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Development of Slurry Surfacing with Electric Arc Furnace Slag for Pavements with Friction Problems

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Abstract: Pavement maintenance is an essential activity for maintaining the quality of the pavements. It is common for the ageing pavement to present problems of friction, so a proper solution must be provided. In this work, electric arc furnace slags are incorporated in slurry surfacing to provide adequate friction with this technique. The electric arc furnace slag was studied with physical, chemical, and mechanical tests to evaluate its suitability in the formation of the bituminous mixture. At the same time, different groups of samples were made with increasing percentages of bitumen emulsion and slag as coarse aggregate, determining the wear of the different families and the cohesion. The results reflected the excellent characteristics of the electric arc furnace slags, and an optimal combination of materials (slag, aggregate, water, and bitumen emulsion) could be obtained to develop slurry surfacing applicable to important traffic roads. This provided a use for the electric arc furnace slag in which its mechanical properties were used and a sustainable bituminous mixture with excellent characteristics and respectful of the environment was developed.

Keywords: slurry surfacing; electric arc furnace slag; bitumen emulsion; friction; sustainability; pavement

1. Introduction

Pavement maintenance is one of the primary activities within road infrastructures. It is common to design and build pavements with high performance and large investments that are not subsequently cared for in their useful life. On the other hand, the pavement is an element that suffers throughout its service life, whether due to the loads of heavy traffic, vehicles, or exposure to the elements [1,2]. Consequently, the characteristics that it had at the beginning of its construction have not been maintained unchanged during time. Maintenance work is mandatory.

These maintenance tasks are not always carried out properly. The low availability of investment, the non-technical considerations in the investment, and the passage of time mean these tasks are not developed [3]. However, the lack of adequate maintenance in the pavement encourages the deterioration produced to grow exponentially, so the cost of these tasks in subsequent years will increase rapidly.

In response to this problem, it is essential to develop maintenance activities that extend the useful life of the pavement, are carried out regularly, and do not entail a high economic cost.

Furthermore, pavement ageing manifests itself in different ways [4], not always similar, and depending to a large extent on the materials used and the execution process followed. A very aged pavement will display surface cracks with irregular shapes and will imply structural exhaustion of the pavement. However, it is also common to find a pavement that does not have these defects but does have a very low coefficient of friction. In other words, the continuous passage of vehicles wears the surface layer and causes the macrotexture and microtexture of the pavement to lose the necessary friction of vehicle tires [5]. Consequently, this decreases coarse aggregate microtexture significantly and creates an unsafe surface for traffic [6], even more so in the rainy season.

This fact is mainly due to the aggregates used in the bituminous mix that, because they do not have resistance to polishing, because they do not have an adequate resistance, or simply because, for an extended period of use, have lost the surface roughness to condition a comfortable and safe running surface.

The solution to this type of problem is found in slurry surfacing, mainly. There are other types of techniques to correct the problem of friction, but the ease of execution of this technique, the rapid openness to traffic, and the manufacture of the asphalt mix at ambient temperature [7] make it an excellent solution [8].

Slurry surfacing is an asphalt mixture containing mainly aggregates (coarse aggregate in high proportion), bitumen emulsion, water, and additives. Its extension is fast about on the pavement performing the standardized mixing, extension, and compaction by the same machinery. In turn, the opening to traffic is usually in a short period of time, thus avoiding interaction with traffic and safety problems.

This type of mixture, with an important percentage of coarse aggregate of a maximum size of 8 mm or 11 mm, achieves a layer on the surface of the pavement of reduced thickness (the thickness being approximately equal to the maximum aggregate size) and with high friction between the vehicle (tire) and the pavement. It is therefore an ideal solution for the recovery of pavements that have lost part of their roughness or friction but still have sufficient structural characteristics to support the loads of traffic. In other words, it is neither a structural nor a resistant layer; however, if there were a series of cracks in the aged pavement, this treatment could maintain the union of the crack and, in turn, prevent water from penetrating into the pavement causing major problems. In addition, the cost of this surface treatment is much lower than that of a traditional bituminous mixture, due to its reduced thickness and the fact that it is not necessary to mill the most superficial layer of the pavement for its execution.

Therefore, this surface treatment obviously needs an aggregate of sufficient quality to maintain the friction during the continuous passage of vehicles, and adequate adhesion to the emulsion so that no problems of raveling occur [9]. The aggregate used has usually been of a siliceous nature to obtain greater abrasion and resistance.

In line with the above, and in order to find sustainable solutions that reduce the environmental impact [10], reduce greenhouse gas emissions, and reduce waste deposition in landfills [11,12], this study uses electric arc furnace slag as the surface treatment. It should be noted that the construction sector, and more specifically the pavement sector, is the sector with the greatest environmental impact [13]. This is mainly due to the huge dimensions of the infrastructures, the high volumes of virgin materials used, and the manufacturing processes that are not very optimized, as most bituminous mix manufacturing plants employ fossil fuels to heat the mix with the associated greenhouse gas emissions.

Electric arc furnace slag is a waste product of the steel industry in the manufacture of steel from scrap [14]. This process has different phases, mainly fusion and refining, which are developed in different furnaces and achieve different effects on the material. The first stage of fusion takes place in the electric arc furnace, where oxidation (for the elimination of manganese and silicon), dephosphorization, and the formation of slag, in which impurities are accumulated, take place. This slag is removed, cooled with water, and called as electric arc furnace slag. On the other hand, in the subsequent refining stage, the ladle furnace slag is produced, which is not used in this work.

Analyzing the surface treatment developed in this research according to objective criteria and relating to sustainability and production economy, a series of advantages of the present project are obtained in comparison with traditional techniques. According to environmental criteria, the reduction in the consumption of raw materials, such as aggregates, through the use of electric arc furnace slag means a significant reduction in greenhouse gas emissions and environmental impact. This is due to the fact that the work of extracting aggregates is reduced, with the reduction in emissions from machinery and the impact caused by the producing quarries. On the other hand, the deposition of industrial waste such as slag in a landfill is avoided, providing a new use for it. At the same time, the implementation of a technique with bitumen emulsion makes it possible to avoid heating the bitumen mixture to high temperatures, thus reducing the consumption of fossil fuels. Finally, its direct execution without the need to mill the existing pavement makes it possible to reduce machinery and emissions. In short, and under the aforementioned objective criteria, it can be stated that the use of this research has a positive influence on sustainability and the environment.

On the other hand, and according to economic criteria, the use of a waste in a significant percentage implies a reduction in the cost of the technique, since the price of the slag is lower than that of a quality siliceous aggregate. The conformation of the bituminous mixture is carried out with more economical equipment than those currently used for mixtures with bitumen, and there is also a reduction in fuel consumption due to the non-heating of the mixture. In addition, the extension is fast on the pavement, reducing the costs of operators and machinery, as well as traffic cuts. All these factors have a significant influence on the lower cost of carrying out this research as opposed to traditional techniques.

For the success of this surface treatment, it is essential to achieve two fundamental objectives: on the one hand, that the electric arc furnace slag shows adequate resistance characteristics [15], and in addition, that the emulsion does not have adhesion problems with the slag and that the process is carried out correctly. These parameters are quantified in this study and are evaluated with different tests.

Based on the above, this paper presents the study of the incorporation of electric arc furnace slag in high-friction surface treatments. For this purpose, the slag was chemically analyzed, obtaining its chemical composition; its grading was analyzed, to study the percentage of silica sand in addition to fit the grading curve within the grading envelope defined by the standard; and the physical and mechanical characteristics of the electric arc furnace slag and the addition silica aggregate were evaluated. Once the suitability of the materials was evaluated, different samples were manufactured with increasing percentages of emulsion until acceptable results were obtained. With the results obtained from the different families of samples, the optimal combination of materials reflecting the best properties was defined, and therefore, it will be the most suitable for its execution.

The different test results showed the suitability of electric arc furnace slag for the production of bituminous mixtures. An optimal combination of materials (electric arc furnace slag, silica sand, bitumen emulsion, and water) was obtained, giving the asphalt mixture excellent physical and strength characteristics. This demonstrates the feasibility of using the slag as an aggregate for slurry surfacing.

It should be noted that there are different national standards for the use of this construction technique. However, given the profusion of this type of asphalt mixture in Spain and the great number of successes obtained, the Spanish standard ORDER FOM/2523/2014 [16] is used to evaluate the suitability of the surface treatment designed.

2. Materials and Methods

This section describes the materials used as well as the methodology followed to study the suitability of developing surface treatments for pavements with electric arc furnace slag and bitumen emulsion.

2.1. Materials

The materials used are those described in this section. It must be taken into account that each one of them performs a function within the asphalt mixture, and therefore, there must be compatibility between all of them for the mixture to be suitable. In order to understand the function of each of the materials used, in the following sections it describes their origin, formation, and general characteristics, and then in the methodology, the tests that have been carried out to study their suitability as a whole.

2.1.1. Electric Arc Furnace Slag

The electric arc furnace slag (EAFS) comes from the steel industry located in Andalusia, Spain. These companies are engaged in the manufacture of steel from soft iron or steel scrap. Therefore, the process is similar over time, and consequently, the physical, mechanical, and chemical properties of the EAFS will be relatively stable. This fact is fundamental for the use of a waste. The slag has been received directly from the factory without any variation in grading, humidity, or other conditions that could alter the sample.

2.1.2. Silica Sand

The silica sand belongs, like the electric arc furnace slag, to the area of Andalusia, Spain. They come from the crushing of siliceous rocks and have been traditionally used in surface treatments. This is due to the good resistance they offer as well as the adequate adhesion with the bitumen emulsion. The physical properties will be determined later in the tests carried out in the methodology, evaluating their suitability as well as compatibility with the slags and the emulsion.

2.1.3. Bitumen Emulsion

The bitumen emulsion used is the one named according to the European standard [17] as C60B4 MIC. It is an emulsion traditionally used and currently used for surface treatments, of a cationic nature and slow breaking times. The cationic nature makes it suitable for the breaking of the emulsion in contact with the siliceous aggregates, so it is discarded the use of emulsions of anionic nature. The slow breaking time conditions the adequate time for the coating of all the aggregates, fine and course, and the correct adhesion with them. Shorter breaking times, such as medium or fast, would result in incorrect coating of the aggregate. The commercial reference of the bituminous emulsion is detailed in Table 1.

Table 1. Commercial reference of the bituminous emulsion C60B4 MIC.

Characteristics	Unit	Standard	Min.	Max.
Original Emulsion				
Particle polarity	-	UNE EN 1430 [18]	Positive	
Breaking value (Forshammer filler)	-	UNE EN 13075-1 [19]	110	195
Efflux time (2 mm, 40 °C)	s	UNE EN 12846 [20]	15	70
Binder content (per water content)	%	UNE EN 1428 [21]	58	62
Residue on sieving (0.5 mm)	%	UNE EN 1429 [22]	-	0.10
Setting tendency (7 days storage)	%	UNE EN 12847 [23]	-	10
Water effect of binder adhesion	%	UNE EN 13614 [24]	90	-
Binder after distillation (UNE EN 1431) [25]				
Penetration (25 °C; 100 g; 5 s)	0.1 mm	UNE EN 1426 [26]	-	100
Softening point	°C	UNE EN 1427 [27]	43	-
Evaporation residue (UNE EN 13074-1) [28]				
Penetration (25 °C; 100 g; 5 s)	0.1 mm	UNE EN 1426 [26]	-	100
Softening point	°C	UNE EN 1427 [27]	43	-
Stabilizing residue (UNE EN 13074-2) [29]				
Penetration (25 °C; 100 g; 5 s)	0.1 mm	UNE EN 1426 [26]	-	100
Softening point	°C	UNE EN 1427 [27]	43	-

2.1.4. Additive

The main function of the additive is to modify the breaking times of the emulsion, and consequently, to vary the working times of the asphalt mixture. The emulsion breaking time is essential in surface treatments. A short emulsion breaking time would result in poor workability of the mix and incorrect spreading, thus not spreading homogeneously and not producing adequate adhesion with the surface course of the aged pavement. On the other hand, long breaking times would result in the mixture not acquiring the properties of strength and cohesion in a short period of time, thus delaying the work of opening the pavement to traffic. The additives are usually made up of soaps, emulsifiers, and natural resins. Added to the mix in percentages between 0% and 2%, they control the emulsion breaking time, adapting it to the working times and even to the weather. It is a fundamental tool used in this work.

2.1.5. Water

The water used in this project is distilled water, in order not to induce more study variables and to maintain the purity of the methodology. Water plays a fundamental role in the bituminous mixture, since its addition prior to the emulsion makes it possible to achieve longer breaking times and to produce a homogeneous mixture with the bitumen emulsion, facilitating its spreading. It, therefore, makes it possible for the viscosity of the bituminous mix to be reduced and for the bitumen emulsion to adhesion properly to the aggregate. The water used in the execution of the surface treatment on the pavement must be analyzed. Mainly the sulphate and chlorine content must be monitored, as well as the pH [16].

2.2. Methodology

The methodology of this project comprises a series of logical and ordered tests in order to determine all possible properties of the materials and the mixture; thus, achieving the development of high-friction surface treatments with electric arc furnace slags.

For this purpose, electric arc furnace slag and silica sand first were dried at a temperature of 105 ± 2 °C for 24 h to remove the humidity. The elimination of the humidity is carried out with the aim of reducing the variables under study. However, the existence of humidity in the aggregates in the factory does not represent a problem, it should simply be taken into account to modify the pre-coating water. The dry materials will be the ones used in the whole methodology.

Chemical analysis of the electric arc furnace slag as a waste is essential. Elemental analysis and X-ray fluorescence tests will determine its composition, and ultimately its suitability for the intended purpose. Essentially, the detection of the polluting elements present and the chemical elements could cause problems in the bituminous mixture.

Subsequently, the physical and mechanical properties of the electric arc furnace slag, as well as of the silica sand, were studied. In these tests, the particular characteristics of the slags were evaluated to order to take appropriate remedial action. The physical and mechanical tests were divided into three main sections: coarse aggregate, fine aggregate, and filler.

After evaluating the characteristics of the electric arc furnace slags, we studied the percentage of combinations of both aggregates from the grading curve of the same. This combination of materials was tested with different percentages of emulsion and water, in order to determine the minimum abrasion loss in the test.

Finally, the emulsion breaking times and the cohesion of the surface treatment were adjusted for opening to traffic. The optimum combination of materials was the one that obtained the best properties in the different tests and the lowest economic and environmental cost.

The following sections describe the methodology divided into three main blocks: analysis of electric arc furnace slags, conformation of the bituminous mix and testing, and optimal combination of materials.

2.2.1. Analysis of Electric Arc Furnace Slags

The materials under study, electric-arc furnace slag, and silica sand, after removal of moisture, were subjected to a series of chemical, physical, and mechanical tests to assess their suitability.

On the one side, the of electric arc furnace slag was chemically analyzed for the detection of contaminating elements or elements that could damage the final mixture. For them, the elemental analysis test was performed, completely burning the sample and analyzing the gases for the detection of hydrogen, nitrogen, carbon, and sulfur. The equipment used for this purpose was the TruSpec Micro model of the commercial brand Leco. On the other side, X-ray fluorescence provided the elemental composition of the electric arc furnace slag thanks to the use of the commercial equipment ADVANT'XP+ of the Thermo Fisher brand. These chemical tests are essential to ascertain the composition and therefore to ensure that there are no problems with the leaching of pollutants [16].

Once the chemical composition of the slag had been defined and the presence of chemical elements that could cause problems had been evaluated, the physical and mechanical properties of the electric arc furnace slag and the silica sand were studied. The slags were divided according to particle size, filler, fine aggregate, or coarse aggregate.

The tests carried out on the filler of both materials were those of particle density (standard UNE-EN 1097-7) [30] and apparent density in kerosene (standard UNE-EN 1097-3) [31]. The density of the particles was evaluated by the pycnometer method with water, studying with successive measurements of mass and volume the density of the filler of both materials. Moreover, the density of the filler in kerosene indicated how powdery a material is, since a powdery material would cause dosage problems.

The fine aggregate, both of the electric arc furnace slag and of the silica sand, was tested for sand equivalent (standard UNE-EN 933-8) [32]. The sand equivalent test determines the percentage of colloidal particles in the aggregate under study. After a flocculation and coagulation process, the proportion of these particles was measured. It was therefore an essential test to avoid undesired problems of expansivity due to clayey materials.

The coarse aggregate, formed mainly by the slag of electric arc furnace, was responsible for providing sufficient friction to the pavement to prevent the sliding of the vehicles. It was therefore the material that must provide the appropriate characteristics of durability. Based on this, the physical tests carried out on the electric arc furnace slag were the calculation of the percentage of crushed surfaces (standard UNE-EN 933-5) [33] and the flakiness index (standard UNE-EN 933-3) [34]. These tests visually evaluated two fundamental characteristics of the aggregate for the friction of the surface treatment. In turn, resistance was evaluated through the tests of resistance to fragmentation (standard UNE-EN 1097-2) [35], resistance to freeze–thaw cycles (standard UNE-EN 1367-1) [36], and determination of the polished stone value (standard UNE-EN 1097-8) [37].

In this way, and after carrying out all the mentioned tests, the electric arc furnace slag and silica sand were defined for the correct conformation of the bituminous mixture, the evaluation of the absence of expansion problems and the study of the appropriate resistance for surface treatment.

2.2.2. Conformation of the Bituminous Mix and Testing

Once the chemical, physical, and mechanical suitability of the electric arc furnace slag and silica sand had been evaluated, the bituminous mixture was conformed.

As previously mentioned, the Spanish standard was used for this type of asphalt mixes given the great profusion that this type of technique has obtained in Spain and the number of successes that have accumulated in its manufacture. This standard is ORDER FOM/2523/2014 [16]. This document details a grading envelope for slurry surfacing manufactured with a maximum aggregate size of 8 mm. This grading envelope is the one used in the present study, being the grading curve of the electric arc furnace slag and the silica sand inside its limits. For this purpose, initially the particle size of the electric arc furnace slag and the silica sand were analyzed. As the electric arc furnace slag contained particles with sizes above 8 mm, these particles were removed by sieving leaving the particle distribution below 8 mm unchanged. The silica sand obviously does not contain particles larger than 6 mm.

With the curves of both materials, the final grading curve was conformed corresponding to the combination of the electric arc furnace slag and the silica sand. This curve was obviously inside the grading envelope. It should be noted that the function of the materials is very different; on the one hand, the slag provides the larger sizes and causes the tire to friction to the pavement. Furthermore, the silica sand, together with the emulsion, is in charge of supporting the traction and shear loads that may be induced in the pavement.

The above-mentioned standard defines the intervals of addition of the precoating water and the emulsion. These intervals are 10% to 15% for water and 6% to 8% for bitumen. It should be noted that the emulsion is composed of bitumen, which will remain in the mix after curing, and water, which facilitates the conforming operations at ambient temperature and is eliminated after breaking the emulsion by evaporation. It is therefore the bitumen that provides the mechanical characteristics of the bituminous mix. The change between bitumen and emulsion percentages is immediate with the knowledge of the bitumen emulsion data sheet. On the other hand, the percentages of emulsion, bitumen, water, and additive will always be defined in this document as percentages by mass over the total mass of aggregates (electric arc furnace slag plus silica sand).

The emulsion's ability to adhere to the aggregates was tested with the coating test according to the Spanish standard NLT-196/84 [38]. The test consisted of mixing the aggregated material with the precoating water and the bituminous emulsion in the average percentages of the defined intervals. It was mixed until breaking and poured on a filter paper to evaluate the adhesion of the bitumen emulsion and the aggregates. Water was then added to the rest of the bituminous mix in large quantities and re-sprinkled on the filter paper, thus evaluating the effect of water on the adhesion of the aggregate to the bitumen emulsion.

After studying the suitability of the bitumen emulsion, the mixtures were manufactured with different percentages of pre-coating water and bitumen emulsion. The percentage of water referred to in the standard, between 10% and 15%, corresponds to the water of the precoating and the water of the bitumen emulsion. This percentage of water was set at 12.5%, with the double purpose of not inducing more study variables, and on the other hand, to provide an intermediate percentage of water between the maximum and minimum values. The percentage of bitumen should be between 6% and 8%, therefore three families of test samples were made with bitumen percentages of 6%, 7%, and 8%. The bitumen, emulsion, and water percentages are listed in Table 2 for the three families.

Table 2. Percentages of bitumen, bitumen emulsion, and water of the different families of samples formed.

Percentages	MIC1	MIC2	MIC3
% bitumen	6	7	8
% bitumen emulsion	10.0	11.7	13.3
% water in the emulsion	4.0	4.7	5.3
% precoating water	8.5	7.8	7.2
% mixing water	12.5	12.5	12.5

Once the families were defined, the water wearing test was performed according to the UNE-EN 12274-5 [39] standard on all the samples of each family of asphalt mixtures. The test consists of subjecting a test specimen of cured bituminous mix for a specific time and immersed in water at 25 ± 1 °C, to the action of a rubber roller that rotates on the surface of the mix. Later, the sample is extracted and the variation of the mass is calculated, determining the loss by wearing. It is therefore a test that offers reliable results of the behavior of the asphalt. The results of this test for the three families were compared with the maximum results permitted by the Spanish technical specifications.

The percentage of additive required to obtain an adequate breaking time was then calculated. A long breaking time would cause a considerable delay in the acquisition of strength of the bituminous mixture and consequently a longer time for opening to traffic. Therefore, of the three families of asphalt mixes, the percentage of additive to be added was calculated to obtain a breaking time of 35 s and good initial cohesion.

Finally, to evaluate the friction of the mixture for the rapid opening of the pavement to traffic after the execution of the surface treatment, the test to determine the cohesion of the mixture was carried out in accordance with standard UNE-EN 12274-4 [40]. This test consists of applying a load on a rubber rammer that rests on the surface treatment, then it is turned at different times and the necessary torque is measured. The main result of this test is the torque at 60 ± 1 min.

With all the results of the different families of bituminous mixtures manufactured, the best economic, technical, and environmental option was evaluated.

2.2.3. Optimal Combination of Materials

The results of the different families were evaluated in order to obtain the optimal combination of materials. This combination will be based on technical principles, since it is necessary that all the prescriptions established by the technical specifications are fulfilled. In turn, economically based criteria are essential to decide between families with acceptable results, since adding increasing percentages of bitumen emulsion to achieve similar results is not an adequate option. In addition, the use of a higher percentage of natural raw materials creates a sustainable mix but in a smaller proportion.

On the basis of detailed analyses, the best option was evaluated and tests were repeated to confirm those obtained previously.

3. Results and Discussions

3.1. Analysis of Electric Arc Furnace Slags

The materials analyzed in this section are electric arc furnace slags and silica sands. The electric arc furnace slag, being a waste from the steel industry, was analyzed chemically in order to better understand its physical and mechanical behavior.

For this purpose, the elemental analysis test was first performed to detect the percentages of carbon, nitrogen, hydrogen, and sulphur in the sample. The results of this test are shown in Table 3.

Table 3. Elemental analysis of electric arc furnace slag (EAFS).

Sample	Nitrogen, %	Carbon, %	Hydrogen, %	Sulphur, %
EAFS	0.005 ± 0.000	0.164 ± 0.003	0.04460 ± 0.001	0.000 ± 0.000

As can be seen the percentages of the chemical elements, carbon, nitrogen, hydrogen, and sulphur in the sample of electric arc furnace slag are very low. This fact is mainly due to the inorganic nature of the material. It can be seen that the percentage of carbon is low, reflecting the absence of organic matter or carbonates in the sample. On the other hand, it is worth noting the zero value of sulphur obtained. If otherwise there would have been an important percentage of this chemical element in the sample, it would imply a special care in the study, since the leachates produced should be evaluated and ensure that they are acceptable by the standard in this respect.

The X-ray fluorescence test was performed on the electric arc furnace slags in order to obtain the chemical composition. The results of this test are shown in Table 4.

The chemical composition of the electric arc furnace slag is derived directly from its formation process. High percentages of iron are to be expected since they come from steel, as well as high percentages of calcium oxide due to its addition in the steel process to obtain the final material. Silicon and aluminum oxides are common in the scrap used for the manufacture of new steels. In turn, magnesium, manganese, and chrome are common in the composition of steel. The other elements are found in such a small percentage that they cannot be extrapolated. The very low percentage of sulphur ensures that leachate from the slag does not represent an environmental problem, as is the case with other contaminating elements and is limited in leaching by the standards in this respect. It should be noted that the presence of oxides in the chemical composition of electric arc furnace slag does not imply an expansion of the material in contact with water. This fact is due to the fact that the production industry, after removing the slag from the furnace, waters it with abundant water to lower its temperature and it is stored in the open air. Therefore, a carbonation process is produced that makes the geometric characteristics of the slag stable.

Table 4. X-ray fluorescence of electric arc furnace slag.

Composite	wt., %	Est. Error
CaO	31.75	0.23
Fe_2O_3	21.96	0.21
SiO_2	17.52	0.19
Al_2O_3	12.26	0.16
MnO	6.15	0.12
MgO	5.05	0.11
Cr_2O_3	2.73	0.08
TiO_2	0.955	0.047
BaO	0.658	0.033
P_2O_5	0.319	0.016
MrO	0.1860	0.0093
V_2O_5	0.1590	0.0079
Nb_2O_5	0.0659	0.0033
S	0.0645	0.0032
ZrO_2	0.0551	0.0028
K_2O	0.0289	0.0016
CuO	0.0254	0.0017
ZnO	0.0245	0.0016
Co_3O_4	0.0147	0.0016
Eu_2O_3	0.0137	0.0065
WO_3	0.0104	0.0031
Y_2O_3	0.0018	0.0005

After analyzing the chemical composition of the electric arc furnace slag and evaluating its suitability for use in bituminous mixtures, the physical characteristics of the slag and the silica sand were studied. For this purpose, first the filler was studied and then the fine and coarse aggregate.

The tests carried out on the filler of both materials are the density of the particles, showing density values of 3076 ± 77 kg/m^3 for the filler of the electric arc furnace slag and 2511 ± 53 kg/m^3 for the filler of the silica sand. It can be clearly seen how the chemical composition of the slag conditions the higher density in relation to a conventional aggregate. In turn, it was performed in the apparent density test in kerosene showing values of 700 ± 50 kg/m^3 and 600 ± 50 kg/m^3 for the filler of the electric arc furnace slag and silica sand, respectively. Both values are acceptable and reflect a non-pulverulent behavior of the materials, ensuring a good mass dosage.

In addition, in fine aggregates, the test of sand equivalent in the electric arc furnace slag reflected a value of 85 ± 2% and the silica sand a value of 60 ± 1%. Both values are acceptable by the technical specifications; however, it is remarkable the high value of the slag reflecting the low percentage of colloidal particles, and consequently, the cleanliness of the aggregate so that there are no subsequent problems of adhesion with the bituminous emulsion.

The coarse aggregate of the electric arc furnace slag was evaluated with the physical tests of percentage of crushed surfaces, with a result of 100 ± 0%, and flakiness index, with a result of 0 ± 0 %. The achievement of these excellent results for the electric arc furnace slag derives directly from its formation process. The gasification in the electric furnace of all the impurities makes it possible that after their removal and cooling, the particles acquire irregular shapes, with dimensions in the three axes similar and without the need for crushing. It is therefore an essential characteristic that makes the slag a very suitable aggregate for the formation of asphalt mixtures, even in very important traffic.

The mechanical characteristics of the coarse aggregate of the electric arc furnace slag were evaluated with the tests of resistance to fragmentation (standard UNE-EN 1097-2) [35], resistance to frost–thaw cycles (standard UNE-EN 1367-1) [36], and determination of the polished stone value (standard UNE-EN 1097-8) [37]. Fragmentation resistance of the electric arc furnace slag reflected a value of 13 ± 1%. This value shows a very good mechanical resistance of the slags to fragmentation, similar values being achieved only in natural aggregates of high quality and economic cost. In addition, the resistance to the frost–thaw cycles of the slag of electric arc furnace steel is 0.551 ± 1%. This means that the loss of mass after a series of freezing and thawing cycles was negligible, again reflecting the excellent characteristics of the electric arc furnace slag. Finally, the determination of the polished stone value for the electric arc furnace slag showed a value of 58 ± 1. The result of this test reflects the high friction resistance of the slag, which can even be used for very high-traffic roads [16].

All chemical, physical, and mechanical characteristics of the electric arc furnace slag and silica sand have been evaluated and the suitability of both materials has been demonstrated. The particle density of the entire grading curve of the slag and sand was calculated. These results reflected 3351 ± 69 kg/m^3 for the electric arc furnace slag and 2498 ± 50 kg/m^3 for the silica sand, again reflecting the high density of the slag due to its metallic chemical composition.

3.2. Conformation of the Bituminous Mix and Testing

In order to form the different bituminous mixtures with electric arc furnace slag and silica sand, it is first necessary to obtain the grading curve of both materials. It should be noted that the materials in this work are used as they are in the factory, so their grading is analyzed and not made in the laboratory. This is due to the direct use of this work in pavements without having to modify the grading of the slag and creating processes with a higher economic cost. Firstly, the particle size distribution of the electric arc furnace slag was analyzed (Figure 1). The grading curve of the electric arc furnace slag belongs to a discontinuous grading, there being mainly coarse aggregate and to a lesser extent fine aggregate. Since the maximum particle size is 16 mm and the surface treatment developed is a maximum particle size of 8 mm, sizes larger than 8 mm should be discarded without altering the lower ones. This process is fast and economical if done in the factory, so it does not imply a major problem. Based on this, the grading of the electric arc furnace slag with maximum aggregate size of 8 mm will be used and is represented in Figure 1.

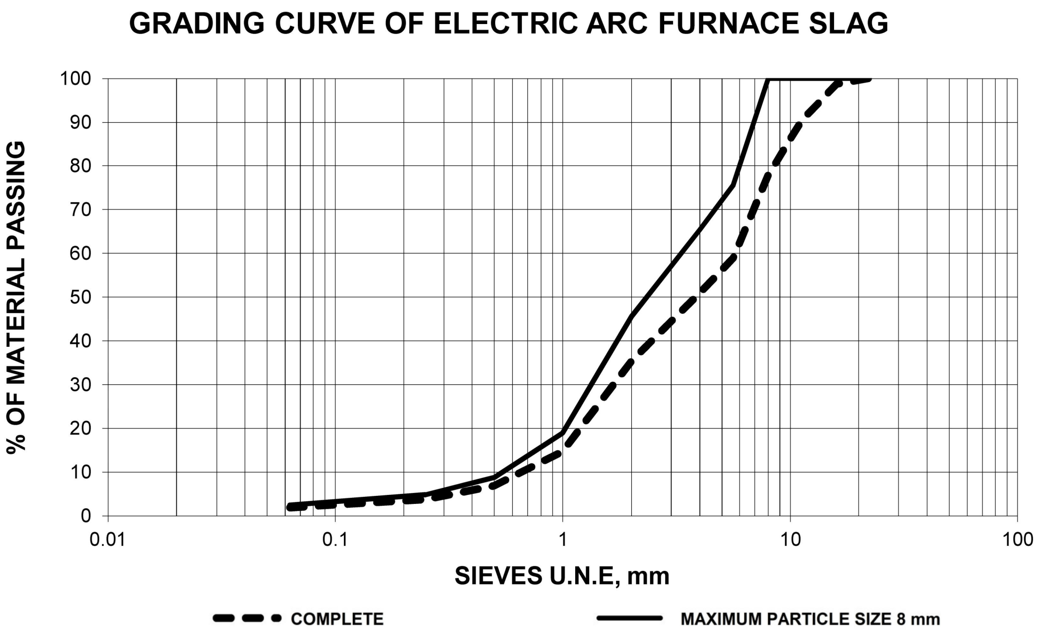

Figure 1. Grading curve of electric arc furnace slag.

On the other hand, the grading of the silica sand was studied with the same sieves and represented in Figure 2.

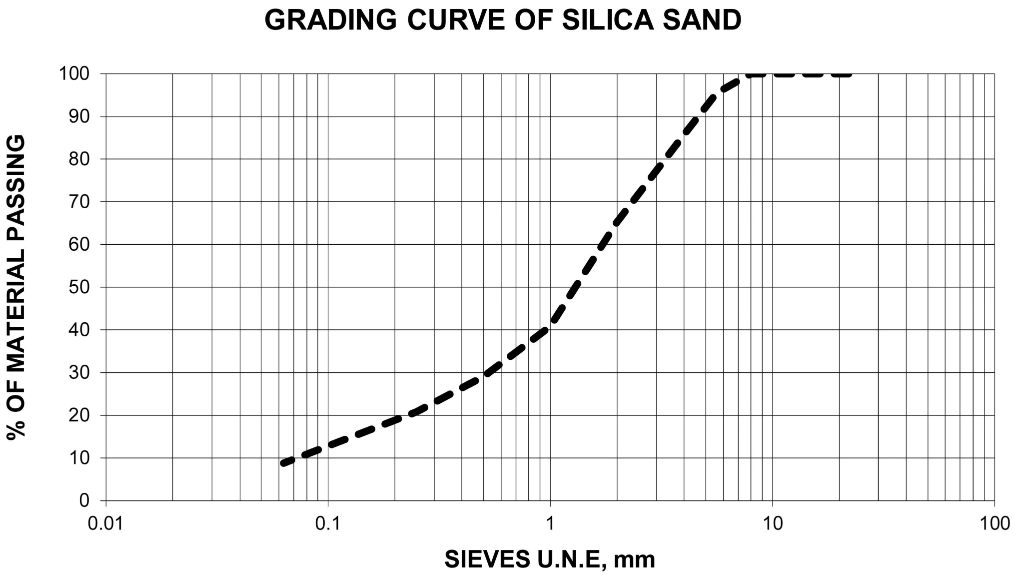

Figure 2. Grading curve of the silica sand.

It can be seen that the grading curve of the sand coincides with a continuous grading. This material will correct the grading of the electric arc furnace slag by providing it with the fine aggregate needed for the asphalt mix. In this way, the slag provides the adequate friction of the surface treatment and the sand, together with the bitumen, is in charge of providing the necessary mastic for the tensile strength and the coating of the electric furnace slag. This is the main reason for the incorporation of the silica sand, as it is more economical to incorporate it than to distribute the slag into different particle sizes distribution.

Since the Spanish standard fixes the grading envelope of this type of surface treatment with a maximum size of aggregates of 8 mm, the grading curve of the electric arc furnace slag and silica sand must be adjusted to the defined grading envelope. The grading curve of the mass mixture of 33.3% electric furnace slag and 66.6% silica sand is represented together with the grading envelope defined in Figure 3 and Table 5.

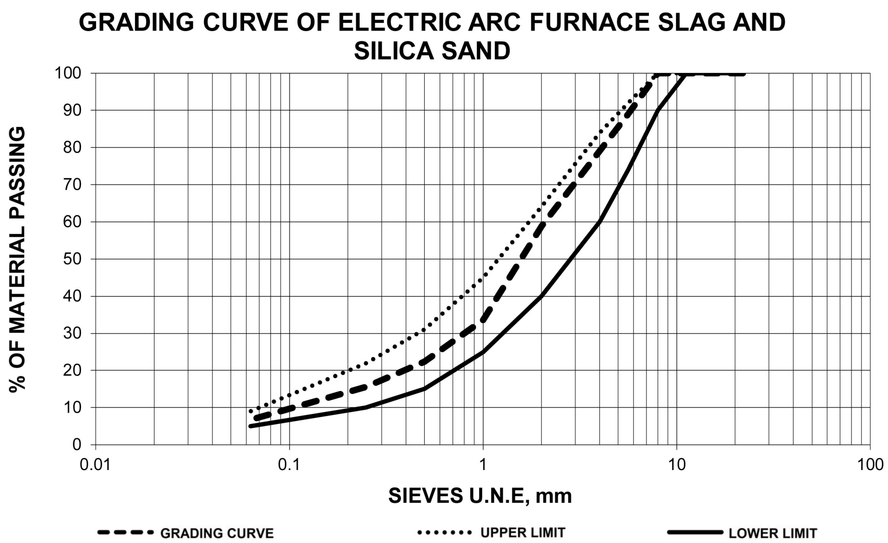

Figure 3. Grading curve obtained by the combination of 33.3% of electric arc furnace slag and 66.6% of silica sand.

Table 5. Grading curve of electric arc furnace slag, of silica sand, and of the combination of both materials.

Sieves UNE	22.00	16.00	11.20	8.00	5.60	4.00	2.00	1.00	0.50	0.25	0.06
EAFS	100	98.70	90.40	77.90	58.90	51.00	35.50	14.70	6.90	3.80	1.90
EAFS < 8 mm	100	100	100	100	75.60	65.50	45.60	18.90	8.80	4.90	2.50
Silica sand	100	100	100	100	95.50	85.70	65.30	40.80	29.10	20.80	8.80
Combination	100	100	100	100	88.93	79.03	58.80	33.57	22.40	15.55	6.72
Upper limit	100	100	100	100	92.00	84.00	64.00	45.00	31.00	22.00	9.00
Lower limit	100	100	100	90.00	74.00	60.00	40.00	25.00	15.00	10.00	5.00

These combination percentages have been selected by the appropriate grading curve obtained in relation to the grading envelope prescribed by the standard. It can be seen that it practically coincides with the intermediate grading curve of the grading envelope, so it is very suitable for use.

Once the percentage of combination of slag and sand was determined, the compatibility of the aggregates with the emulsion was studied, as well as the percentages of emulsion and water required. It should be noted that from now on, when referring to aggregate, it refers to electric arc furnace slag at 33.3% and silica sand at 66.6%. Therefore, all percentages of bitumen, bitumen emulsion, and water will refer to the aggregate obtained by the combination of both materials.

The compatibility of the bitumen emulsion with the aggregates was determined through the coating test. The coating test, detailed in the methodology, was carried out with a percentage of mixing water of 12.5%. This percentage of water corresponds to the precoating water and the water of the emulsion. The percentage of bitumen will be the intermediate of the interval fixed by the standard, therefore, 7%. This percentage will correspond to a percentage of emulsion of 11.7% and, in short, a percentage of pre-coating water of 7.8%. All the materials were mixed with these prescriptions in dry conditions and with water. The images of the coating test are shown in Figure 4.

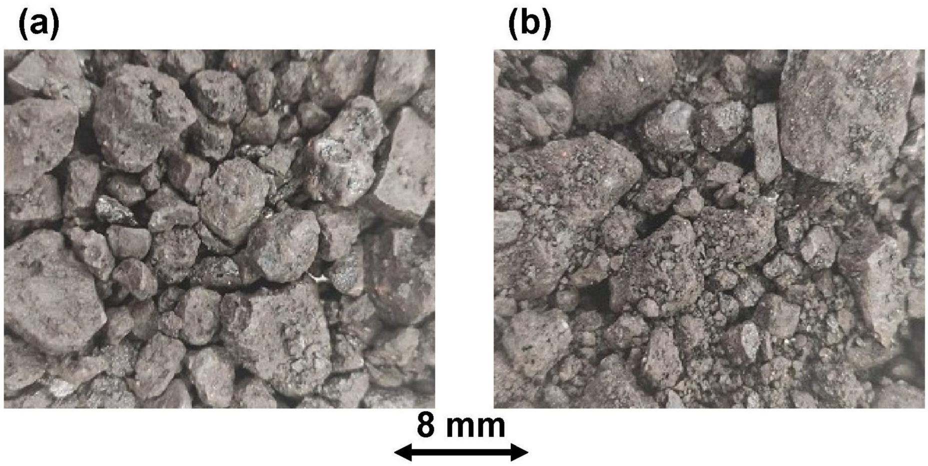

Figure 4. Coating test with the precoating water and the bitumen emulsion C60B4 MIC. (**a**) Coating test. (**b**) Coating test after washing in water.

Figure 4 shows that the adhesion of the bitumen emulsion in dry conditions and with water is very good. The aggregate (electric arc furnace slag and silica sand) is completely covered by the emulsion and does not come off after mixing with water. Therefore, it can be concluded that the C60B4 MIC emulsion is suitable for use with this type of aggregate.

Once the compatibility of the emulsion with the aggregate was determined, different specimens of each family were conformed with the percentages of emulsion and water set in Table 2, and the grading detailed in Figure 3. Subsequently, the test to determine wearing in water was carried out on the different samples of each family, according to the procedure detailed in the methodology. The results of the wearing test are shown in Figure 5.

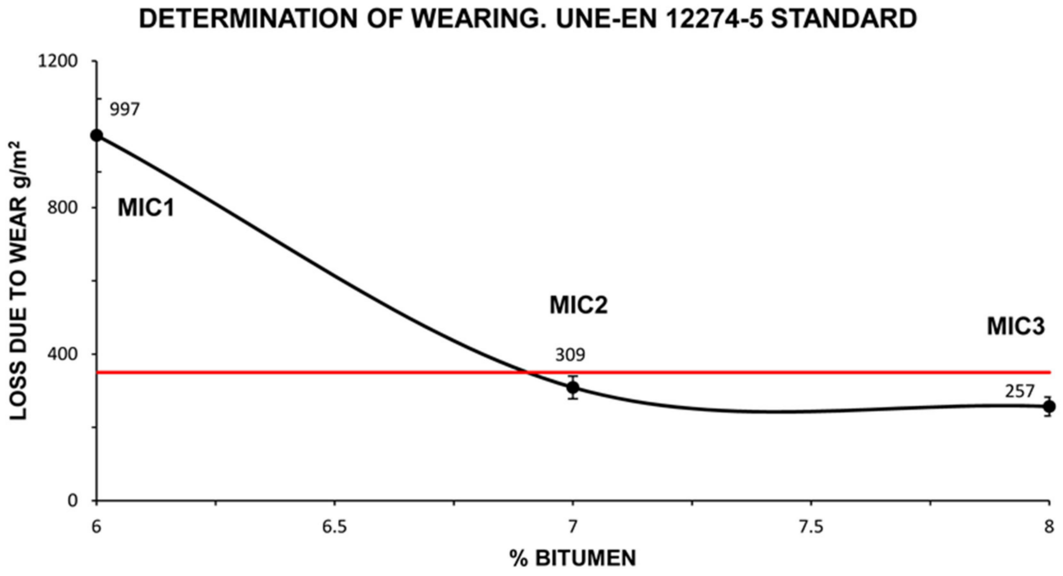

Figure 5. Determination of the wearing pattern of different families of bituminous mixtures according to the percentage of bitumen (standard UNE-EN 12274-5 [39]). The red line represents the minimum value accepted by the corresponding regulation.

The water wearing test of the different families shows a decrease in mass loss with an increase in the percentage of bituminous emulsion. This is to be expected, since a higher percentage of emulsion implies a higher percentage of bitumen, and thus a more complete coating of the slag that prevents its raveling. The MIC2 and MIC3 families obtain acceptable results, since the Spanish standard limits the maximum wearing value to 350 g/m^2 for important traffic.

At the same time, it is essential that the breaking times are adapted to the working timing of the manufacture and extension of the asphalt mixture. For this purpose, 35 s was taken as the appropriate breaking time. The choice of this time is because it is usual in the working world in the formation of this type of surface treatment. However, depending on the climatic conditions, the pace of construction, and various factors, the breaking time can be modified with the addition of the additive for this purpose. The additive described in materials will be incorporated into the different families of bituminous mixtures until a breaking time of 35 s is obtained in all of them. The percentages of additive for each family of samples to obtain the stipulated breaking time are shown in Figure 6.

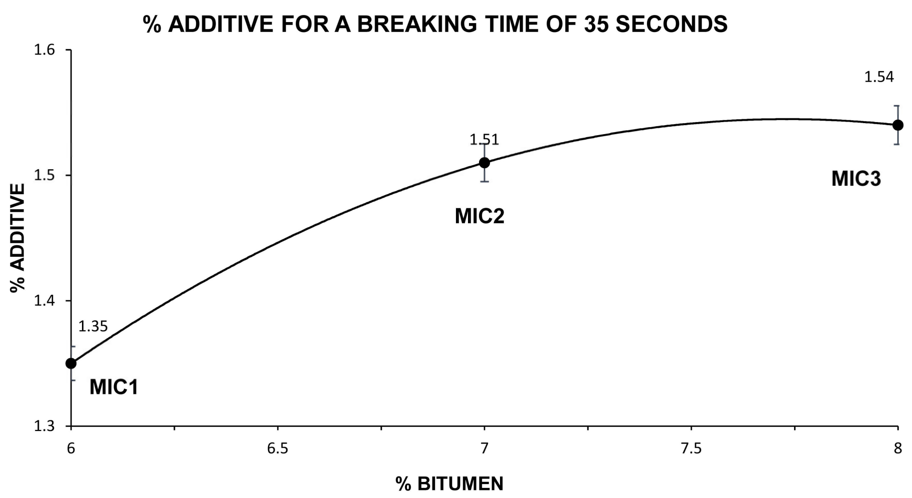

Figure 6. Percentage of additive needed in each family to obtain a 35-s breaking time of the emulsion.

Figure 6 shows how a higher percentage of emulsion requires a higher percentage of additive, but the variations are minimal. This fact is mainly due to the lower percentage of emulsion for the coating of the aggregates, so their absorption is higher and their breaking time is shorter. However, variations are minimal.

Finally, the cohesion test determined the resistance offered by the surface treatment to the tangential stresses applied. This is directly related to the good friction of the treatment to the lower layer, as well as to the time required for opening the pavement to traffic after the execution of the treatment. The results of the cohesion test for the different families of bituminous mixtures are detailed in Figure 7.

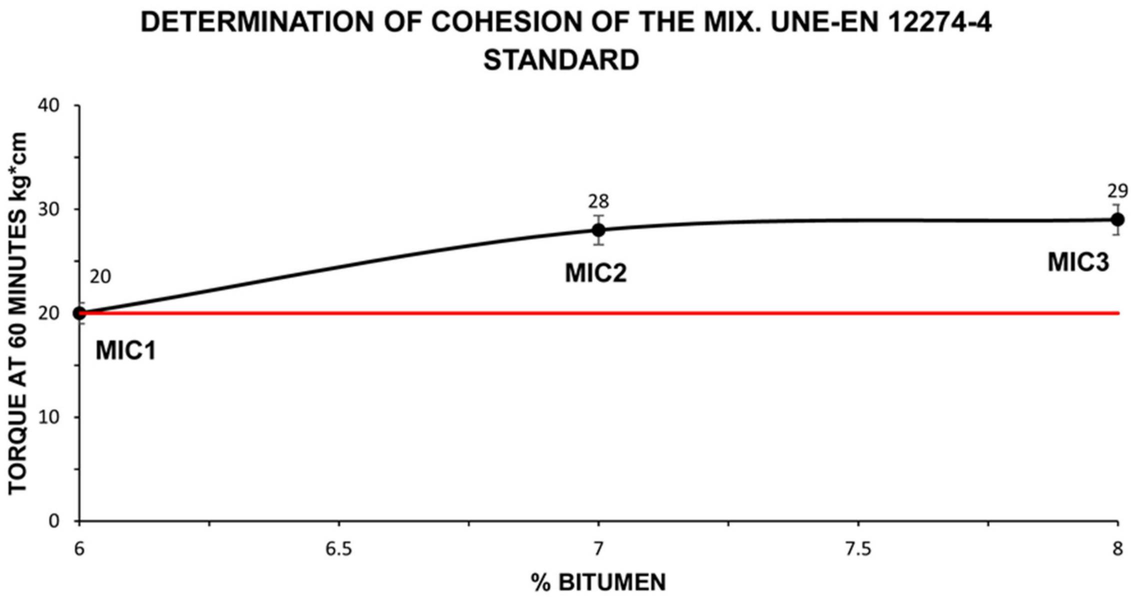

Figure 7. Determination of the cohesion of the different families of bituminous mixtures according to the percentage of bitumen (standard UNE-EN 12274-4 [40]). The red line represents the minimum value accepted by the corresponding regulation.

The results show a similarity between the MIC2 and MIC3 families of bituminous mixtures, and a much lower value for the MIC1 family. The standard for this is that the minimum torque for important traffic is 20 kg·cm, therefore all values are acceptable. However, the value of the MIC1 family is at the limit for acceptance, so its use may be inadvisable.

3.3. Optimal Combination of Materials

Based on the results of the different tests on the three sample families, in this section, the family that provides acceptable technical results and at the same time has the lowest economic and environmental cost will be selected.

The MIC1 family with a bitumen percentage of 6% showed negative results in the wet abrasion test. This test is essential for the correct functioning of the surface treatment, as it reflects its behavior in the pavement. Therefore, the family called MIC1 has been discarded for use.

On the other hand, the MIC2 and MIC3 families present acceptable and similar results in the various tests. Moreover, these results are acceptable according to the current standards, not only for intermediate traffic but also for important traffic [16]. The physical and mechanical characteristics of the furnace electric slag show the suitability of its use in surface treatments.

Within the choice between the two families, it should be noted that the MIC2 family obtains acceptable results with a bitumen percentage lower by one percent, therefore more respectful of quality and sustainability levels, since with the use of a lower proportion of raw materials, it achieves similar and acceptable results. Therefore, this optimum combination of materials was proposed as the ideal one for use in high-friction surface treatments in pavements with important traffic and electric arc furnace slag.

The samples were re-conformed and the tests on this family were redone. The results of the different tests are shown in Table 6.

Table 6. Results of tests of bituminous mixture with electric arc furnace slag and the optimal combination of materials.

MIC2	Value
Aggregate	33.3% EAFS + 66.6% silica sand
% bitumen	7
% bitumen emulsion	11.7
% precoating water	7.8
% additive	1.5
Determination of wearing, g/m^2	301 ± 9
Breaking time, s	35 ± 0
Determination of cohesion, kg·cm	29 ± 1

4. Conclusions

The results of the different tests carried out in the methodology show a series of partial conclusions that converge in the final conclusion on the use of electric arc furnace slag in pavement surface treatments. The importance of the use of industrial waste in activities within the construction sector should be highlighted for different reasons; on the one hand, the extraction of virgin materials is reduced, with the consequent reductions in environmental impact and greenhouse gas emissions; on the other hand, the deposition of this waste in landfills is avoided; and finally, exceptional characteristics are achieved for the planned purpose without the use of high quality and costly commercial materials. The partial conclusions obtained from this study are presented below.

- The electric arc furnace slag is mainly conformed by coarse aggregate and to a lesser extent by fine aggregation. They contain a low proportion of colloidal particles.
- The chemical composition of the electric arc furnace slag is adequate. There are no high percentages of pollutants that could cause environmental problems, or other elements that could damage the manufacture of bituminous mixtures.
- The shape of the different particles of the electric furnace slag are suitable for use in surface treatments for friction, as they have a high microtexture and a very irregular surface. This fact, together with the excellent resistance to fragmentation and frost–thaw cycles, makes the electric arc furnace slag an ideal aggregate for use in high-friction surface treatments and in important traffic.
- The density of electric arc furnace slag is higher than that of a conventional aggregate, so while this is not a problem, it must be taken into account in the manufacturing and transportation process.
- In the different families of test specimens made up of electric arc furnace slag and silica sand, it was observed that the increase in the percentage of emulsion caused greater resistance to wear of the asphalt mixture, obtaining acceptable values from 7% bitumen.
- The cohesion of the bituminous mix increases as the percentage of emulsion increases, with all families reflecting adequate cohesion from 6% emulsion to 8%. This fact results in a better adhesion of the treatment to the surface layer of the pavement where it is applied and a good reaction to traffic loads.
- The family selected as optimal has a grading formed by 33.3% of slag of electric arc furnace screened by the sieve 8 mm and 66.6% of silica sand. The percentages of bituminous emulsion are 11.7% and 7.8% of precoating water. In turn, the additive was added at 1.5% to achieve adequate breaking times.

- The tests carried out show the technical feasibility of this surface treatment for its execution. The excellent results obtained imply adequate friction characteristics of the pavement. In turn, the execution of this research does not imply important changes in comparison with traditional surface treatments, so that only the usual care should be taken for the execution of this technique.

Based on the detailed conclusions, it can be stated that it is possible to carry out surface, waterproofing, and high-friction treatments with bituminous emulsion and electric arc furnace slag. This will create, therefore, a sustainable bituminous mixture with adequate physical and mechanical characteristics, with a lower environmental impact thanks to the use of waste and the conformation at ambient temperature of the mixture by the use of the emulsion.

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