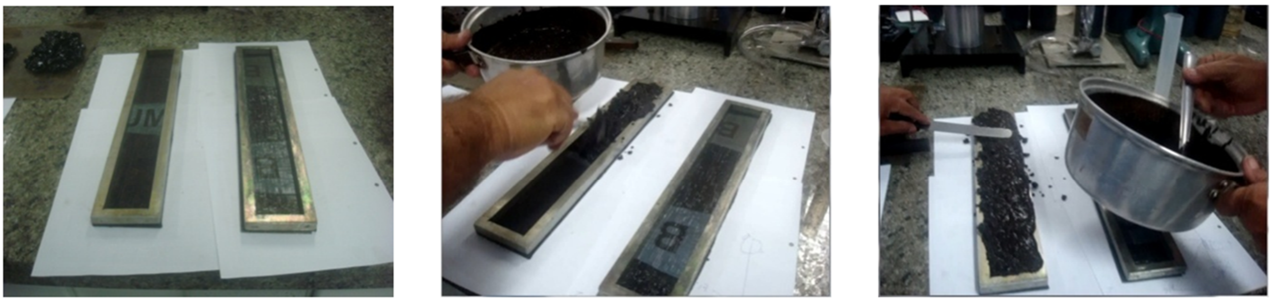
In order to perform the MS mix design, the Wet Track Abrasion Test (NBR 14746/2001) was performed with four different binder content for each type of aggregate studied. The binder contents, water, cement and additives vary according to the mix design, defined in the laboratory. The mold used for the WTAT is a 279 mm diameter metal disc. The molding procedure followed the same methodology adopted by Castro (2011) and is shown in Figure 1.

In the WTAT, the specimen is measured and then the minimum binder content is defined. The test starts by weighing the specimen and after that they are kept immersed in water for one hour. At the end of this immersion period, the specimen are subjected to WTAT test through the equipment for 5 minutes. At the end of WTAT test, the specimen is washed to remove all loose material and the specimen is again taken to the oven at a temperature of 60° C until reaching constant weight. The result is obtained by calculating the weight loss suffered by the specimen subjected to WTAT test. The DNIT (DNIT - ES 035/2005) establishes a maximum loss of 538 g/m^2. This process is illustrated in Figure 2.

a) Specimen cured b) Test performance c) Specimen tested

Figura 2. WTAT procedure (adapted from Castro, 2011)

The other test to be performed to determine the binder optimum content for the MS is the sand adhesion by the LWT machine (NBR 14841/2002). The molding sequence is shown in Figure 3. The mixing process is also carried out in the same way as mentioned in WTAT procedure.



a) LWT mold b) MS dump c) Molded specimens

Figura 3. Molding procedure for LWT (adapted from Castro, 2011)

The sand adhesion test by the Loaded Wheel Tester (LWT) allows the exudation measurement of the specimen and determines the maximum binder content to be employed in the MS. The procedure is divided into two parts. In the first part the MS specimen is subjected to a load of 56 kg during 1000 cycles on the LWT machine. The second part consists in measuring the sand adhesion to the specimen which varies according to the binder rate employed. The process is illustrated in Figure 4.

a) Specimens cured   b) 1000 cycles performed   c) Specimens after 1st part

d) 100 cycles (2nd part)   e) Sand adhesion

Figura 4. Conducting the LWT test (Castro, 2011)

The Mixture Adhesion Test (NBR 14757/2001) verifies the binder-aggregate compatibility. This standard, based on the US ISSA TB-114/1990, determines the water resistance of residual asphalt adhered to the aggregate. The result is obtained by visual analysis, an area that remained covered by the asphalt residue.

The Minimum Mixing Time Determination Test (NBR 14758/2001) was performed to calculate the additive content to be employed in the MS and consists in measuring the emulsion set time by performing a laboratory mix. The standard establishes a minimum time of 120 seconds for the initiation of the process of emulsion set. If the measured time is lower, it is necessary to add an amount of additive to reach the time of 120 seconds. However, technicians and specialists in MS, as well as Ceratti and Reis (2011), indicate that the laboratory mixing time should be between 180 and 300 seconds, thus ensuring adequate time for emulsion disruption in field applications. The time considered in this research was 240 seconds.

The MS laboratory behavior was measured by analyzing the surface wear (NBR 14746/2001) and the cure time for the traffic release (NBR 14798/2002) of MS specimens molded at the optimum design level. The cure time test consists of measuring the pull-out resistance of aggregates on a surface of a MS specimen during its curing process. The samples were molded and tested at 30 min, 60 min, 90 min, 120 min and 150 min times. In each period, it was obtained the torque value. The molding sequence is shown in Figure 5.

According to specification concerning the time of 30 min, the minimum torque value accepted is 12 kg.cm, has indicated that the cure occurs in a satisfactory way. For the time of 60 min, it is expected to obtain a torque with a value greater than 20 kg.cm, minimum acceptable value to occur the release to traffic. The procedure sequence is illustrated in Figure 6.

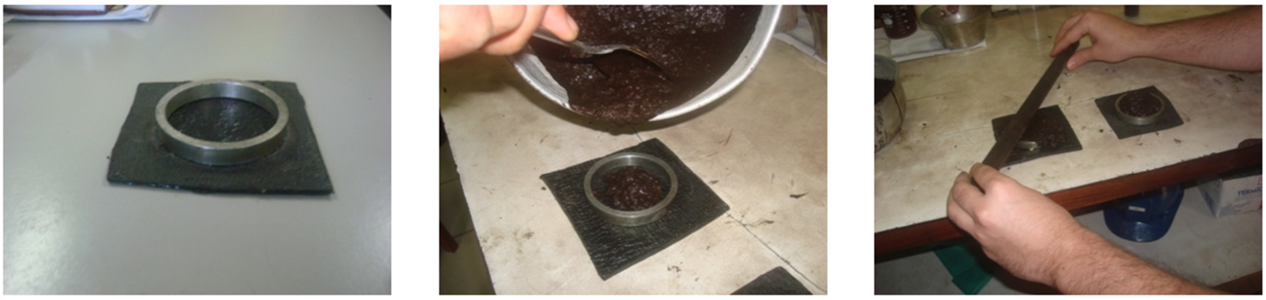
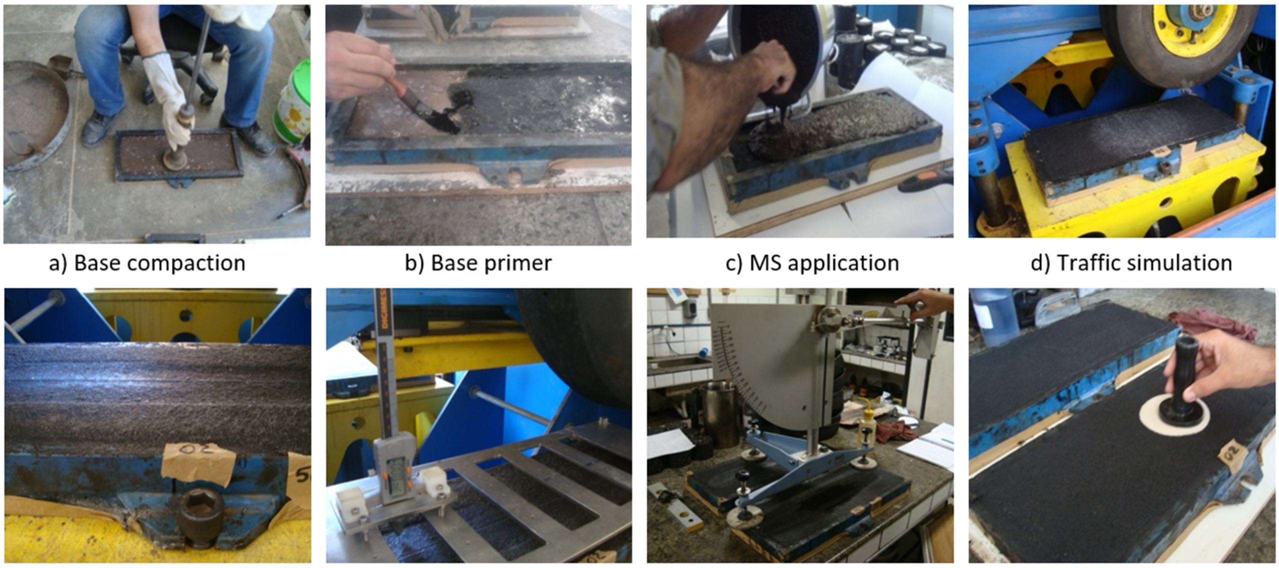

a) Cohesion test b) MS dump c) Surface regularization

Figura 5. Molding procedure for cohesion test (adapted from Castro, 2011)


a) Torque adjustment b) Torque application (90º) c) Specimen decompression

Figura 6. Conducting the cohesion test (adapted from Castro, 2011)

This research also evaluated the MS behavior under the action of the small-scale laboratory traffic simulator following the French standard guidelines NF P98-253-1 (AFNOR, 1991). In order to eliminate variables that could interfere in the analysis of results, it was chosen to use the methodology developed by Vasconcelos (2013) as shown in Figure 7. The aspects observed in the simulator test were: accumulated permanent deformation; surface wear; micro texture and macro texture. The macrotexture was measured by the Sand Patch Test (ASTM-E-965-96) and the micro texture was analyzed by the British Pendulum Test (ASTM-E-303-93).


a) Base compaction b) Base primer c) MS application d) Traffic simulation

e) Rutting with 500 cycles f) Rutting measurement g) British pendulum test h) Sand patch test

Figura 7. Stages of the molding, simulation and measurement of the properties of the MS in the simulator LCPC

According to NF P98-253-1, the rutting measurement must occur in specific positions marked on the test plate and the recommended load application is 500 kg for hot mixes. Vasconcelos (2013) used the small traffic simulator to evaluate cold mix asphalt pavements designed for low-traffic. The author mentioned that for the loading proposed by the standard led the plates to rupture during the first 100 cycles.

However, the mentioned author chose to use a load of 75 kg where it was possible to evaluate the surface wear and rutting along the cycles. For this research, the same load magnitude was adopted, and it was possible to make a comparison of the MS behavior with the DST and Cape Seal studied by Vasconcelos (2013). The rutting measurement readings were performed at 100, 500, 1000, 3000, 5000, 7000 and 10000 cycles.

The financial feasibility of using alternative materials studied in this paper was verified through the application cost (U$$/m^2) based on DNIT referential cost system (SICRO). The binder cost was defined according to National Petroleum Agency of Brazil (ANP) referential table.

3. RESULTS PRESENTATION

3.1. Characterization of materials

In order to select the grain size, it was decided to use the materials included in band II DNIT specifications for MS (Figure 8), which is the most adopted particle size distribution range used by the Brazilian road agencies. The results are shown in Table 1 and met the requirements of current specifications. Specifically, for the SSA, the type used in this study was iron slag and it is important to mention that they were cured for 8 months with water injections and the percentage of slag on MS with SSA was 100%. However, it was not possible to use the slag size distribution from the steel industry, so it was necessary to build a grain size curve in laboratory.

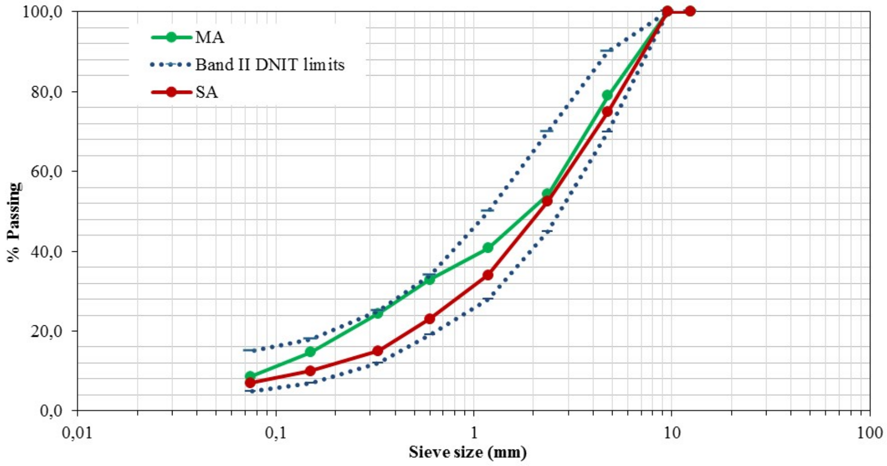


Figura 8. Grain size curve of selected aggregates

According to the specification limits, both aggregates studied in this research attend the required standard limits to be used for MS applications. It is important to note that the Los Angeles abrasion test resistance of alternative aggregate was a little bit over the limit (40%) while the result obtained for SSA was only 17 %. DNER-ME 262/94 specifies that the SSA should not have an expansion value greater than 3 %. For cured iron slags low expansion results are expected. Therefore, the SSA can be used without causing damage to the coating.

Table 1 – Summary table of the aggregates characterization

Tests	MA	SSA	Standards	Limits
Shape Index	0.64	0.96	DNER-ME 086/94	Close to 1
Los Angeles Abrasion (%)	40.8	17.0	DNER-ME 035/98	40
Methylene Blue (mg/g)	1.5	2.0	NBR 14949/2003	max 7 (granite) 10 (basaltic)
Sand Equivalent (%)	66.2	83.0	DNER-ME 054/94	Min 60
Expansion (%)	Not applicable	0.02	DNIT-ME 113/2009	Max 3
Leaching and Solubilization	Not applicable	Class II	NBR 10005/2004 NBR 10006/2004	Class II (non-hazardous inert)

Table 2 – Results of asphalt emulsion CCS-1P characterization

Tests	1ª	2ª	3ª	Specification	Standards
Saybolt-Furol Viscosity, s, at 50ºC	35	41	39	70 max.	NBR 14491/2000
Screening, 0,84mm, max (%)	0.01	0.01	0.01	0.1	NBR 14393/99
Particle Charge	Positive	Positive	Positive	Positive	NBR 6567/2000
Residue by Evaporation (%)	63.6	62.4	63.2	62.0	NBR 14376/2007
Penetration at 25ºC, 100g, 5s	58	61	60	45-150	DNER-ME 003/99
Elastic Recovery, 20cm, 25ºC (%)	73.0	71.0	71.7	< 70	DNER-ME 382/99
Softening Point (ºC)	70	72	67	< 55	NBR 6560/2008
Sedimentation (%)	0.8	0.7	0.8	< 5	DNER-ME 006/2000

3.2. Mix Design and Analysis of MS Laboratory Behavior

The Mixture Adhesion Test (NBR 14757/2001) verified aggregate-emulsion compatibility. Then it was possible to verify that, through the MS sample visual inspection for both aggregates, over 90 % of the area was covered and it was considered satisfactory. For both aggregates, the binder content was 10.8 %.

The Minimum Mixing Time Determination was performed for the SSA as well as for the MA. The emulsion set time measured was greater than 300 seconds and higher than the minimum time limit. It was not necessary for the use of additives. It is emphasized that the incorporation of additives in the MS mixtures is only intended to delay the emulsion set time. Their use does not imply improvements in the wear surface and reduction concerning traffic time.

The results obtained regarding the surface wear for the two aggregates studied reached the limits established in the current specifications, and the SSA presented a lower wear when compared to the MA. This can be justified since MA Los Angeles abrasion test results (40.8 %) are higher than SSA (17.0 %). Regarding the traffic time release, the torque values obtained for the time of 60 min are above the standard specifications. This way, the traffic can be released within one hour without causing any damage to the quality of the coating just applied. Table 3 summarizes the results obtained in the mix design and analysis of the laboratory behavior performed for the two groups studied.

Table 3 – Summary table for MS mix design

Results	MA	SSA	Specification
Adhesion	Satisfactory	Satisfactory	Satisfactory
Additive Content (%)	0.0	0.0	-
Binder Content (%)	10.8	10.8	> 10.5
Medium Wear (g/m^2)	252.2	195.3	< 538
Release to Traffic (h)	1.0	1.0	1.0

It should be (Table 3) noted that the binder content for AS, which has a higher specific weight was the same used for AM. However, these percentages are in relation to the weight of the aggregate used. As for costs, since there is a higher aggregate rate for AS one can affirm that this will result in a higher consumption of binder.

3.3. Analysis of the MS Submitted to the Laboratory Traffic Simulator

Before starting the rutting test, the application rate in kg/m^2 of MS was calculated. For the case of MS-MA, considering a thickness of 1.5 cm, the application rate was 29.83 kg/m^2. For the SSA, this rate was higher and equal to 38.33 kg/m^2. Following the same procedure adopted by Vasconcelos (2013), the MS plates were submitted to the traffic simulator. Figure 9 shows the evolution of the deformation suffered by the MS with MA and SSA.

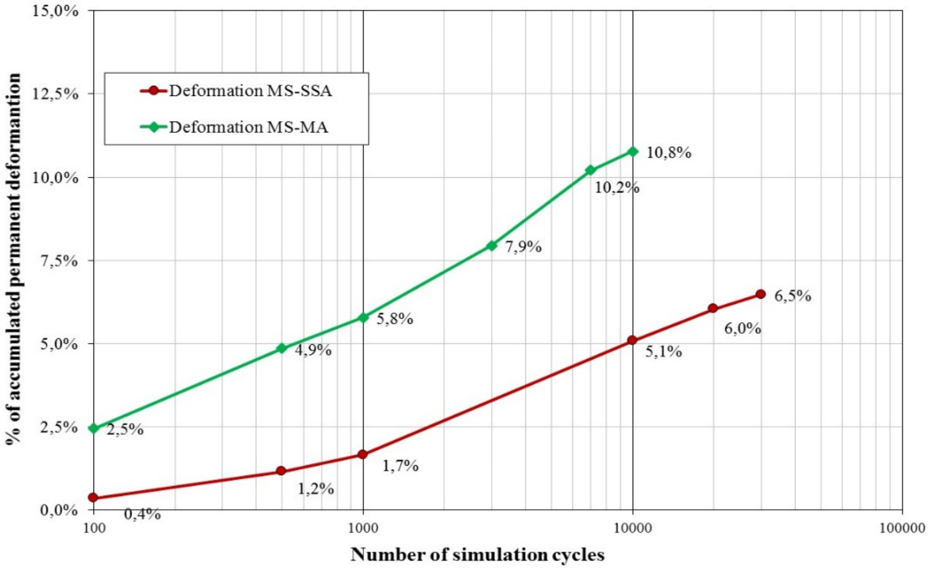


Figure 9. Accumulated permanent deformation for both aggregates

By analyzing the plate deformation, it can be seen that the rutting when the SSA is used as an aggregate is about 50% lower for 10000 cycles when compared to MA, using the same criterion adopted by Vasconcelos (2013). Also, in this situation, it was decided to continue up to 30000 cycles only with the SSA, in order to analyze its behavior when submitted to a larger traffic volume, certifying its better behavior to permanent deformation.

Based on this, it can be seen that with the MS-SSA is more rutting resistant. In relation to surface wear and aggregate detachment, none of these phenomena was observed during the simulation, indicating a suitable involvement of the aggregates by the binder and a good behavior of the coating when the two types of aggregate were used.

Table 4 – Summary of laboratory traffic simulator trials

Results	MS–MA	MS–SSA	Specification
Application rate (kg/m²)	29.83	38.83	-
Texture depth (mm) before	0.78	0.90	0.60 ≤ TD ≤ 1.20
Texture depth (mm) after	0.61	0.70	0.60 ≤ TD ≤ 1.20
Pendulum test value before	76	81	≥ 45
Pendulum test value after	53	59	≥ 45

Regarding macro and micro texture parameters, the results reached the current specifications for the studied aggregates. Table 4 shows the results summary obtained for the granulometric combinations submitted to the simulation cycles. After conducting the simulator procedure, it was found that the SSA in the MS presented better behavior when compared to the MA.

3.4. Financial Evaluation

The financial evaluation was presented in US$/m^2. The cost compositions were based on DNIT referential cost system (SICRO) and the binder cost was based on National Petroleum Agency of Brazil (ANP) referential table. The value for each solution was calculated according to the mix design parameters and application rates.

Considering Medium Transport Distances (MTD) about 60 km for MA and analyzing the final application costs in US$/m^2, the application cost of MS with SSA was about the same compared to the MA solution. For MTD bigger than 60 km, the MS-SSA will be cheaper than MS-MA solution. Table 5 presents the cost comparison between applying the MS with different aggregates studied.

Table 5 – Comparison of MS application costs

Fees/Costs	MS–MA	MS–SSA
Aggregate rate (kg/m²)	26.90	35.04
Binder content in relation to the weight of the aggregate (%)	10.8	10.8
Binder amount (kg/m²)	2.90	3.78
Binder cost (without transport) ($/m²)	1.80	2.34
Material cost + labor (without transport)	0.63	0.42
Material transport cost (60 km)	0.35	-
Final cost ($/m²)	2.78	2.76

Therefore, considering regions with SSA suppliers located nearby roadway maintenance services, the MS-SSA application can be cheaper than MS-MA, because in this case it will be not necessary to purchase MA and spend more with transportation. Moreover, its behavior in wear and in the rutting test was better, concerning superior durability. This tendency is also observed in other studies that use SSA. It should be emphasized that this higher durability should be tested in real-scale experimental sections, so that other factors that may alter coating performance can also be analyzed.

4. CONCLUSIONS

The main objective of the present research was to verify the technical, financial and environmental viability of using steel slag aggregate in Micro Surfacing applications. The aggregates and emulsion characterization, the mix design process and the MS behavior were evaluated through laboratory procedures and a comparison with the MA results was made. This paper also evaluated the results obtained in laboratory traffic simulator.

A cost analysis was made with the use of different types of aggregates. The results obtained showed that the SSA studied has the potential to be used in MS. The SSA was considered viable in the technical and environmental scope. Regarding the costs involved in the use of the SSA, it is important to mention that MTD can be decisive in choosing SSA instead of MA.

It should also be noted that the MS with SSA has better wear resistance and presented the smallest deformations in the laboratory traffic simulator. In addition, road safety standards have all been reached. This improved MS behavior with SSA can extend the useful life of the pavement, making the cost-benefit ratio of this alternative a long-term advantage.

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