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# Development of Porous Asphalt with Bitumen Emulsion, Electric arc Furnace Slag and Cellulose Fibers for Medium Traffic Roads

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**Abstract:** The construction of road infrastructure is one of the most polluting activities that exists today. Therefore, the use of waste from other industries is an excellent solution, since it reduces the consumption of raw materials, reduces CO<sub>2</sub> emissions and avoids the disposal of waste in a landfill. In this study, electric arc furnace slag, cellulose fibers from the papermaking industry and bitumen emulsion were used for the conformation of sustainable and porous bituminous mixtures. Electric arc furnace slag was used as a high-resistance aggregate with a capacity sufficient to support traffic loads. Cellulose fibers were added to increase the percentage of binder in the mixture without bleeding problems, thereby achieving greater tensile strength. To do this, first the waste was physically and chemically characterized, then different mixtures were conformed and finally the mixtures were studied by means of the loss by wear and Marshall tests. The results reflected an optimal combination of materials that provided the best results in the mechanical tests, obtaining much better results than the mixtures with discontinuous grading and traditional bitumen emulsion. Therefore, a sustainable, porous and economical mixture for road use is obtained in this research.

**Keywords:** Bituminous mixtures; discontinuous grading; electric arc furnace slags; cellulose fibers; bitumen emulsion; waste; skid resistance; porous asphalt; Marshall tests; sustainability

## 1. Introduction

Recent developments in society, including greater environmental sensitivity and, consequently, more restrictive environmental regulations, have created ideal circumstances for the formulation of new materials that are more sustainable for the environment [1,2]. These materials represent a new working paradigm, with the sole purpose of providing materials with similar or superior characteristics to the traditional ones but with an optimization in their manufacturing process and in the use of raw materials [3]. Therefore, they significantly reduce the carbon footprint in their life cycle assessment [4].

In line with the above, and based mainly on the reduction of the use of raw materials for the creation of the different products, the so-called Circular Economy arises [5]. This type of production differs from the previous linear economy in several ways, essentially in the reduction of the Environmental Impact [6,7]. The old linear economy was based on the extraction of the different raw materials for the conformation of the material, its later manufacture with little optimized industrial processes, the use of the product and, at the end of its useful life, the withdrawal of the product in landfill [8,9]. It is clear that in each and every one of the mentioned phases there is an important environmental impact, creating at the same time a great exploitation of the resources and a remarkable generation of waste [10].

As a solution to this problem, the Circular Economy has arisen, the basis of which is the use of different unusable products to make new materials [11,12]. Moreover, this form of production is not only a reduction of the extraction of the initial materials, but also takes into account more optimized industrial processes, responsible use of the product in its useful life and withdrawal for new production. In other words, the entire life cycle assessment of the product [13].

This more environmentally friendly methodology is the basis of this applied research in the construction sector, more specifically in linear infrastructure [14]. The road construction sector is one of the most harmful to the environment, as the interaction with the environment in most cases is quite intense. However, the construction of road infrastructure is essential for the economic development of a region, as well as for improvement of the quality of life of the population [15,16]. It should be noted that most land transport is carried out by road, moving huge volumes of products and facilitating the market [17]. In turn, the good condition of pavement has been demonstrated in various publications as having a significant influence on fuel consumption, and consequently, on CO<sub>2</sub> emissions, and even more so, on accidents [18–20]. Therefore, far from trying to avoid the construction of new roads or maintenance, quality infrastructure must be provided, which affords a comfortable and safe wearing course, and at the same time, is as sustainable as possible [21,22].

The present study is based on the aforementioned, however, its field of action is restricted to medium and low traffic roads [23]. The study of this type of infrastructure is motivated by two factors; on the one hand, this type of infrastructure receives the least investment in their construction and maintenance, so the quality of the pavement is not always assured during its useful life. On the other hand, medium and low traffic roads represent a significant percentage of all roads, and are the most likely to produce accidents and mortality.

On this basis, the foundation is the creation of quality pavements, economical and with techniques as sustainable as possible. It is therefore the discontinuous grading bituminous mixtures with bitumen emulsion that is the most adequate solution to this problem [24].

Discontinuous grading bituminous mixtures with bitumen emulsion are bituminous mixtures with low CO<sub>2</sub> emissions, as a result of using bitumen emulsions that allow them to be manufactured and applied at ambient temperature [25,26]. At the same time, they provide a comfortable and safe road surface for vehicles and possess several particular characteristics [27]. Among these characteristics are: the capacity to drain water, due to its high content of voids; high skid resistance, provided by its macrotexture derived from the use of mainly coarse aggregate; the reduction of noise emissions, as it has a high content of voids that is capable of absorbing noise [28,29]; as well as a comfortable bituminous mixture in terms of regularity, safety and sonority for drivers [30–32]. They are, therefore, bituminous mixtures with very good characteristics that have, however, not always been developed successfully, because of the use of low-quality materials or inadequate execution processes [33].

All of the aforementioned characteristics derive from its grading, which is mainly composed of coarse aggregate and, to a lesser extent, of fine aggregate. On the one hand, coarse aggregate works by friction resisting the important loads of traffic, and on the other hand, fine aggregate in conjugation with the bitumen of the emulsion provides the adequate characteristics to resist the tractions created by traffic. They are therefore both essential elements for the production of a bituminous mixture suitable for traffic, and for durability. In both elements, important improvements have been made in this research to obtain a product of maximum quality, differentiable from the conventional one [34].

As mentioned, the tensile strength of the bituminous mixture is supported by the mixture of the bitumen of the emulsion and fine aggregate. To improve this property, cellulose fibers discarded by the papermaking industry were incorporated. These cellulose fibers have the main function of being able to retain higher percentages of bitumen without the production of exudations. In this way, this higher percentage of bitumen makes possible the higher tensile strength of the bituminous mixture, and consequently, a substantial increase in its durability [35]. An example of this use are the bituminous mixtures called Stone Mastic Asphalt, which are hot mixes with commercial fibers. This type of bituminous mixture achieves higher percentages of bitumen and, consequently, a long

life [36,37]. In this case, and based on the principles of the circular economy mentioned, discarded fibers were used, avoiding the use of new raw materials, which, in turn, are highly expensive.

It has also been shown that the use of a quality aggregate capable of withstanding the compressive stresses of traffic is essential for achieving a resistant bituminous mixture. The extraction of virgin materials to obtain quality aggregates entails higher CO<sub>2</sub> emissions as well as a higher economic cost. To solve this problem and substantially improve the bituminous mixture, electric arc furnace slags from the steelmaking industry were used [38]. These electric arc furnace slags are discarded in the conforming process of new metallic materials through the initial scrap, and are therefore a high production byproduct with unbeatable resistance and textural characteristics.

In short, this study develops a new bituminous mixture composed of electric arc furnace slags as a coarse and fine aggregate, and cellulose fibers discarded by the papermaking industry, as an additive. The result is a porous asphalt [39] that is sustainable, with low CO<sub>2</sub> emissions, storable, easy to apply, highly skid resistance and comfortable for the driver.

Current research has evaluated the suitability of electric arc furnace slag as an aggregate for bituminous mixtures with bitumen [40] or bitumen emulsion [41]. All these investigations agree on the quality of slag as an aggregate for bituminous mixtures and the acceptable results it provides. In turn, cellulose fibers have been used in bituminous mixtures with bitumen emulsion [42] and with bitumen [36], reflecting the increase in the percentage of binder that can be obtained and the increase in service life. Bituminous mixtures have even been developed with electric arc furnace slag, bitumen and cellulose fibers [43], obtaining good mechanical resistance from the mixtures developed. However, the combination of materials presented in this research of electric arc furnace slag, cellulose fibers rejected by the paper industry and bitumen emulsion, represents the development of a new sustainable and economical bituminous mix. This is because it uses waste from the industry in very high percentages and uses construction techniques with lower CO<sub>2</sub> emissions.

There are different regulations depending on the country that controls the quality of this type of bituminous mixture with discontinuous grading and bitumen emulsion. However, given the importance and development that this type of technique obtained in Spain, with several success stories, the Spanish regulations were used to assess the suitability of the bituminous mixture.

Therefore, the initial materials conforming the bituminous mixture (electric arc furnace slags and cellulose fibers) were analyzed [44–46]. After physical and chemical analysis of the materials, we proceeded to conform different bituminous mixtures that were formed with electric arc furnace slags, cellulose fibers and increasing percentages of bitumen emulsion, up to the maximum percentage that produced bitumen exudation in the curing process. The conformed samples after the curing process were tested to determine their physical properties, bulk density, maximum density and void content. The subsequent particle loss test without immersion and after immersion in water reflected the wear resistance of the bituminous mixture, as well as the cohesion of the aggregate and the emulsion. Given the high percentage of bitumen created by the incorporation of the fibers, the plastic deformations of the different groups of samples were evaluated with the Marshall test.

The results of the aforementioned tests have been able to establish an optimum combination of materials based on the grading curve made up of electric arc furnace slags, 0.5% cellulose fibers, and 10.8% emulsion. This optimal combination, after the manufacture of the bituminous mixture and its curing, provides a percentage of residual bitumen of 6.5%, and in turn, reflects optimal values of the Marshall test as well as the particle loss test. A bituminous mixture with a void content of more than 20% has therefore been created, which is comfortable, safe and has draining characteristics, using industrial byproducts and manufacturing techniques with low CO<sub>2</sub> emissions.

## 2. Materials and Methods

This section of the present study details the materials used in the conformation of the bituminous mixtures, as well as the research methodology followed to achieve the mentioned objectives.

## 2.1. Materials

The materials used in this study have been selected in order to provide to the final bituminous mixture with the best physical and mechanical characteristics. Based on this, we proceed to define these materials in a general way, indicating the type of material, its function, as well as its origin.

The reproducibility of the results is essential, not only in a scientific manner, but also because of the alterations that could occur in the byproduct due to variations in the manufacturing process of primary companies. In other words, for a byproduct to be usable with viability and quality, it is necessary for it to be stable over time, which can be derived from the equality of results obtained in the different tests throughout different productions. Therefore, the chemical, physical and mechanical characteristics are maintained in different sets.

A clear example of the nonreproducibility of a byproduct is water treatment plant sludge. In this byproduct, its composition varies greatly depending on the region, location, treatment plant and even the temporary station where it is obtained. Therefore, it will be difficult to establish characteristics for its use in a final product.

Unlike the previous case, both the electric arc furnace slags and the cellulose fibers are stable over time, varying only slightly in their composition and physics or mechanical characteristics.

For the study of the materials and their forming into bituminous mixtures, the electric arc furnace slag and cellulose fibers were dried at a temperature of  $105 \pm 2$  °C so that they did not contain water that could affect the results. The existence of humidity or water in the industry does not affect the final mixture, but that percentage must be taken into account for adding the different elements in the right proportion.

### 2.1.1. Electric Arc Furnace Slags

The electric arc furnaces slags of the steelmaking industry, hereinafter EAFS, has been supplied by companies in the area of Andalusia, Spain. These EAFS, obtained from the fusion phase, have a maximum particle size of less than 20 mm and constitute the granular material (coarse aggregate, fine aggregate and mineral filler). The mission of the EAFS is twofold: on the one hand, they provide the mineral skeleton for the bituminous mixture; and on the other hand, together with the bitumen, they support the traction loads of traffic. The tests carried out on EAFS are detailed in the methodology for evaluating their suitability.

The EAFS received from the industry all have particle sizes below 20 mm. Therefore, they were sieved in the sieves necessary for the grading envelope, according to regulations, and washed afterwards to ensure the fine aggregate content.

### 2.1.2. Cellulose Fibers from the Papermaking Industry

The cellulose fibers are a currently unused waste product from companies located in the province of Jaen, Spain. These fibers are discarded in the industrial process of manufacturing cardboard.

In the process of manufacturing packaging paper from recycled paper, the recycled paper is shredded in combination with water, in order to place the fibers in suspension. The mixture of fibers and water is subjected to a process of physical depuration, as it passes through different sieves. It is also subjected to a process of cyclonic separation of light and heavy elements. The rejects from these depurations are sent to a press to reduce the water content. This resulting waste is used in this study and is called cellulose fibers, hereinafter CFP.

These CFP have been used, after treatment, as an additive to the bituminous mixture created. They are the element suitable for the retention of the highest percentage of bitumen and consequently provide the greatest resistance and durability to the bituminous mixture. The analysis through different tests of the CFP, as well as the treatment for their use is described in the methodology.

### 2.1.3. Bitumen Emulsion

The bitumen emulsion used is the commercial C60BF3 MBA emulsion. This emulsion is suitable for bituminous mixtures with discontinuous grading, with its cationic nature and medium breaking time. The choice of this type of emulsion is motivated by two fundamental reasons; the grading of the final bituminous mixture makes it suitable for the coating of the aggregates in the stipulated breaking time; and the chemical nature of the emulsion is suitable for breaking in contact with the EAFS. Therefore, the use of emulsions of an anionic nature has been eliminated, due to incompatibility with the slags. This is also the case for emulsions with other breaking times, fast or slow, because they are not suitable for the grading curve of the bituminous mixture. In Table 1, the technical data sheet of the C60BF3 MBA emulsion is detailed.

**Table 1.** Technical details of the bitumen emulsion C60BF3 MBA used.

Characteristics	Unit	Standard	Min.	Max.
Original Emulsion				
Particle polarity	-	UNE EN 1430	Positive	-
Breaking value (Forshammer filler)	g	UNE EN 13075-1	70	155
Binder content (per water content)	%	UNE EN 12846-1	58	62
Oil distillate content	%	UNE EN 1431	-	5
Efflux time (2 mm, 40 °C)	s	UNE EN 12846	40	130
Residue on sieving (0.5 mm)	%	UNE EN 1429	-	0.10
Setting tendency (7 days storage)	%	UNE EN 12847	-	5
Water effect of binder adhesion	%	UNE EN 13614	90	-
Binder after distillation (UNE EN 1431)				
Penetration (25 °C; 100 g; 5 s)	0.1 mm	UNE EN 1426	-	220
Softening point	°C	UNE EN 1427	35	-
Evaporation residue (UNE EN 13074-1)				
Penetration (25 °C; 100 g; 5 s)	0.1 mm	UNE EN 1426	-	330
Softening point	°C	UNE EN 1427	35	-
Stabilizing residue (UNE EN 13074-2)				
Penetration (25 °C; 100 g; 5 s)	0.1 mm	UNE EN 1426	-	220
Softening point	°C	UNE EN 1427	35	-

### 2.2. Methodology

The methodology followed in this study is based on a series of sequential and ordered tests capable of detecting possible problems in the manufacturing of the final bituminous mixture. The aim of this study is to obtain a sustainable and economical bituminous mixture with particular characteristics, which is possible by the incorporation of byproducts and optimized industrial processes.

First, the materials were characterized chemically, physically and mechanically, to see if they are appropriate. Since they are not commercial and standardized materials, they may have particular characteristics that require special care in the different processes. In order to know these particularities, it is necessary to carry out tests to detect them.

Subsequently, and after determining the suitability of the industrial byproducts for use in bituminous mixtures, the grading curve of the EAFS was determined to form a mixture with discontinuous grading. The grading envelope of this type of asphalt mixture is defined in the Spanish regulations, General Technical Specifications for Roads of 1976 [47]. Once the grading curve was defined, Marshall type samples were conformed without the addition of CFP. The percentage of bitumen emulsion that produced bitumen exudation was selected as the starting point for the manufacture of mixtures with EAFS and CFP. In this way, the retention of bitumen by the CFP could be evaluated. Starting with this percentage of emulsion and with the defined grading curve of the

EAFS, different groups of samples were conformed with increasing percentages of emulsion. These sample groups were manufactured up to the percentage of emulsion that created inadequate emulsion breaking times or was rejected by its compaction. All of the sample groups conformed with emulsion and CFP were subjected to the usual physical tests for bituminous mixtures, as well as the particle loss tests without immersion and after immersion, detailed by the Spanish standards. The Marshall test was carried out to evaluate plastic deformations.

The results obtained from the different groups of samples were analyzed graphically and mathematically to determine the optimal combination of all materials that would provide the best mechanical characteristics. With this optimal combination, the samples were made to check that the best physical and mechanical properties had indeed been achieved. Obtaining this optimal combination of materials creates the final bituminous mixture, corroborating the efficiency of the use of EAFS and CFP in the manufacturing of bituminous mixtures of discontinuous grading with bitumen emulsion.

Figure 1 shows an outline of the different phases of the methodology of this research, as well as the main tests carried out.

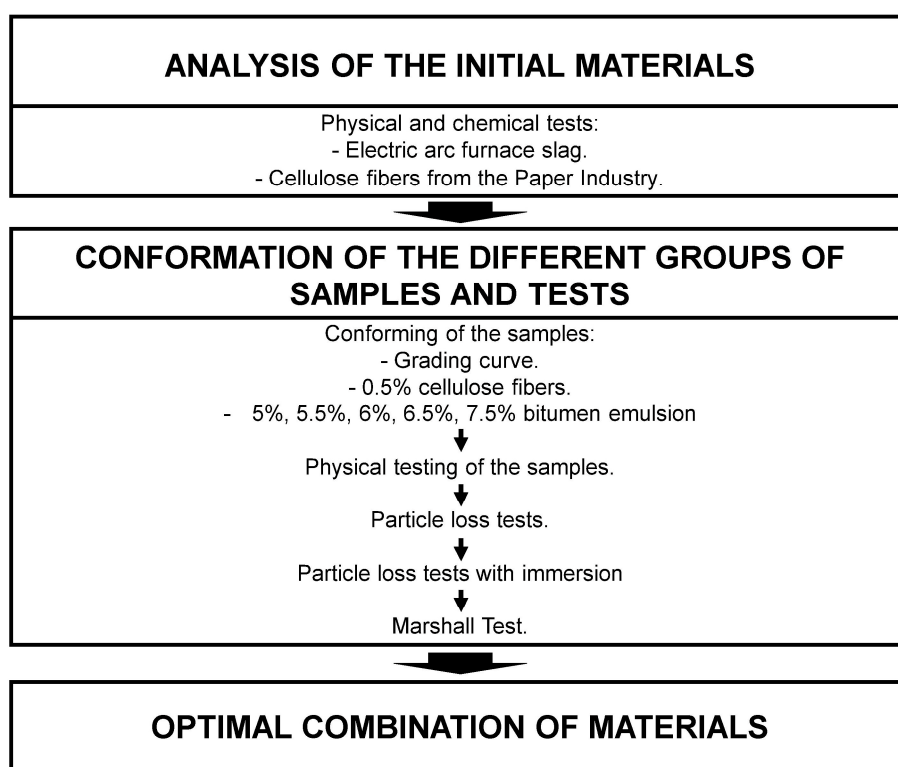


Figure 1. Diagram of the different phases of the methodology.

The following sections describe the detailed tests divided into three main blocks: analysis of the initial materials, conformation of the different groups of samples and tests, and optimal combination of materials.

### 2.2.1. Analysis of the Initial Materials

Initially, the CFP produced as waste in the papermaking industry were studied. These CFP, because of their function to homogenize in the bituminous mixture and absorb the binder, must be treated.

The CFP, as received from the factory, were washed to remove potential dirt and then treated with a solution of sodium hydroxide at 30%. There are two main reasons for carrying out the treatment with sodium hydroxide: the first is to paralyze any organic reaction that may occur; and the second is to remove any natural waxes present that may affect adherence to the bitumen. Once the CFP has been

subjected to this process, it is milled in order to obtain the smallest possible fibers, to cause an excellent homogenization in the mixing process in the bituminous mixture.

The CFP were then subjected to chemical tests: elemental analysis, to determine possible hazardous elements such as sulfur, and scanning electronic microscopy, to observe a large magnification of the shape and length of the final CFP obtained.

The EAFS of the steelmaking industry must be subjected to all existing tests for the corroboration of the quality of an aggregate in roads, but not without first determining the composition, through different chemical tests, for the study of compatibility between materials.

Based on this, the chemical analyses of elemental analysis and X-ray fluorescence were carried out. These tests show the existence of elements that may be hazardous to the bituminous mix and even to the environment. The chemical composition has a significant influence on the compatibility with the emulsion.

Once the chemical suitability of the slag had been assessed, the physical and mechanical characteristics were evaluated. For this purpose, the tests were divided into two groups depending on the size of the aggregate, coarse and fine aggregate, and mineral filler.

The tests carried out on the mineral filler were those of particle density UNE-EN 1097-7 and bulk density in kerosene UNE-EN 1097-3. At the same time, physical tests were carried out on coarse and fine aggregates: particle density UNE-EN 1097-7, sand equivalent test UNE-EN 933-8, percentage of crushed or rounded particles UNE-EN 933-5 and Flakiness index UNE-EN 933-3. The mechanical resistance of the EAFS was evaluated through the tests of resistance to fragmentation UNE-EN 1097-2 and resistance to freezing and thawing UNE-EN 1367-1. It should be noted that both the mineral filler and the coarse and fine aggregates were EAFS with obviously different sizes.

### 2.2.2. Conformation of the Different Groups of Samples and Tests

Once the chemical, physical and mechanical suitability of EAFS and CFP has been analyzed, the discontinuous grading bituminous mixture is formulated, hereinafter AF12. It should be noted that the Spanish legislation on this type of bituminous mixture was repealed, but because the scope of this study is mainly research, the legislation is still valid for the corroboration of the suitability of the bituminous mixture. Apart from the values of the General Technical Specifications for Roads 1976 [47], this study will use the good practice guide provided by the Technical Association of Bituminous Emulsions (hereinafter ATEB) [48], a guide written by experts in the field that sets out the necessary steps for evaluating the suitability of a bituminous mixture of this type.

The grading curve of the EAFS is the one established by the grading enveloped detailed in the aforementioned regulations. This grading curve, in order not to induce more variables, is the intermediate one between the upper and lower spindle; with the exception of the fine aggregate, which is slightly higher so as to form the perfect mixture with the percentages of bitumen and avoid exudations.

Once the grading curve is defined, the compatibility analysis of the aggregate with the emulsion is carried out. To do this, the adhesivity test is carried out according to the UNE-EN 13614 standard.

This test evaluates the quality of the aggregate coating by the emulsion, and consequently, the quality of the final mix to be developed.

First, AF12 bituminous mixtures with EAFS and without the addition of CFP were made. This was done to determine the starting point of the mixture with CFP as the one that produces exudation of the bitumen in the mixture that does not contain CFP. For this purpose, the percentage of emulsion to be added to the bituminous mixture was calculated according to the mathematical formula described by ATEB in its good Practice Guide. It should be noted that EAFS has a higher particle density than conventional aggregates, so in order to avoid problems with dosage, the appropriate volumetric corrections were made.

Once the point considered to be optimal was empirically calculate through the formula provided by ATEB, different groups of samples were made with bitumen, with increasing percentages of 0.5%.

In the conformation, it must be taken into account that the water in the emulsion will later be evaporated, so the reference values are the bitumen that, after evaporation, remain in the bituminous mixture.

The groups of samples carried out for the study of bitumen exudation consisted of three samples of each percentage of emulsion. Subsequently, all of the samples were subjected to a curing process to remove water from the emulsion. The Marshall type samples were flush with the mold and placed on sieves with an opening of less than 2 mm. The curing process consisted of two days at a temperature of  $75 \pm 2$  °C and five more days at a temperature of  $90 \pm 2$  °C (the curing processes are detailed in ATEB). During the curing process, the presence of bitumen exudation was continuously observed, through use of filter paper at the bottom of the sample during the process. The group of samples that caused the bitumen to exude was the starting point for dosing the emulsion into subsequent mixes with the addition of CFP.

Subsequently, the same type of bituminous mixture was made but with the addition of 0.5% of CFP in the aggregate, and with an initial bitumen percentage equal to that which caused binder runoff in the previous groups. The choice of the detailed grading curve is mentioned above, and the addition of 0.5% of CFP was motivated by two factors, one of them being the use in other similar works but in hot bituminous mixture (for example Stone Mastic Asphalt), and the other factor being the corroboration of this percentage as optimal in various studies and regulations on the subject [49].

The different groups of samples were conformed and cured according to the procedure described above, to finally carry out the appropriate physical and mechanical tests. The test carried out for the study of the quality of bituminous mixtures was the particle loss test, according to the UNE-EN 12697-17 standard. Next, and with all of the groups of samples, the study of plastic deformations was carried out with the Marshall test, UNE-EN 12697-34.

To complete the study, and to study the effect of the mentioned groups under adverse conditions, as well as the adequacy of the adhesiveness between the aggregate and the binder, a particle loss test after water immersion NLT-362/92 was performed. This procedure comprised the execution of the particle loss test UNE-EN 12697-17 with the immersion of the specimens before the test and after their curing in water at  $45 \pm 1$  °C for 24 h.

It should be noted that all the test pieces had a total mass of EAFS equivalent to 1000 g of a conventional aggregate. As EAFS have a higher density, volumetric corrections had to be made. CFP were added after the EAFS and before the bitumen emulsion, with the mix stirring time equal to the emulsion breaking time. At the same time, all of the samples were compacted in the impact compactor with 50 impacts per side, UNE-EN 12697-30. After the curing process, the maximum density, bulk density and void content were obtained for all groups of samples, in accordance with standards UNE-EN 12697-5, UNE-EN 12697-6 and UNE-EN 12697-8, respectively.

### 2.2.3. Optimal Combination of Materials and Obtention of Final Characteristics

With the results of the mentioned tests for the different groups of samples, it was possible to observe, graphically and mathematically, the improvement produced in the groups with the addition of the CFP. In turn, the study of graphic and mathematical models provided an optimal percentage of bituminous emulsion that developed the best physical and mechanical characteristics. This combination is the one that was denominated as optimal and with which all the mentioned tests were carried out again for the corroboration of the mathematically determined properties. These tests to determine the physical properties of the final bituminous mixture were: maximum density UNE-EN 12697-5, bulk density UNE-EN 12697-6 and void content UNE-EN 12697-8; and for the mechanical properties: particles loss without immersion and after immersion UNE-EN 12697-17 and the Marshall test UNE-EN 12697-34.

## 3. Results and Discussion

This section describes the results obtained from the tests mentioned in the methodology, subdivided into the three detailed study blocks.



### 3.1. Analysis of the Initial Materials

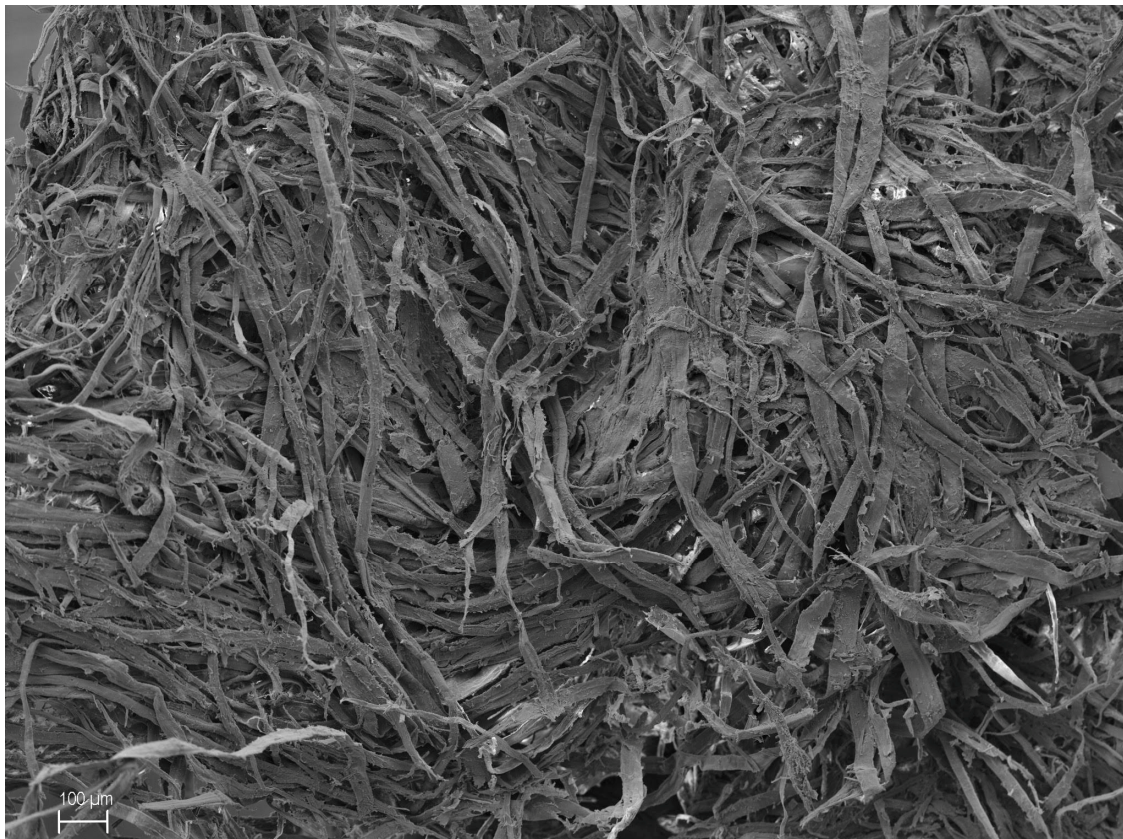
First the CFP were analyzed. The CFP after treatment were subjected to a series of tests. The fundamental test for the study of its chemical composition is the elemental analysis, since it is an organic material. The results of this test are shown in Table 2.

**Table 2.** Elemental analysis of cellulose fibers discarded by the Paper Industry.

Sample	Nitrogen, %	Carbon, %	Hydrogen, %	Sulfur, %
CFP	0.447 ± 0.008	44.489 ± 0.325	5.884 ± 0.178	0.000 ± 0.000

The results reflect a main composition of Carbon and Hydrogen, as expected from a natural fiber. There is also a small amount of Nitrogen, unavoidable because of the type of byproduct, and is not of concern for its use. Sulfur, which could be one of the elements harmful to the bituminous mixture and the environment, does not appear in the fiber composition. Note that the sum of the four elements is not 100%, indicating that there are other inorganic chemical elements in the sample. Sodium may be one of them as the fiber has been washed with sodium hydroxide.

The Scanning Electron Microscope provided an image of the CFP with higher magnifications for this study. Figure 2 shows the image of the CFP in the secondary option obtained with the Scanning Electron Microscope.



**Figure 2.** Image of the cellulose fibers of the Paper Industry obtained with the Scanning Electron Microscope in the secondary option.

The image of the cellulose fibers shows a similarity between them in terms of dimension and surface appearance. In addition, there are no gross fibers or fiber clusters that could damage the bituminous mixture due to incorrect distribution. The average size of the cellulose fibers measured by microscope corresponds to millimeters. They are therefore suitable for use in bituminous mixtures if

the mixing times with the emulsion established in the laboratory are respected and they are distributed homogeneously in the bituminous mixture.

The EAFS were also chemically analyzed through elemental analysis and X-ray fluorescence tests. The X-ray fluorescence test provides further information, as the material has an inorganic composition. The results of the elemental analysis of the EAFS are detailed in Table 3.

**Table 3.** Elemental analysis of electric arc furnace slag.

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

The percentage of Carbon, Nitrogen and Hydrogen in the EAFS sample is very low, as the EAFS is an inorganic waste from the steelmaking Industry. It should be highlighted that there is no Sulfur, which makes the use of the EAFS as an aggregate for the bituminous mixture reliable without leachate problems.

The X-ray fluorescence test performed on the EAFS determined its inorganic composition. The results of the test are shown in Table 4.

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

Compound	Wt %	Est.Error
CaO	31.75	0.23
Fe <sub>2</sub> O <sub>3</sub>	21.96	0.21
SiO <sub>2</sub>	17.52	0.19
Al <sub>2</sub> O <sub>3</sub>	12.26	0.16
MnO	6.15	0.12
MgO	5.05	0.11
Cr <sub>2</sub> O <sub>3</sub>	2.73	0.08
TiO <sub>2</sub>	0.955	0.047
BaO	0.658	0.033
P <sub>2</sub> O <sub>5</sub>	0.319	0.016
SrO	0.186	0.0093
V <sub>2</sub> O <sub>5</sub>	0.159	0.0079
Nb <sub>2</sub> O <sub>5</sub>	0.0659	0.0033
S	0.0645	0.0032
ZrO <sub>2</sub>	0.0551	0.0028
K <sub>2</sub> O	0.0289	0.0016
CuO	0.0254	0.0017
ZnO	0.0245	0.0016
Co <sub>3</sub> O <sub>4</sub>	0.0147	0.0016
Eu <sub>2</sub> O <sub>3</sub>	0.0137	0.0065
WO <sub>3</sub>	0.0104	0.0031
Y <sub>2</sub> O <sub>3</sub>	0.0018	0.0005

The chemical composition of EAFS is directly derived from its formation process. A high percentage of iron is to be expected, as it comes from steel, as well as a high percentage of calcium oxide due to its addition to obtain the final material. Silicon and aluminum oxides are common in the scrap used for the manufacture of new steels. Magnesium, manganese and chromium are also common in the composition of steel. The other elements are found in such small percentages that they cannot be extrapolated. The very low percentage of sulfur ensures that the leachate from the EAFS does not pose an environmental problem, as is the case with other pollutants. Otherwise, we would have to study the leaching of these chemical pollutants and compare them with the limit values established by the regulations. It should be noted that the existence of oxides, mainly calcium oxide, in the unaltered sample of electric arc furnace slag does not cause any subsequent problems of expansion in contact with water. This fact is derived from the industrial process of slag formation—after extracting the

residue, the mixture is watered. In this way, a carbonate of the oxides is produced and therefore stability in its physical structure.

Once the CFP and the chemical composition of the EAFS were analyzed, the physical and mechanical properties were studied. As commented in the methodology, the tests were divided into two large groups depending on the size of the EAFS particles; on the one hand, the coarse and fine aggregate, and on the other, the mineral filler.

In the case of EAFS mineral filler, the particle density was  $3076 \pm 77 \text{ kg/m}^3$ . This density is higher than that of a conventional aggregate that has a density of around  $2650 \text{ kg/m}^3$ . The higher density of the mineral filler of the EAFS makes it necessary to proportion by volume to make the correct combination of materials. On the other hand, the bulk density of the EAFS mineral powder showed the value of  $700 \pm 50 \text{ kg/m}^3$ . The mentioned density value was adequate for its use, reflecting that it is not a pulverulent material that could cause problems in its dosage.

The particle density of the coarse and fine aggregate of EAFS was made for all the grading fractions used in the grading curve for the formulation of the mixture, with these fractions being: 0.063–2 mm, 2–4 mm, 4–8 mm, 8–12.5 mm and 12.5–20 mm. In this way, volumetric corrections were made for each fraction and the mixture dosed as accurately as possible to its density. The results for each particle size fraction are shown in Table 5.

**Table 5.** Particle density of the different grading fractions of electric arc furnaces slags (EAFS).

Grading Fraction	Particle Density, $\text{kg/m}^3$
0.063–2 mm	$3390 \pm 92$
2–4 mm	$3356 \pm 147$
4–8 mm	$3356 \pm 121$
8–12.5 mm	$3199 \pm 72$

The densities of the different grading fractions differ from the density of a conventional aggregate,  $2650 \text{ kg/m}^3$ , which is higher than the density of the EAFS. Volumetric correction is necessary for the dosage, thus ensuring that the percentage of emulsion is not excessive with respect to the aggregate if we proportion by weight.

The absorption coefficient for the coarse aggregate was also evaluated. The reason for carrying out this test was twofold: the calculation of the absorption of the emulsion in comparison with a conventional aggregate, and the study of the possible problems that a high absorption coefficient can trigger in the mineral skeleton of the bituminous mixture. The absorption coefficient of the coarse aggregate showed a value of  $1.50 \pm 0.03\%$ . As can be observed, the value of water absorption was slightly superior to 1%, so it should be taken into account in the dosage of the emulsion since it will absorb more. It could also cause problems due to freezing and thawing cycles in service. However, in order to fully determine its viability, the resistance of the EAFS to freezing and thawing cycles has been calculated.

The result of the fine aggregate sand equivalent test was  $77 \pm 2\%$ . The value is greater than 50%, and therefore the use of EAFS for bituminous mixtures is acceptable, as it does not contain a high percentage of colloidal particles that could cause future problems.

Conversely, the broken surfaces in coarse aggregate particles was calculated for EAFS with a result of  $100 \pm 0\%$ . The achievement of these excellent results is determined by the process of formation of the EAFS, since the shape derives from their formation process with oxygenation in the furnace, making them irregular and with various sharp edges. They are therefore excellent for working in this type of bituminous mixture that requires the formation of a strong and well-fitted mineral skeleton.

To complement the previous test, the flakiness index was calculated, showing a value of  $0 \pm 0\%$ . As in the previous test, these excellent results were obtained due to the process of EAFS formation. Therefore, there are particles of similar dimensions in the three axes, but with irregular surfaces typical of processes with high temperatures. This test, together with the previous one, shows the excellent

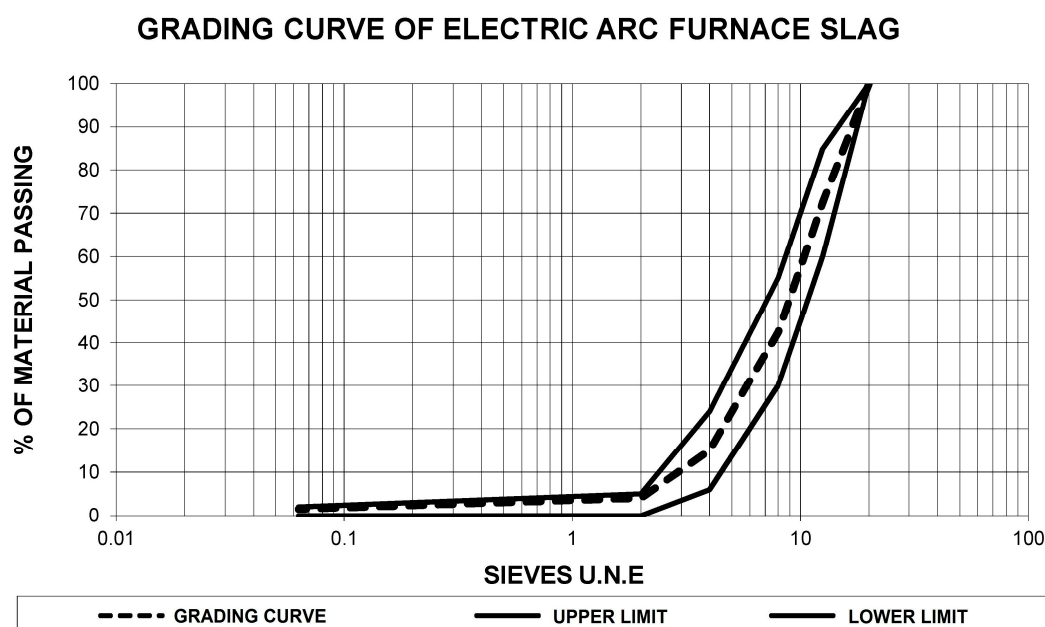
suitability of the EAFS for use in aggregates for bituminous mixtures with discontinuous granulometry, contingent on the results obtained in terms of their mechanical characteristics.

Finally, in order to evaluate the mechanical resistance of the EAFS, the tests of resistance to fragmentation and to the freezing and thawing cycles were carried out. The result of  $13 \pm 1\%$  of the test of resistance to fragmentation makes the slag an ideal material for use in bituminous mixtures for roads, as well as in layers that are mechanically very demanding, such as the wearing course. In turn, the percentage of mass reduction of  $0.551 \pm 0.016\%$  after the freezing thaw cycle test is negligible. Therefore, even if the EAFS has a slightly higher absorption coefficient than the established one, it can be seen that its mechanical behavior during the freezing and thawing cycles is ideal.

The previous tests have reflected the excellent suitability of the EAFS for the conformation of bituminous mixtures, not only in medium traffic roads, but also in roads with important traffic. However, a number of properties must be considered that, while not negative, may cause the bituminous mixture to fail if they were not known. Mainly, these are that the particle density and the absorption coefficient are higher than those of a conventional aggregate.

### 3.2. Conformation of the Different Groups of Samples and Tests

Once the suitability of the EAFS and CFP for the conformation of bituminous mixtures has been studied, the grading curve of the bituminous mixture is defined. The bituminous mixture to be developed is a discontinuous granulometry mixture with bituminous emulsion. The grading curve adopted has an intermediate composition between the upper and lower envelope for the coarse aggregate. On the other hand, and with the purpose of improving the useful life of the bituminous mixture and the resistance to tensile strength, as well as making it possible to absorb increasing percentages of bitumen, the proportion of fine aggregate was slightly increased with respect to the intermediate curve between the upper and lower grading envelope. The grading envelope for this bituminous mixture of discontinuous granulometry with a maximum aggregate size by 12 mm, as detailed in the Spanish regulations, was mentioned in the methodology [47]. The grading curve of the EAFS is detailed in Figure 3 below.



**Figure 3.** Graph of the grading curve of the EAFS referring to the grading envelope established by the regulations

For a conventional aggregate the density is approximately  $2650 \text{ kg/m}^3$ , however, the EAFS has a density that differs from this value. Therefore, the appropriate volumetric corrections were made so as not to add excess emulsion with respect to the aggregate. The density corrections are those detailed in Table 6, also showing the necessary mass of EAFS for each grading fraction for the conformation of Marshall type samples with the established grading curve.

**Table 6.** Composition of the grading curve of EAFS for the manufacture of a Marshall type sample.

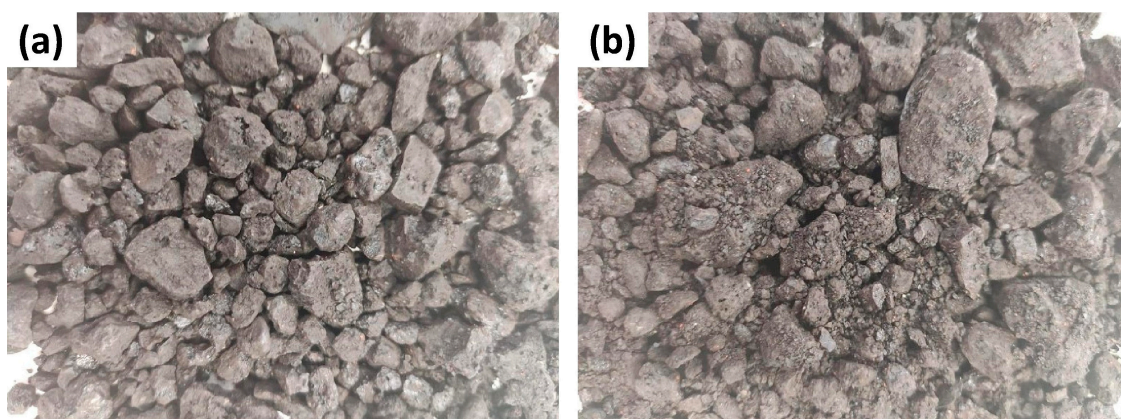
Sieve	% Passing	% Mass	Mass by Particle Size, g	EAFS Density, $\text{kg/m}^3$	EAFS Mass by Particle Size, g
20	100.0	0.0	0	-	0
12.5	72.5	27.5	275	3124	324
8	42.5	30.0	300	3199	362
4	15.0	27.5	275	3356	348
2	4.0	11.0	110	3356	139
0.063	1.5	2.5	25	3390	32
Filler	0.0	1.5	15	3076	17
Total	-	100.0	1000	-	1223

It is observed that the EAFS samples obtained a mass of 1223 g; to obtain a similar sample using conventional aggregate, it should be 1000 g. This fact must be taken into account not only in the dosing of the aggregate, but also in the dosing of the emulsion and the CFP in terms of the mass of a conventional aggregate test sample, that is, to the density of  $2650 \text{ kg/m}^3$ .

Once the grading curve of the EAFS was determined, the compatibility of the EAFS with the bitumen emulsion was evaluated by means of the adhesivity test. This test distinguishes two types of adhesivity; one called immediate adhesivity and corresponding to the aggregate coating with the bitumen emulsion; and the other, aggregate-bitumen adhesivity by studying the aggregate coating by bitumen after the curing process and a 24 h period in water at a temperature of  $60 \pm 1 \text{ }^\circ\text{C}$ . Both values are measured quantitatively, expressing the percentage of EAFS coating by bitumen at the end of the test.

The emulsion used for this test and evaluated for use in bituminous mixtures is a medium breaking cationic bitumen emulsion, more specifically, and according to European standard C60BF3 MBA.

Figure 4 shows the image of the EAFS after the immediate adhesivity test with the aforementioned emulsion and the image of the aggregate-bitumen adhesivity. The result of the adhesivity test is shown in Table 7.



**Figure 4.** Adhesivity test of EAFS and bitumen emulsion C60BF3 MBA. (a) Immediate adhesivity emulsion—EAFS. (b) Adhesivity EAFS—bitumen (Right).

**Table 7.** Adhesivity test of EAFS and bituminous emulsion C60BF3 MBA.

Adhesivity Test	Value, %
% adhesivity of the EAFS to the emulsion. Immediate adhesivity	100
% adhesivity of the EAFS to the bitumen. Aggregate adhesivity—bitumen	100

Both adhesivity measures show an excellent behavior of the emulsion in conjugation with the EAFS, making the use of this emulsion suitable for the studied bituminous mixtures.

On the other hand, the formula provided by ATEB [48] in Equation (1) was used to calculate the percentage of emulsion needed for the AF12 bituminous mixture without CFP. This formula is based on the specific surface area of a conventional aggregate and is detailed below:

$$BR = (K/100) \cdot (1.5A + 2.5B + 4C + 6D + 9E + 12F), \quad (1)$$

where:

- BR = Proportion of residual bitumen on the dry mass of the aggregates.
- K = Coefficient of enrichment, the value of which is 1 in the wearing course and 0.9 in the lower course.
- A = Proportion of aggregates retained by the sieve UNE 20 mm.
- B = Proportion of aggregates passing through the sieve UNE 20 mm and is retained by the sieve UNE 8 mm.
- C = Proportion of aggregates passing through the sieve UNE 8 mm and is retained by the sieve UNE 4 mm.
- D = Proportion of aggregates passing through the sieve UNE 4 mm and is retained by the sieve UNE 2 mm.
- E = Proportion of aggregates passing through the sieve UNE 2 mm and is retained by the sieve UNE 0.063 mm.
- F = Proportion of aggregates passing through the sieve UNE 0.063 mm.

Applying this formula, taking into account a K factor of 0.1 and the values in Table 6 for the other coefficients, gives a bitumen percentage of approximately 3.6% aggregate. Therefore, the percentage of emulsion on aggregate must be calculated. As bitumen represents 60% of the emulsion, in Table 1, the percentage of emulsion is 6% over aggregate. The bituminous mixture with this percentage of emulsion and the detailed grading curve will be the initial one for the study.

It should be noted that the aim of this study is to develop a bituminous mixture with a higher percentage of bitumen due to the incorporation of CFP. In turn, EAFS has a higher absorption coefficient than conventional aggregate. Therefore, tests were made without the addition of CFP, with increasing percentages of bitumen, to observe exudation during the curing process. The percentage of bitumen, and consequently of bituminous emulsion, that led to exudations was the initial percentage for the study of bituminous mixtures with CFP. Therefore, their suitability was corroborated, as no exudation for that percentage occurred when CFP were added, and bituminous mixtures with increasing bitumen percentages of 0.5% were developed. The percentage of emulsion was increased until the breaking time of the bituminous mixture in its manufacture was inadequate, compaction was unacceptable or exudations of bitumen occurred during curing.

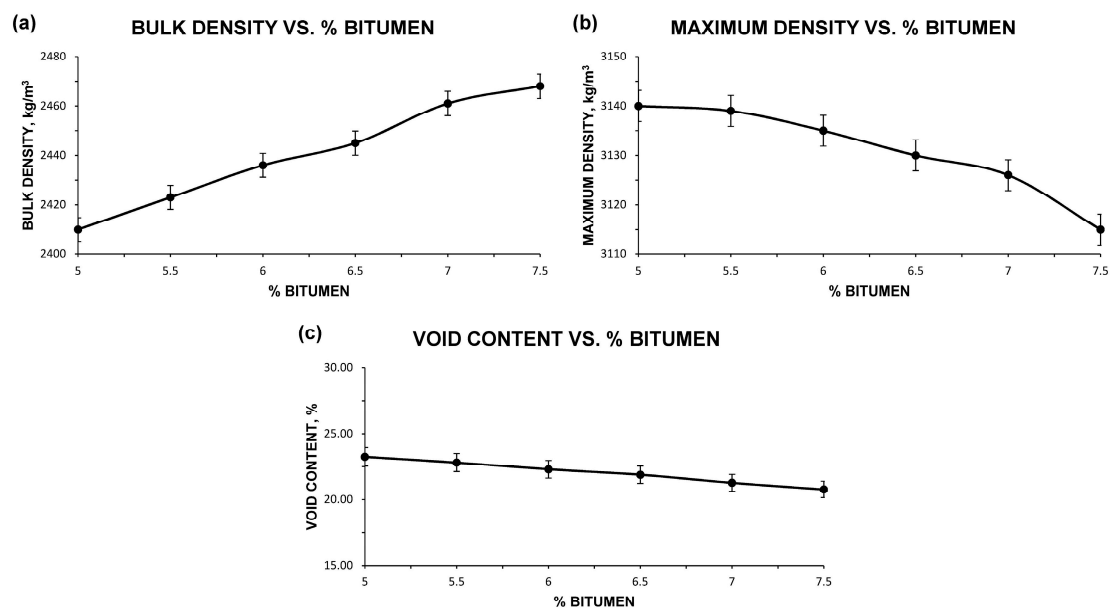
Based on the above, the CFP free samples with 8.3% emulsion and 5% bitumen produced exudation of bitumen during the two days of the oven curing process at  $75 \pm 2$  °C and a further five days at  $90 \pm 2$  °C. Therefore, this is the initial bitumen percentage for the study of new bituminous mixtures with CFP and increasing bitumen percentages of 0.5%.

To complete the information, the groups of samples that were manufactured with the addition of CFP for the tests mentioned in Table 8 are defined.

**Table 8.** Percentages of emulsion and bitumen for groups of samples conformed to bituminous mixtures with EAFS and cellulose fibers (CFP).

Group	Emulsion, %	Bitumen, %
A12F5.0	8.3	5.0
A12F5.5	9.2	5.5
A12F6.0	10.0	6.0
A12F6.5	10.8	6.5
A12F7.0	11.7	7.0
A12F7.5	12.5	7.5

Once the percentage of starting emulsion had been determined, the samples were manufactured with 0.5% CFP and increasing percentages of 0.5% bitumen. The process of compacting and curing the samples were as detailed previously. The breaking and curing times of the bituminous mixtures increased slightly with the increase in the percentage of bituminous emulsion, with the difference being negligible. For each group of samples manufactured, the physical properties were then determined, which were bulk density, maximum density and void content. Figure 5 shows the values obtained from the different tests to determine these physical properties of the different groups of samples with CFP and EAFS.

**Figure 5.** Graphs of physical properties of sample groups with EAFS, bitumen emulsion and CFP. (a) Bulk density, (b) maximum density and (c) void content.

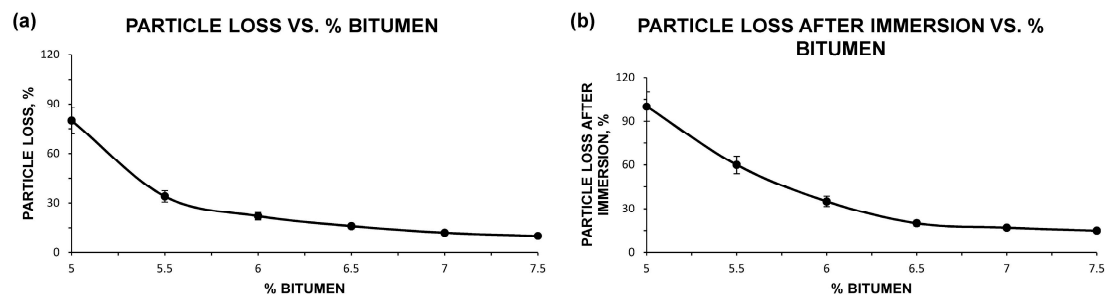
As can be seen, the bulk density increases with the percentage of bitumen added. This is mainly due to the higher compaction possible with the increasing percentage of emulsion and the same compacting energy. The results of this physical parameter influence subsequent parameters such as the void content and, indirectly, the resistance characteristics.

Conversely, the maximum density of the samples is abnormally high compared to the densities of samples of similar mixtures made from conventional aggregate. This increase in density is obviously due to the use of EAFS for their conformation, which is not a problem in principle, but is a detail to be taken into account in their proportioning, storage and transport. The maximum density decreases with the increase in the percentage of bitumen, which is to be expected, as the density of bitumen is much lower than that of EAFS.

Finally, the void content results are high for all groups, with all of them being higher than 20%. This fact, far from being a disadvantage, is one of the properties pursued by the present study, since a

high content of voids in the bituminous mixture means a greater drainage capacity of the pavement in rainy periods, and at the same time, provides an excellent macrotexture. This macrotexture, together with the resistance of the EAFS, gives the wearing course a high level of safety. Also, the fact that it has a high content of voids in the bituminous mixture conditions the comfort of the road, since it absorbs the noise produced by the contact between the tire and the pavement. The disadvantage of a higher void content derives from the possible collapse of the bituminous mixture due to freezing and thawing cycles, or from the introduction of clayey material into the voids, i.e., problems caused by the loss of particles and breaking. This usual disadvantage in discontinuous bituminous mixtures with bitumen emulsion is compensated for with a higher percentage of bitumen provided by the CFP.

Once the good results of their physical properties were obtained, the loss of particles was evaluated, as mentioned previously, in order to study the influence of this high content of voids. The particle loss test was also carried out with a substantial modification in its procedure, namely with the immersion of the samples in water at  $45 \pm 1$  °C for 24 h after curing and before testing. This test modification is shown in the NLT-362/92 standard and allows for an accurate evaluation of the adhesivity of the emulsion and the aggregate, as well as the influence of such a high percentage of void content. The values of the test results of the samples of each family, after their curing process and for the loss of particles without or with immersion, are detailed in Figure 6.



**Figure 6.** Graphs of the particle loss test of bituminous mixtures made with EAFS, bitumen emulsion and CFP. (a) Particle loss tests and (b) particle loss after immersion test.

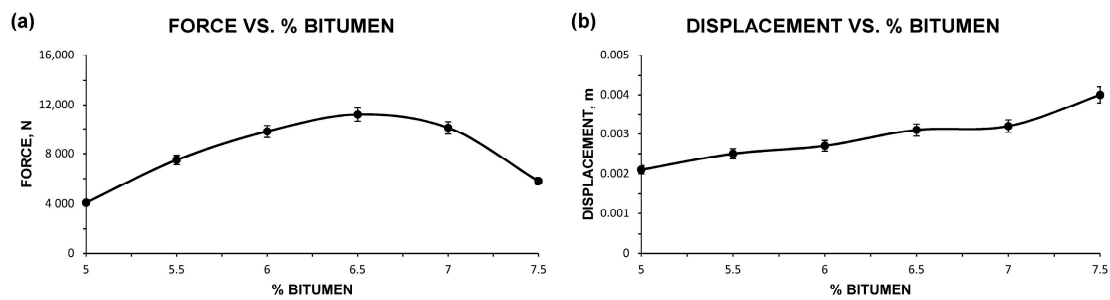
The results of the nonimmersion particle loss test reflect a significant decrease for wear loss of dry bituminous mixtures with the addition of higher percentages of emulsion. This fact is logical if we think that a higher percentage of bitumen will enable a better coating of the aggregate and will also support better external loads.

As established in the Spanish regulations for this type of bituminous mixture with discontinuous grading, values lower than 25% are acceptable for this test [47]. The values from the A12F6.0 group are therefore acceptable results, with a percentage of bitumen of approximately 6%.

Conversely, subjecting the samples of the different groups to the conditions of the loss of particles test after immersion leads to worse results than the loss of particles test without immersion, with the loss being greater by this method in all groups of samples. If we take as a reference what is established by the Spanish regulations and value the bituminous mixture from a safety perspective, then only the A12F6.5, A12F7.0 and A12F7.5 groups have produced results lower than 25%, with these percentages being that to which the field of action is restricted. In the groups indicated as suitable, the difference between particle loss without immersion and after immersion is relatively low. This fact confirms the effectiveness of the bituminous mixtures obtained.

Finally, in order to fully characterize the bituminous mixture, a Marshall test was carried out on all the groups of samples. It should be noted that an increase in the percentage of bitumen will create a bituminous mixture that loses less particles due to wear, however, a higher percentage of bitumen can create important plastic deformations that are totally unacceptable. It is therefore the Marshall test that assesses this characteristic for all sample groups. The results of the Marshall test are shown in Figure 7.





**Figure 7.** Graphs of the Marshall test for all families of samples with EAFS and CFP. (a) Force and (b) displacement.

First, it should be noted that the flow is obviously increasing with the percentage of bitumen added, but that all flow values are acceptable and even reduced compared to other types of bituminous mixtures. Conversely, and as established in the Spanish standards [47], a bituminous mixture with discontinuous grading or porous asphalt must provide a stability value in the Marshall test in excess of 7500 N. Based on this, it can be stated that all groups, with the exception of the first A12F5.0 and the last A12F7.5, are suitable according to this test and this limitation, even if they have very high percentages of bitumen in bituminous mixture and are impossible to carry out without the incorporation of CFP in bituminous mixture.

In addition, all bitumen mix samples after the Marshall test showed that the cellulose fibers were perfectly distributed, without agglomerations and coated with bitumen.

### 3.3. Optimal Combination of Materials and Obtention of Final Characteristics

The families of samples conformed with EAFS as coarse and fine aggregate and mineral filler had 0.5% CFP and increasing emulsion percentages from 8.3% to 12.5%. With this formulation, numerous samples of each group were made for each of the tests, after demonstrating the suitability of the emulsion for the EAFS coating. These tests generated a series of values that were compared with that established in the Spanish regulations General Technical Specifications for Roads of 1976 [47], in order to discard those groups that did not comply with any of the conditions.

The particle loss test removed the A12F5.0 and A12F5.5 groups, the Marshall test removed the A12F5.0 and A12F7.5 groups, and the immersion particle loss test removed the A12F5.0, A12F5.5 and A12F6.0 groups. Therefore, those bituminous mixtures corresponding to the formulations of the groups A12F6.5 and A12F7.0 would be suitable for manufacturing and spreading on roads.

Nevertheless, and with the idea of optimizing the materials to the maximum, it can be seen, how in the graph of the representation of the results of the Marshall stability with respect to the percentage of bitumen, there is a quadratic tendency delimiting a maximum value. This variation is conditioned by the percentage of bitumen, since a defect or an excess of bitumen can and does cause a reduction in Marshall stability. By approximating the series of points through a polynomial function and then obtaining the maximum in the interval under study, the optimum bitumen and emulsion dosage is calculated. This value is roughly in line with 6.5% bitumen and 10.8% emulsion (A12F6.5), as can be seen in the graph of Figure 7.

This will therefore be the optimum combination of materials, consisting of the aforementioned grading curve of the EAFS, a percentage of emulsion of 10.8% and an addition of CFP of 0.5% (percentages referring to the density of an aggregate of density 2650 kg/m<sup>3</sup>).

Therefore, the results of these tests for the optimal combination of materials are described in the Table 9.

**Table 9.** Results of all tests for the optimal combination of materials.

<b>Optimal Combination of Materials 6.5% Bitumen y 0.5% cfp (Group 4)</b>	
Bitumen emulsion about aggregate, %	10.8
Bitumen about aggregate, %	6.5
CFP about aggregate, %	0.5
Bulk density, kg/m <sup>3</sup>	2445
Particle density, kg/m <sup>3</sup>	3130
Void content, %	22.04
Loss of particles without immersion, %	16
Particle loss with immersion, %	20
Marshall stability, N	11,245
Marshall flow, m	0.0031
Wet Wear Loss, %	20

#### 4. Conclusions

The tests carried out in the methodology reflect a series of partial conclusions that are detailed below and will serve to define the final conclusion. It is worth noting, the importance of using of waste has no use currently in the creation of bituminous mixtures, consuming large quantities of these materials and avoiding the extraction of virgin materials.

- Electric arc furnace slags are ideal for use in the proposed bituminous mixture, as well as for use on high traffic roads. The resistance to fragmentation, resistance to the freezing-thaw cycle and the absence of particles in the form of flakes or rounded, make the electric arc furnace slag an excellent aggregate for this purpose. It is also a very low price and environmentally friendly. At the same time, the lack of large quantities of contaminating chemical elements in its composition avoids later problems of leaching. However, its absorption coefficient and density are greater than those of a conventional aggregate, and must be taken into account for its dosage and use.
- Cellulose fibers do not show contaminating elements such as sulfur in their composition. This fact, as well as their uniform and individualized size and shape, have made possible the homogeneous distribution of them in the bituminous mixture absorbing important percentages of bitumen without producing exudations.
- Electric arc furnace slags as a fine aggregate and the higher percentage of bitumen in the bituminous mixture due to the incorporation of the fibers, has led to a suitable mastic capable of withstanding the tensile loads. In turn, the excellent resistance and shape of the coarse aggregate of the electric arc furnace slag has created a mineral skeleton in the bituminous mixture capable of withstanding the compressive loads of traffic. This fact can be seen in the good mechanical behavior of the bituminous mixture in the nonimmersion particle loss tests and postimmersion particle loss tests, as well as in the Marshall test.
- The bituminous mixture with discontinuous grading obtained with the optimal combination of bituminous emulsion, electric arc furnace slags and cellulose fibers has produced better results in the mechanical tests than those usually obtained for this type of bituminous mixture and required by the regulations. Fact derived from the use of both wastes.
- The high voids content, due to the discontinuous grading curve and formed mainly by coarse aggregate, makes the bituminous mixture ideal for most climates and low-cost district roads where it is not profitable to apply a porous asphalt but where a good road surface is essential in periods of rain, as the high voids content, together with the inclination of the subgrade, will allow water to be absorbed from the road surface and withdraw to the ditches.
- The void content favors the macrotexture of the bituminous mixture by the fitting of coarse aggregates, thus ensuring a safe and grippy surface for vehicles. In turn, these voids are capable of absorbing the noise of the pneumatic pavement contact, creating a comfortable road for the user.

- The bituminous mixture developed has a number of objective environmental advantages over traditional mixtures. Firstly, it uses waste from different industries, so gas emissions from the extraction of raw materials are reduced. Furthermore, the use of bitumen emulsion reduces gas emissions compared to the use of mixtures with bitumen. Finally, the creation of a comfortable and safe wearing course significantly reduces the fuel consumption of vehicles due to a deteriorated pavement.
- The bituminous mix developed is less expensive than a traditional bituminous mix. This cost reduction is mainly due to the use of waste instead of raw materials. At the same time, equipment for manufacturing bituminous mixtures with bituminous emulsion is much more economical, reducing the consumption of fossil fuels for heating the mixture. Obtaining a mix with a high percentage of bitumen creates a durable mix where the service life will be longer, reducing repair activities.

On the basis of the partial conclusions, it can be stated that a sustainable bituminous mixture has been achieved, with particular physical characteristics, with acceptable mechanical characteristics and with the use of waste from other industries and bituminous emulsion. This aim has been achieved because of the selection of the most suitable materials for this particular type of road, the selection of the most suitable and sustainable techniques, and the care in the critical points of the methodology with a continuous process of information feedback. It is therefore an example within the field of the circular economy, creating interesting solutions without harming the environment and without sacrificing the quality of the infrastructure

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