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Evaluation of the Use of Electric Arc Furnace Slag and Ladle Furnace Slag in Stone Mastic Asphalt Mixes with Discarded Cellulose Fibers from the Papermaking Industry

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Abstract: The construction sector is one of the most demanding of raw materials that exist at present. In turn, the greenhouse gas emissions that it produces are important. Therefore, at present there are several lines of research in which industrial by-products are incorporated for the manufacture of bituminous mixtures and the reduction of CO_2 emissions, framed inside the circular economy. On the base of the aforementioned, in this research, bituminous mixtures of the Stone Mastic Asphalt type were developed with electric arc furnace slag, ladle furnace slag and discarded cellulose fibers from the papermaking industry. To this end, the waste is first characterized physically and chemically, and its properties evaluated for use in bituminous mixtures. Later, different groups of samples are conformed with conventional materials and with the waste in order to be able to compare the physical and mechanical properties of the obtained bituminous mixtures. The physical tests carried out were bulk density, maximum density and void index, as well as the Marshall test for the evaluation of the strength and plastic deformations of all the bituminous mixtures manufactured. The study and evaluation of the results showed that the incorporation of slag makes it possible to absorb a greater percentage of bitumen and obtain better mechanical properties, while maintaining a similar deformation and void content. Therefore, it is feasible to use the mentioned slags to create sustainable, resistant and suitable pavements for important traffic.

Keywords: pavement; bituminous mixtures; electric arc furnace slag; ladle furnace slag; cellulose fibers; stone mastic asphalt; sustainability; steel; circular economy

1. Introduction

Road construction is an essential activity for the economic development of a nation and the enhancement of social welfare. Moreover, road transport accounts in different countries for a high percentage of total goods transport, being essential for short and medium distance communication. Therefore, the construction of higher quality and with greater safety roads for vehicles is an unquestionable fact [1,2]. However, this type of infrastructure affects the environment throughout its life cycle assessment [3].

The environmental impact produced by the construction of roads begins with their laying out, altering the landscape. Subsequently, for construction a series of materials are required in significant quantities which are mainly extracted from nearby quarries. In turn, during the manufacture of bituminous mixtures creates CO_2 emissions and fossil fuels are consumed. Transport equipment, extension of the bituminous mixture and compaction also represent an important source of greenhouse gas emissions. Once the infrastructure has been executed, the conservation and maintenance work [4], as well as the continuous flow of vehicles, implies a significant effect on the environment during their working life. At the end of their working life [5], the aged materials are removed and dumped in landfills in most cases, without taking advantage of the usefulness they still offer [6].

According to the scheme detailed above, corresponding to the so-called Linear Economy, significant greenhouse gas emissions are produced throughout the life cycle assessment of the road. Consequently, and in line with the new Circular Economy [7], these emissions must be reduced with different methods [8]. Among these different forms of reducing environmental impact is the use of industrial by-products as raw materials [9]. In this way, the extraction of natural materials is reduced, with the consequent decrease in gas emissions, and the deposition of industrial waste in landfills is avoided [10]. Furthermore, the use of the techniques of manufacturing bituminous mixtures more sustainable with the environment and with a much more optimized processes it also offers a significant reduction in environmental impact. In turn, the development of sustainable materials with industrial by-products, with a longer working life and with a higher quality, also creates the reduction of greenhouse gas emissions [11,12]. Finally, the use of aged materials for the manufacture of new materials avoids the dumping of waste in landfills and reduces the extraction of new raw materials. In this manner, the environmental impact is significantly reduced and the flow of materials is closed [13].

In line with the comments above, various investigations have been carried out in which waste has been incorporated for the manufacture of bituminous mixtures and as a substitute for traditional aggregates. Among these wastes are recycled concrete waste [14], copper slag [15], ceramic and brick dust [16], polymer waste [17], recycled glass [18], recovered asphalt pavement [19] and crumb tire rubber [20], among others.

The use of waste is therefore a good option within the Circular Economy that tries to obtain final products of similar quality. However, in this research, Stone Mastic Asphalt (SMA) type bituminous mixtures are developed with electric arc furnace slags and ladle furnace slags in order to improve the properties of the final mixture with respect to those made with virgin materials [21]. This is made possible by optimizing the strength characteristics of the electric arc furnace slag and the cementitious qualities of the ladle furnace slag. Furthermore, the use of industrial by-products derived from the steel of the siderurgical industry allows it to be considered a sustainable material.

Stone Mastic Asphalt (SMA) bituminous mixtures have a discontinuous grading. This discontinuous grading gives them greater resistance to plastic strains, a better surface texture, greater friction of the tire with the pavement [22], greater permeability to evacuate rainwater, and even greater absorption of noise caused by the contact of the tire with the pavement. At the same time, the incorporation of a higher percentage of bitumen compared to other types of discontinuous grading bituminous mixtures, gives it greater resistance to repetitive traction loads and consequently a longer working life [23,24]. This higher percentage of bitumen is achieved by the addition of fibers. These fibers absorb the excess bitumen and prevent it from bleeding out during the working life of the pavement. Therefore, Stone Mastic Asphalt has a high quality and the resistance suitable for use on roads with important traffic during their working lives.

However, the discontinuous grading of the detailed mixture, as well as the required quality, make the use of high-strength aggregates necessary. Aggregates of higher quality and mechanical resistance mainly correspond to siliceous rocks that are difficult to extract and process, producing important CO_2 gas emissions in their extraction and continuous wear of the equipment during processing [25]. Therefore, the use of high resistance electric arc furnace slags, with excellent shape and reduced price [26], means an important reduction of the environmental impact [27]. In addition, the coating of the electric arc furnace slag with bitumen, reduces in most cases, the possible leaching of contaminating elements that it may contain.

The electric arc furnace slag has been used in road infrastructures as an aggregate in concrete pavements [28,29], demonstrating good mechanical behavior of the resulting material. They have also been used as substitutes for natural aggregate in different percentages in hot mix asphalts, showing excellent results in terms of workability, rigidity and fatigue resistance [30,31]. At the same time, warm mix asphalt has been developed with electric arc furnace slag [32,33], reflecting the improvement in the mechanical properties of the bituminous mixes manufactured [34]. Stone mastic asphalt mixtures have even been made with partial replacement of the aggregate with electric arc furnace slag [35], demonstrating that bituminous mixtures with slag were more resistant to cracking at low temperatures than those that incorporated natural aggregate.

In turn, siliceous aggregates have less adhesion with the bitumen than calcareous aggregates, mainly due to their chemical composition and compatibility between materials. Therefore, to execute a correct mastic that coats the aggregates, that supports the traction loads during the working life and avoids the bleeding of bitumen, calcareous filler or cement is usually used. Cement is one of the materials which provides greater resistance to mixing; however, its manufacturing is a process with a significant environmental impact, as it is a high source of greenhouse gas emissions. To solve this fact, in this research, ladle furnace slag was used as a filler. Ladle furnace slags have been studied in different investigations as additives to cement [36–38] or even for soil stabilization [39], showing very interesting cementitious properties [40,41]. Nevertheless, very few investigations have been carried out in which ladle furnace slag is used as a filler in bituminous mixtures [39] and even fewer in mixtures of such high quality as Stone Mastic Asphalt.

On the other hand, for bituminous mixture containing a higher percentage of bitumen to have adequate resistance to repeated traction loads and that no bitumen bleeding occurs, cellulose fibers must be incorporated. These cellulose fibers, introduced in a low percentage into the bituminous mix, are capable of retaining the bitumen in the mix and forming a quality mastic in conjunction with the bitumen and filler. Specially treated commercial fibers are usually used for this purpose; however, in this research and with the aim of making a sustainable mix, cellulose fibers that have been discarded by the papermaking industry were incorporated. These cellulose fibers discarded by the papermaking industry have no current use, so in most cases they are deposited in landfills.

In conclusion, this research develops a quality hot mix asphalt, Stone Mastic Asphalt type, for roads with important traffic with electric arc furnace slag as a coarse and fine aggregate, with ladle furnace slag as a filler and with discarded cellulose fibers from the papermaking industry as an additive. For this purpose, the waste was initially characterized and its properties compared with conventional materials. Subsequently, different families of samples were conformed by increasing percentages of bitumen and the physical properties and Marshall Stability of the mixtures obtained were evaluated. Finally, an optimal material combination was obtained for the asphalt mixtures developed, and the advantages of using the waste over virgin materials were compared.

The tests carried out, as well as their quality limits, will be governed by Spanish regulations, which in turn coincide with European regulations. This Spanish regulation corresponds to the Circular Order OC 3/2019 [42] and was selected because of the profusion of these techniques that have reached the Spanish territory, there existing an infinity of success cases. However, the comparison of the results obtained in bituminous mixtures with waste and bituminous mixtures with traditional materials, objectively reflects the quality of the incorporation of the by-products, and the results can easily be extrapolated to other international regulations.

The results showed that the incorporation of electric arc furnace slag, ladle furnace slag and cellulose fibers created an SMA mix with a higher percentage of bitumen and better mechanical performance, compared to the use of traditional aggregates and fillers.

2. Materials and Methods

This section describes the materials used for the development of the research, as well as the scientific methodology followed to reach the final conclusions. The final objective is the study of the benefits of incorporating the waste mentioned for the manufacture of SMA-type bituminous mixtures.

2.1. Materials

The materials used in this project are mainly waste and commercial materials. These materials are detailed in Section 2.1, defining their origin, production process and particular characteristics, making possible the reproduction of the present tests.

It should be noted that the industrial waste from this research (electric arc furnace slag (EAFS), ladle furnace slag (LFS) and cellulose fibers) was supplied by the producing company in an unaltered form. The process that has been carried out on these wastes is detailed in the following sections.

In turn, it should also be mentioned that the tests carried out have been executed for different production batches of the waste. In this way it has been confirmed that the physical and chemical properties of the waste are maintained over time. This fact is essential, since if the characteristics of the waste were to be modified to a large extent it would make their use in the construction of road infrastructure unfeasible, since large quantities of materials are consumed and could lead to changes in the final characteristics of the bituminous mixtures. It can therefore be stated that the waste studied maintains its physical and chemical properties over time, unlike other wastes such as sewage sludge, cutting sludge, etc.

Finally, it should be mentioned that the ladle furnace slag, electric arc furnace slag, cellulose fibers, as well as the hornfels aggregates and calcareous filler, were dried at a temperature of 105 ± 2 °C for 24 h in order to eliminate the humidity in them. The elimination of the humidity from the materials is intended to avoid introducing more variables into the methodology and to provide objective results. In the subsequent manufacturing process in industry, this humidity of the materials should simply be taken into account in order to take the appropriate corrections, if it was necessary.

2.1.1. Electric Arc Furnace Slag (EAFS)

The electric arc furnace slag used comes from the siderurgical industry located in the region of Andalucía, Spain. These slags have a continuous grading with different particle sizes up to a maximum of 22 mm. The existence of particles smaller than 0.063 mm is negligible, and there are mainly coarse and fine aggregates, in smaller quantities. An irregular shape of the particles can be observed by the processes of their formation.

It may be pointed out that electric arc furnace slag is formed in the metallurgical industry in the first stage called melting and in the electric arc furnace. These furnaces are fed with soft iron or steel scrap. In this melting stage, a series of phases are carried out such as oxidation, to remove manganese and silicon impurities, dephosphorization and the formation of foaming slag. All the impurities are accumulated in this foaming slag. The slag is extracted, forming the electric arc furnace slag after cooling and watering with water.

The production company then crushes the material and performs an economical particle size classification for filler of embankments. These slags are used in the present investigation.

In turn, the mission of the electric arc furnace slag is to replace the traditionally used coarse and fine siliceous aggregate. Therefore, it provides the necessary mineral skeleton of the bituminous mix, and it must be sufficiently resistant to support the repeated compressive loads of the traffic, as well as the roughness to provide good friction between the tire and the pavement. The slag from the electric arc furnace was washed and sieved by different sieves, obtaining the grading fractions necessary for the conformation of the grading curve.

2.1.2. Ladle Furnace Slag (LFS)

The ladle furnace slag comes, like the electric arc furnace slag, from the area of Andalucía, Spain. These slags have a very fine particle size derived directly from their formation process.

Ladle furnace slag is produced in the refining stage, after the melting stage in which the electric arc furnace slag is produced. The refining stage includes a series of phases such as deoxidation, allowing the removal of metal oxides from the furnace, desulphurization and decarburization of the steel. For this phase to take place, the liquid from the electric arc furnace is transferred to the ladle furnace, being covered with slag, and continuously stirred by blowing inert gas, usually argon. Finally, this slag of much smaller particle size is removed and deposited in the vicinity for cooling.

The ladle furnace slag was taken directly from the producing industry as an undisturbed sample and will serve as a filler for the bituminous mixtures conformed. These ladle furnace slags provide the desired cementitious characteristics, which have been confirmed by various authors. For this purpose, they were sieved after drying at 105 ± 2 °C for 24 h by the 0.063 mm sieve.

2.1.3. Cellulose Fiber from the Papermaking Industry

Cellulose fibers are currently an unused waste produced from the cardboard manufacturing industry.

These fibers are formed in the process of producing packaging paper from recycled paper. The recycled paper is grinded with water to put the fibers in suspension, and then submitted to a physical separation with different sieves. Finally, a cyclonic separation is carried out. The waste from this cyclonic separation is transferred to a press to remove some of the water contained in the waste. This waste, after being pressed, is the one used in this research and is called cellulose fiber discarded by the paper industry.

Detailed cellulose fibers are the additive that was incorporated into the bituminous mix for the retention of a higher percentage of bitumen in the mix. These fibers have been taken from the production industry and have undergone a process of adaptation for use in bituminous mixtures. This process consists of a washing with a 30% sodium hydroxide solution. This pre-treatment is carried out with a double objective; on the one hand, the organic reactions that could be produced are paralyzed; on the other hand, any natural waxes that could be adhered to the fibers and that would prevent the correct adhesion with the bitumen of the bituminous mix are removed. Once this pre-treatment has been carried out, they are ground to achieve the smallest possible fiber size, making it possible to homogenize them during the mixing process in the bituminous mixture.

2.1.4. Bitumen

The bitumen used is a 50/70 bitumen as defined by European regulations, both numbers being the penetration rate at which it oscillates. This hard penetration bitumen is usually used in the Spanish regions due to the existing hot climates. It is a commercial bitumen without additives. Its technical data can be seen in Table 1.

Table 1. Technical specifications of the bitumen used.

Characteristics	Unit	Standard	Min	Max
Fresh binder				
Penetration (25 °C)	0.1 mm	UNE-EN 1426 [43]	50	70
Penetration index	-	UNE-EN 12591 [44]	−1.5	0.7
Softening point (R & B)	°C	UNE-EN 1427 [45]	46	54
Fraass point	°C	UNE-EN 12593 [46]	-	−8
Solubility in xylene	%	UNE-EN 12592 [47]	99.0	-
Flash point	°C	UNE-EN ISO 2592 [48]	230	-
Resistance to Hardening 163 °C (UNE-EN 12607-1) [49]				
Mass loss	%	UNE-EN 12607-1 [49]	-	0.5
Retained penetration	%	UNE-EN 1426 [43]	50	-
Increase in softening point (R & B)	°C	UNE-EN 1427 [45]	-	11

2.1.5. Hornfels Aggregate

Hornfels aggregate is a commonly used aggregate on important traffic roads mainly due to its excellent characteristics. This aggregate comes from the area of Andalucía, Spain, just like the other materials.

Hornfels rocks are a type of contact metamorphic rocks, very hard and with great resistance to the cycles of freezing and thawing. It contains a high proportion of quartz, graphite, biotite, iron oxide or feldspars, so it can be considered a quality siliceous rock.

The extraction of this material in quarries, being a hard rock, consumes a great quantity of explosives, since its resistance to fragmentation is high. In addition, its siliceous composition means that treatment and processing equipment often wear out, compared to limestone stone.

It is therefore an aggregate of excellent quality, in which significant greenhouse gas emissions are emitted during its extraction and with which electric arc furnace slag is to be compared. Therefore, its function within the bituminous mixtures created is that of a coarse and fine aggregate. To this end, as with the slag, the aggregate is received from the quarry and washed, to be subsequently sieved by different sieves that can form the selected grading curve.

2.1.6. Calcareous Filler

The problems derived from the lack of adhesion between the siliceous aggregates and the bitumen make the use of filler of limestone type common. Calcareous aggregates have much lower resistance than siliceous ones, as well as a lower resistance to the abrasion caused by the tire. Therefore, its use in important traffic roads is not usual or recommended.

However, its use as an inert filler makes possible the formation of a mastic of acceptable quality that coats the siliceous aggregates and forms a structure capable of withstanding the loads of traffic. Therefore, the function of the calcareous filler in the present investigation is the comparison with the properties of the bituminous mixtures conformed with it, with those of the mixtures conformed with ladle furnace slag.

The calcareous filler supplied by the producing company had a very fine particle size and did not need to be sieved, unlike the ladle furnace slag. This filler was dried at 105 ± 2 °C for 24 h to avoid the existence of water during the conformation of the bituminous mixtures.

2.2. Methodology

The methodology followed in the present investigation is composed of a series of logically ordered tests to obtain objective results on the quality of the execution of Stone Mastic Asphalt type bituminous mixtures with electric arc furnace slag, ladle furnace slag and cellulose fibers from the papermaking industry. To this end, bituminous mixtures manufactured were compared with bituminous mixtures conformed with commercial materials.

Based on this, the wastes were analyzed to determine their physical properties and chemical composition. In this way, the suitability of the materials for forming SMA mixtures for roads with high vehicle traffic was evaluated.

Subsequently, mixtures were conformed with traditional aggregates and with waste, as well as increasing percentages of bitumen. The groups of samples conformed were analyzed to obtain the physical and resistant properties, through the Marshall test.

Finally, and after evaluating the properties of the different mixtures, the optimum combination of materials was obtained for each family of samples studying the advantages of using electric arc furnace slags, ladle furnace slags and cellulose fibers.

The following sub-sections describe each of the research phases in detail.

2.2.1. Characterization of Raw Materials

The waste and commercial materials were treated as detailed before in order to be able to carry out physical and chemical characterization tests, as well as for use in subsequent tests.

Firstly, the electric arc furnace slag, ladle furnace slag and cellulose fibers were analyzed by elemental analysis, determining the percentage of carbon, nitrogen, hydrogen and sulfur in the samples. In turn, the slags were subjected to the X-ray fluorescence test, as they are inorganic materials, unlike cellulose fibers from the papermaking industry.

Once their chemical composition had been determined and the presence of contaminating elements that could prejudice the final bituminous mixture analyzed, a series of physical tests were carried out on the different wastes according to the function that each one plays within the bituminous mixture.

The cellulose fibers from the papermaking industry were evaluated with a scanning electron microscope (Carl Zeiss, Oberkochen, Germany) at different magnifications and after metallization with carbon. The size of the fibers obtained after pre-treatment and the existence of agglomerations that could impair the homogeneous distribution of the fibers in the bituminous mixture were thus observed.

The ladle furnace slag was subjected to particle density tests (standard UNE-EN 1097-7) [50], to evaluate the possible volumetric corrections required; bulk density tests (standard UNE-EN 1097-3) [51], to determine whether it is a powdery material that is detrimental to its proportioning; and plasticity index tests (standards UNE 103103 and UNE 103104) [52,53], to evaluate the possible existence of clayey particles that could create expanding problems in the final mix.

The electric arc furnace slag was subjected to particle density tests (standard UNE-EN 1097-7) [50], to determine whether volumetric corrections were necessary; a sand equivalent test (standard UNE-EN 933-8) [54], to evaluate the percentage of colloidal particles that could damage the final mixture; percentage of crushed surface tests (standard UNE-EN 933-5) [55]; and flakiness index tests (standard UNE-EN 933-3) [56], for the qualification of the aggregate, since the SMA mixture resists the loads of traffic on the mineral skeleton, and therefore the particles must have certain shapes; resistance to fragmentation tests (standard UNE-EN 1097-2) [57], to qualify the hardness of the material and its suitability for high traffic; resistance to freezing and thawing cycles tests (standard UNE-EN 1367-1) [58], to evaluate the aggregate's resistance to thermal fatigue; and determination of the value of polished stone (standard UNE-EN 1097-8) [59], to quantify the effect on the aggregate of the continuous tire friction of the with the pavement and, consequently, its durability through time.

2.2.2. Conformed of Bituminous Mixtures and Tests

Once the previous tests had been carried out, specific for each material and in accordance with the role that each material plays in the mixture, we proceeded to make the bituminous mixtures reflected in Table 2 with the materials detailed.

Table 2. Families of bituminous mixtures conformed with electric arc furnace slag, Hornfels aggregate, ladle furnace slag, calcareous filler and fibers from the papermaking industry.

Samples Groups	ACFC	ASFC	ASFS
Coarse aggregate	Hornfels aggregate	EAFS	EAFS
Fine Aggregate	Hornfels aggregate	EAFS	EAFS
Filler	Calcareous	Calcareous	LFS
Additives	Papermaking waste	Papermaking waste	Papermaking waste

As shown in Table 2, there are families of bituminous mixtures conformed with virgin materials and families conformed with waste. In this way, the qaulity of the incorporation of waste is easily comparable.

The materials that perform the function of aggregate, whether waste or natural aggregates, were dried and sieved by different sieves to obtain the desired grading curve. The grading curve used corresponds to the intermediate grading curve established by the grading envelope detailed in the regulations of Circular Order OC 3/2019 [42]. The selection of this grading curve is motivated by an essential reason: to compare the difference between bituminous mixtures made with natural aggregates and those made with slag. To do so, they must have the same grading, thus avoiding secondary variables that could mask the final conclusions. In addition, cellulose fibers discarded from the papermaking industry were incorporated into all bituminous mixtures in a percentage of 0.5% in mass and regarding conventional aggregate (conventional aggregate density 2.65 t/m^3), as indicated by various studies on this type of mixture. The grading curve for the three families of samples is shown in Figure 1.

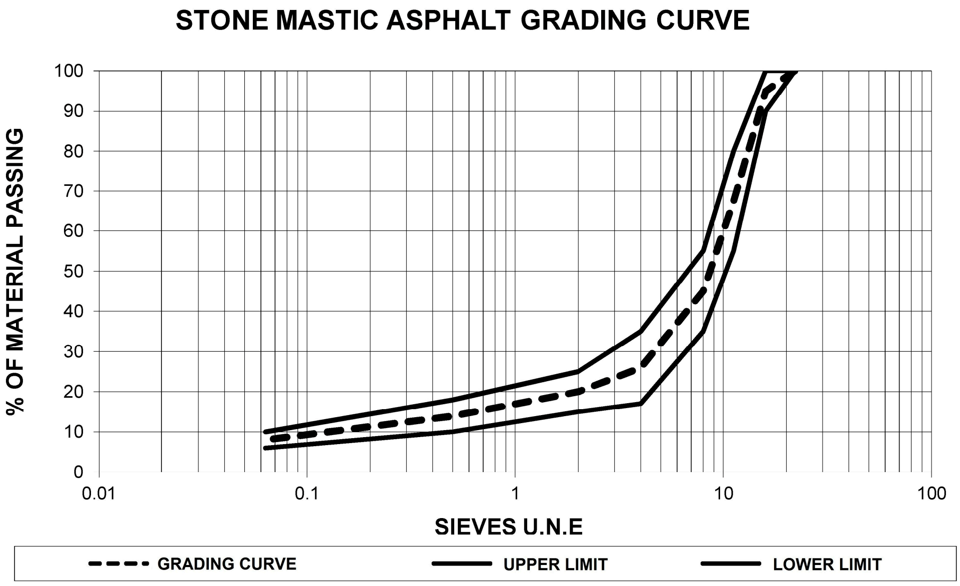

Figure 1. Grading curve of the different families of bituminous mixtures (ACFC, ASFC and ASFC) type SMA.

Once the grading curve was defined, different groups of samples were conformed of the three types of bituminous mixtures detailed in Table 2. In order to be able to compare the results faithfully, and given that the electric arc furnace slag has a higher density than the hornfels aggregates, the percentage of bitumen by volume was proportioned. This proportioning by volume allows an objective evaluation of the bitumen absorption capacity of bituminous mixtures with slag, since if mass proportioning was done, the optimum bitumen percentage would not be comparable due to the high density of the slag.

Based on the comments above, the families of mixtures were manufactured with percentages of bitumen in volume and regarding aggregate from 15% to 18% in 0.5% increments. To this end, the aggregates (natural or waste) were heated in an oven to a temperature of 180 ± 5 °C for 1 h, as was the bitumen and cellulose fibers, and then mixed in an automatic planetary mixer (MECÁNICA CIENTÍFICA S.A., Madrid, Spain) for 10 ± 1 min. The resulting mixture was extracted and compacted by a Marshall compactor (MECÁNICA CIENTÍFICA S.A., Madrid, Spain) with 50 blows per side to each specimen (standard UNE-EN 12697-30) [60]. The conformed specimens were left at ambient temperature for 24 h for subsequent mechanical stripping. A total of 8 Marshall-type samples were made for each percentage of bitumen in each family.

Once the groups of samples with increasing percentages of bitumen from each family of samples had been obtained, the physical properties were characterized. The tests carried out were on the maximum density of the bituminous mixture (standard UNE-EN 12697-5) [61] and bulk density (standard UNE-EN 12697-6) [62]. In turn, the void characteristics of the bituminous mixtures obtained were calculated (standard UNE-EN 12697-8) [63].

The Marshall test was carried out to evaluate the mechanical resistance of the families of bituminous mixtures conformed (standard UNE-EN 12697-14) [64]. With this test, the plastic deformations that occur in each bituminous mix can be evaluated, this being an essential characteristic due to the high percentage of bitumen that SMA bituminous mixes have.

2.2.3. Determination of Optimal Material Combinations and Comparison of the Results

Once the mechanical and physical properties of the three families of samples with different bitumen percentages had obtained, the optimum combination of materials was then obtained. This optimum combination of materials was calculated graphically, taking Marshall stability as the main property. In other words, the percentage of volume of bitumen which provided the highest Marshall stability of each family (ACFC, ASFC and ASFS) was calculated, provided that permissible values were obtained for the physical properties and deformation of the bituminous mixtures.

With the optimum combinations of materials for the three families of samples (ACFC, ASFC and ASFS), samples were again made to evaluate the physical and mechanical properties obtained graphically, thus corroborating the quality of the material selection. In turn, binder drainage tests UNE-EN 12697-18 [65] were carried out, to evaluate that the fibers fulfilled their function within the conformed bituminous mixtures and that there were no bleeding of bitumen due to their high percentage; wheel-tracking tests [66] were also conducted, to evaluate the durability of the mixture before the continuous passage of vehicles.

The results obtained from the different sample families for their optimal material combination were compared. In this manner, the influence of the use of electric arc furnace slag and ladle furnace slag in the manufacture of Stone Mastic Asphalt mixtures with cellulose fibers from the papermaking industry can be objectively evaluated.

3. Results and Discussion

This section describes the results of the trials mentioned in the methodology, as well as the discussion about them. The series of trials logically ordered will condition the final conclusions, there being at all times a continuous process of feedback.

3.1. Characterization of Raw Materials

A significant percentage of waste is used in this research. These wastes are electric arc furnace slag, ladle furnace slag and discarded cellulose fibers from the paper industry. The use of waste has a number of environmental advantages as discussed above; however, this waste must be physically and chemically characterized in order not to induce problems in the final material.

Firstly, the discarded cellulose fibers from the paper industry were analyzed. These fibers were analyzed, after the treatment described in the methodology, in an elemental analyzer (TruSpec Micro, LECO, St. Joseph, MI, USA) to detect the percentage of carbon, nitrogen, hydrogen and sulfur in the sample. This test is essential for the material under study since, unlike slag, it is organic in nature. The results of the elemental analysis of the cellulose fiber waste from the papermaking industry are detailed in Table 3.

Table 3. Elemental analysis of cellulose fibers discarded by the papermaking industry.

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

As can be seen, the percentages of carbon and hydrogen are high, as they correspond to an organic material. On another point, the percentage of nitrogen contained in the sample is low, a fact that should be taken into account as it could damage the final bituminous mix. In turn, the percentage of sulfur is null. The low proportion of elements such as nitrogen and sulfur therefore ensures that these fibers are well incorporated into the bituminous mixtures, since otherwise they could leach contaminant elements and even affect the characteristics of the bituminous mixtures. It is important to note that the sum of the elements analyzed does not correspond to 100% of the chemical composition, so there must be other inorganic chemical elements in the fibers analyzed. These inorganic chemical elements could correspond to the treatment carried out on the cellulose fibers before their use for conforming bituminous mixtures, this main element being sodium, since the fibers are treated with sodium hydroxide.

At the same time, and in order to characterize the cellulose fibers of the papermaking industry in a complete way, the scanning electron microscope test was carried out. This test aims to identify the shape of the fibers with high magnification, focusing mainly on their size and the existence of agglomerations. Both of these detailed factors have a significant influence on the correct mixing of the fibers with the aggregates and the bitumen. The scanning electron microscope therefore provided sufficient physical information to evaluate the suitability of the fibers for homogenization within the bituminous mix and, consequently, the increased retention of bitumen and the elimination of bleeding from the bituminous mix. Figure 2 shows the image of the cellulose fibers obtained with a scanning electron microscope.

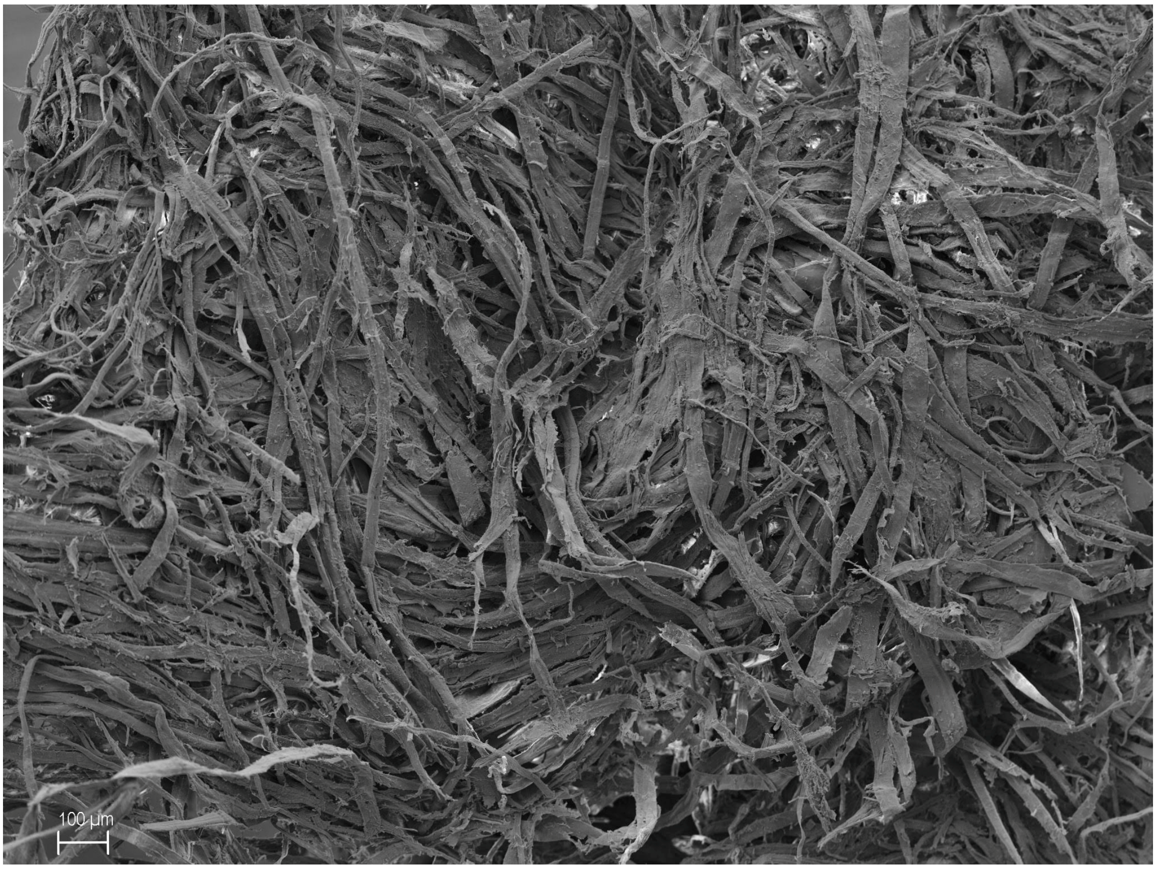

Figure 2. Image of the cellulose fibers of the paper industry obtained with the scanning electron microscope in the secondary option.

As can be seen in Figure 2, the cellulose fibers analyzed have millimetric dimensions, and there are no agglomerations of these fibers that could damage their homogeneous distribution in the bituminous mix. Therefore, they are considered to be suitable for use.

Once the cellulose fibers were analyzed, they were characterized the ladle furnace slag. The ladle furnace slag was used as a filler. Therefore, these slags must form, together with the bitumen and cellulose fibers, a mastic of adequate quality to resist the continuous traction loads of the pavement. For this reason, it is essential to characterize them chemically, determining the existence of chemical cementitious compounds or polluting chemical elements that must be controlled in subsequent processes. Table 4 shows the results of the elemental analysis of the ladle furnace slag.

Table 4. Elemental analysis of the ladle furnace slag.

Sample	Nitrogen, %	Carbon, %	Hydrogen, %	Sulfur, %
LFS	0.007 ± 0.001	3.405 ± 0.068	1.386 ± 0.026	0.000 ± 0.000

Elemental analysis of the ladle furnace slag shows that it does indeed correspond to an inorganic material. The low percentage of nitrogen and sulfur, being the latter, of which is very harmful to the final bituminous mix, should be noted. If significant percentages are available of sulfur in the slag, a leachate test should be carried out later to confirm the retention of this element in the bituminous mixture. On the other hand, and due to the ladle furnace slag production process, the existing percentages of carbon and hydrogen come directly from the carbonate compounds and hydration of the oxides present in the slag, as reflected by X-ray fluorescence. This process is natural in this type of material and is mainly due to the open-air exposure of the waste after its extraction.

The X-ray fluorescence test provided sufficient information about the other chemical elements; this test is detailed in Table 5.

Table 5. Results of the X-ray fluorescence of ladle furnace slag.

Compound	Wt, %	Est. Error
CaO	40.19	0.25
MgO	19.38	0.20
SiO_2	12.49	0.17
Al_2O_3	7.29	0.13
Fe_2O_3	2.38	0.08
MnO	0.936	0.047
S	0.548	0.027
TiO_2	0.486	0.024
BaO	0.240	0.012
Na_2O	0.118	0.042
Cr_2O_3	0.1100	0.0055
Cl	0.0833	0.0042
SrO	0.0733	0.0037
ZnO	0.0681	0.0034
K_2O	0.0506	0.0025
ZrO_2	0.0425	0.0021
V_2O_5	0.0179	0.0017
P	0.0138	0.0012
CuO	0.0117	0.0010
NiO	0.0082	0.0011
PbO	0.0048	0.0010
Nb_2O_5	0.0046	0.0006
MoO_3	0.0028	0.0009
Co_3O_4	0.0021	0.0009
SeO_2	0.0012	0.0005

The X-ray fluorescence (Thermo Fisher Scientific, Waltham, MA, USA) test shows a chemical composition of the ladle furnace slag that is logical and derived from its production process. The existence of calcium oxides, magnesium oxides and silicon oxides in a higher proportion is mainly due to the material added to the ladle furnace for steel purification. The incorporation of lime or dolomites in the ladle furnace creates this composition of the steel oxides. In addition, the function of ladle furnace slag is the deoxidation and desulphurization of steel, so it is logical to find metal oxides and sulfur in its composition. However, there are no chemical elements that could directly damage the mechanical characteristics of the bituminous mixtures, nor are there any polluting elements in large proportion that could be leached out later and cause environmental pollution.

On the other hand, the physical properties of the ladle furnace slag were quantified. The main tests to determine these properties, for a material that plays the role of filler in the bituminous mix, are detailed in Table 6.

Table 6. Density and plasticity tests for the fine portion of ladle furnace slag.

Test	Standard	Value/Unit
Particle density	UNE-EN 1097-7 [50]	2.71 ± 0.07 t/m^3
Bulk density	UNE-EN 1097-3 [51]	0.75 ± 0.01 t/m^3
Plasticity index	UNE 103103/UNE 103104 [52,53]	No plasticity

It can be seen how the particle density of ladle furnace slag is slightly higher than that of a commercial calcareous filler. At the same time, the bulk density in kerosene of the slag reflects the behavior of a powdery material, which without producing proportioning problems in the factory if it has a reduced particle size is capable of adhering correctly with the bitumen and forming a quality mastic. The non-existence of plasticity avoids subsequent problems of expansiveness due to the existence of clayey particles. This lack of plasticity is due to the chemical composition of the ladle furnace slag, as it is mainly composed of calcium and magnesium oxides.

On the other hand, electric arc furnace slag plays the role of a coarse and fine aggregate in the bituminous mix. The tests carried out must therefore check the suitability of the slag for this purpose. For chemical characterization, the elemental analysis test was carried out; this test is reflected in Table 7.

Table 7. Elemental analysis of the electric arc furnace slag.

Sample	Nitrogen, %	Carbon, %	Hydrogen, %	Sulfur, %
EAFS	0.005 ± 0.000	0.164 ± 0.003	0.044 ± 0.001	0.000 ± 0.000

Elemental analysis of electric arc furnace slag mainly shows its inorganic composition. The low percentages of carbon and hydrogen reflect that these slags are a more stable material than ladle furnace slags, as no carbonated or hydrated processes of the chemical compounds take place. The null values of sulfur and nitrogen should be highlighted, so there will be no leaching of these elements in the final bituminous mixtures. The remaining chemical elements present in the sample of electric arc furnace slag were determined with the X-ray fluorescence test. This test is shown in Table 8.

The chemical composition of EAFS derives directly from its formation process. A high percentage of iron is to be expected, since it comes from steel, as well as a high percentage of calcium oxide due to its addition to obtain the final material. The silicon and aluminum oxides are common in the scrap that is used for the manufacture of new steels. Magnesium, manganese and chrome 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 EAFS leachate 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 problem 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. This produces a carbonate of the oxides and therefore stability in its physical structure.

Table 8. X-ray fluorescence of electric arc furnace slag.

Compound	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
SrO	0.186	0.0093
V_2O_5	0.159	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

It should be noted that European or American regulations governing the leaching of chemicals elements of the aggregates for roads show restrictions on heavy metals, chlorides, fluorides or sulphates. These chemical elements are in a proportion of less than 1%, and even much less, in ladle furnace slags and electric arc furnace slags, not existing in their composition in some cases. Therefore, the leaching of these elements is minimal, as the electric arc furnace slag is mainly composed of calcium oxide, iron oxide, silicon oxide and aluminum oxide, as well as the ladle furnace slag of silicon oxide, calcium oxide and magnesium oxide. None of these chemical compounds mentioned are limited in their concentration in the leachate, as they do not produce environmental pollution. In addition, the coating of the slag with bitumen of the bituminous mixture quantitatively reduces the leaching of any element, therefore, the compliance of the quality standards is assured.

Once the chemical composition of the electric arc furnace slag had been analyzed and the absence of chemical elements that could damage the final bituminous mix during its manufacture or its working life had been assessed, the physical and resistance properties of the slag were determined. Table 9 shows the physical tests carried out on electric arc furnace slag.

Table 9. Density and plasticity tests for the fine portion of ladle furnace slag.

Test	Standard	Value/Unit
Particle density (coarse aggregate)	UNE-EN 1097-7 [50]	3.13 ± 0.05 t/m^3
Particle density (fine aggregate)	UNE-EN 1097-7 [50]	3.34 ± 0.07 t/m^3
Sand Equivalent test	UNE-EN 933-8 [54]	77 ± 2%
Broken surfaces (coarse aggregate)	UNE-EN 933-5 [55]	100 ± 1%
Flakiness index	UNE-EN 933-3 [56]	0 ± 1%

As can be seen in Table 9, the particle density of electric arc furnace slag is higher than that of a traditional aggregate (approximately 2.65 t/m^3). This higher density is due to its chemical composition composed of metallic elements, mainly iron. However, a higher density does not affect the process of conforming bituminous mixtures or their final characteristics, it should only be taken into account for the correct proportioning of the bitumen and the additives, as well as their comparison. Therefore, since the density of the ladle furnace slag is higher than that of the Hornfels aggregate, the bitumen was proportioned by volume so that the results were comparable and it was possible to evaluate which material is capable of absorbing a higher percentage of the bitumen. On the other hand, the sand equivalent test reflects the low proportion of colloidal particles that exist in the electric arc furnace slag, so there are no subsequent problems of expansiveness in the bituminous mix due to clayey materials. The excellent results obtained from the tests on the percentage of broken surfaces and the flakiness index should be highlighted. Both tests reflect the aptitude of the slag for the conformation of Stone Mastic Asphalt type mixtures, since this type of bituminous mixture has a discontinuous grading, the compression loads of the traffic are supported by the friction of the coarse aggregate. Therefore, the coarse aggregate is required to have optimum results from these tests so that no subsequent compaction of the bituminous mix occurs due to the continuous passage of vehicles. This excellent shape of the particles in the electric arc furnace slag is due to the production process, since the continuous oxygenation of the furnace causes the irregular shapes and edges that the particles have.

As mentioned, in Stone Mastic Asphalt mixes the repeated traction loads caused by traffic are borne by the mix mastic formed by the filler, bitumen and fibers. In turn, the compression loads are mainly supported by the coarse aggregate due to friction between particles and due to the discontinuous grading. Therefore, if designing bituminous mixtures for high traffic is intended, the coarse aggregate must have an adequate resistance to avoid its fracture. This resistance has been evaluated by the tests of resistance to fragmentation (standard UNE-EN 1097-2) [57] and resistance to freezing and thawing cycles (standard UNE-EN 1367-1) [58] reflecting values of 13 ± 1% and 0.551 ± 0.016%, respectively. These results show the excellent resistance of electric arc furnace slag to both fracture and thermal fatigue and are therefore only comparable with excellent quality and very expensive aggregates, both economically and environmentally.

At the same time, the continuous friction of the tire with the pavement creates a polishing of the aggregate of the bituminous mixture, with the consequent decrease in safety for the driver. Therefore, it is essential to perform the determination test of the polished stone (standard UNE-EN 1097-8) [59]. This test reflected a value of 58 ± 1. This result ensures an adequate resistance of the slag to the continuous passage of vehicles and a durability in time of the surface roughness.

In short, and based on the results of the waste characterization tests, it can be stated that both electric arc furnace slag and ladle furnace slag and cellulose fibers from the papermaking industry have suitable characteristics for use in bituminous mixtures. However, if it is true that special precautions must be taken to achieve successful incorporation into the bituminous mix.

3.2. Conforming of Bituminous Mixtures and Tests

Once the physical and chemical characteristics of the waste, bituminous mixtures of the families detailed in Table 2 were conformed, with the grading curve defined in Figure 1 and with percentages of bitumen in volume of aggregate of 15% to 18%.

All the samples conformed were analyzed to evaluate their physical properties and resistance. The first of the tests carried out on the bituminous mixtures was the bulk density test. This test is shown graphically in Figure 3.

As can be seen, the bulk density of bituminous mixtures with electric arc furnace slag is higher than the bulk density of mixtures with hornfels aggregate. This fact is fundamentally due to the higher density of the electric arc furnace slag, which does not negatively influence the subsequent results but if is a factor to be taken into account. The difference in density between mixtures made with calcareous filler or ladle furnace slag filler is very small, since the density of both materials is similar and as well the percentage of filler incorporation being lower. In turn, the maximum density of bituminous mixtures conformed is detailed in Figure 4.

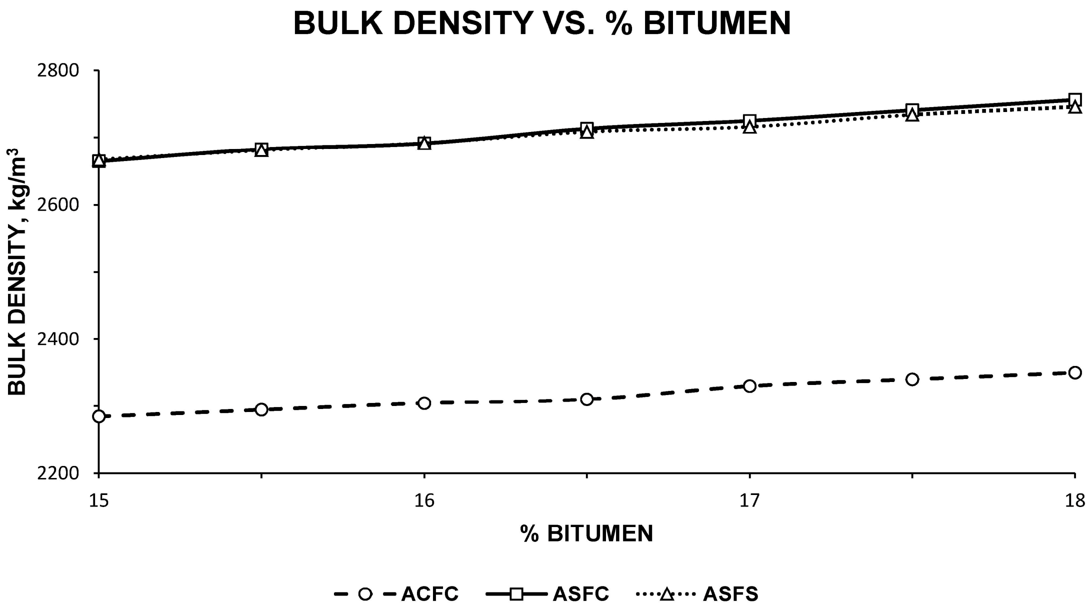

Figure 3. Bulk density of the families of bituminous mixtures ACFC, ASFC and ASFS with different percentages of bitumen in volume of aggregate.

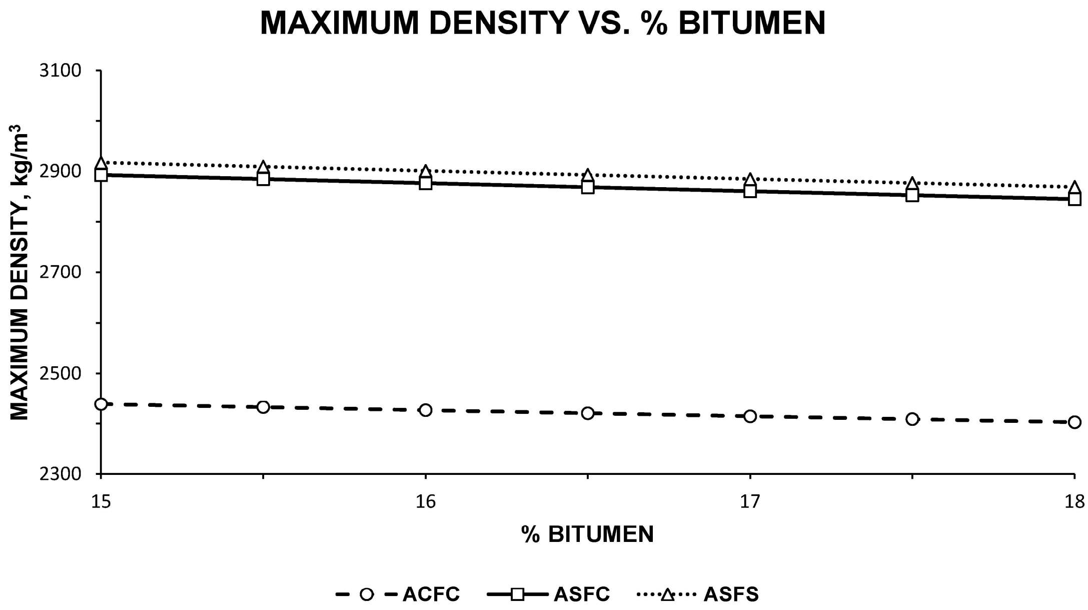

Figure 4. Maximum density of the families of bituminous mixtures ACFC, ASFC and ASFS with different percentages of bitumen in volume of aggregate.

Similarly to the previous case, the maximum density of mixtures that contain electric arc furnace slag is higher than those that incorporate hornfels aggregate, due to the higher density of this material. In turn, mixtures containing ladle furnace slag have a slightly higher density than mixtures conformed with calcareous filler. The results of this test, as well as that of bulk density, directly condition the percentage of voids in bituminous mixtures. The percentage of voids is essential to determine the behavior of the bituminous mixture, being limited by the regulations. The voids content of the different families of mixes is shown in Figure 5.

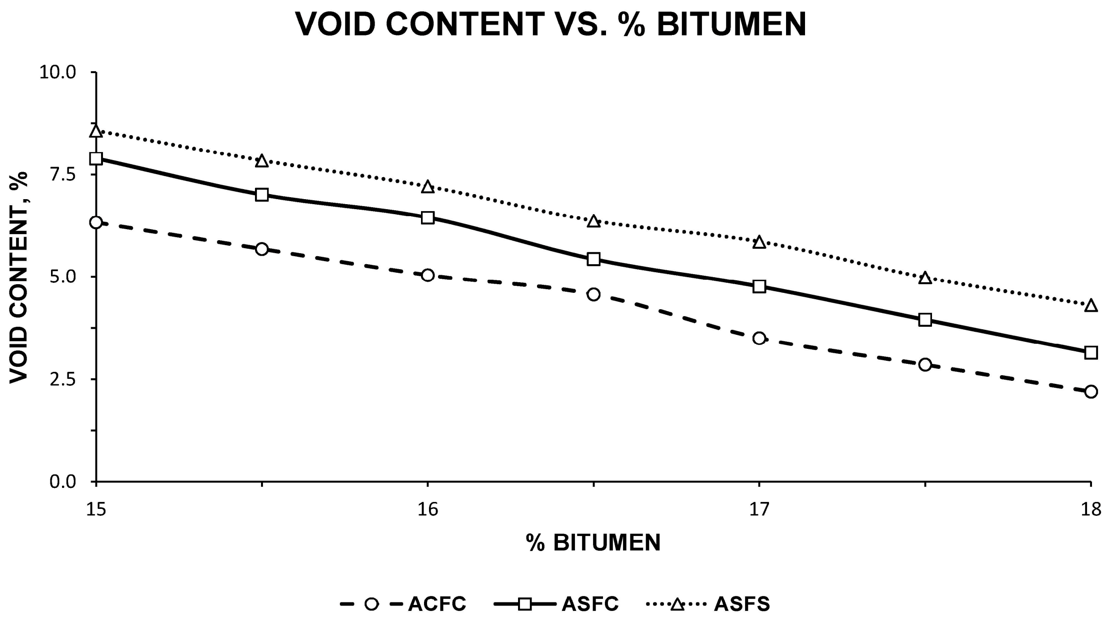

Figure 5. Void content of the families of bituminous mixtures ACFC, ASFC and ASFS with different percentages of bitumen in volume of aggregate.

The percentage of voids is an essential characteristic to avoid the formation of plastic deformations, to drain rainwater from the surface, to achieve greater friction between tire and pavement, and even to reduce noise caused by vehicle traffic. Therefore, Spanish regulations limit the percentage of voids to between 4% and 7% for this type of bituminous mixture. Based on the above, it can be seen that the mixture with hornfels aggregate has a lower void content than mixtures conformed to electric arc furnace slag. This fact indicates a higher absorption of bitumen by electric arc furnace slags and ladle furnace slags.

Depending on the detailed limitations, ACFC bituminous mixtures are valid up to 17% bitumen by volume and of aggregate. Higher percentages of bitumen would develop an unacceptable void content. On the other hand, ACFC bituminous mixtures have acceptable voids percentages from 15.5% to 17.5%, according to the limitations set by the regulations. In turn, ASFS bituminous mixtures show acceptable percentages of bitumen according to the same limitations from 16% to 18%.

The Marshall test will be in responsible for showing the mechanical resistance of the bituminous mixture and, in short, within the range detailed above by the voids content, the optimum combination of materials for each family of samples. Figure 6 shows the Marshall stability of the different families of samples.

The Marshall test reflects the superior mechanical resistance of bituminous mixtures conformed to electric arc furnace slag as an aggregate and ladle furnace slag as a filler. In turn, the mixture with electric arc furnace slag and calcareous filler presents a lower resistance than the previous one but slightly higher than the resistance of the bituminous mixture formed with hornfels aggregate and calcareous filler. Two conclusions can be drawn from this fact. On the one hand, the ladle furnace slag has a significant influence on the mechanical resistance of the bituminous mixes conformed, thanks to its cementitious characteristics; on the other hand, the use of electric arc furnace slag makes it possible to absorb a higher percentage of bitumen than hornfels aggregate and obtaining better mechanical resistance. This higher percentage of bitumen, together with the filler and fibers, obtains a quality mastic to withstand repeated traffic loads and, consequently, a longer durability of the bituminous mix over time. It should be noted that if no volume proportioning had been carried out, the higher density of the electric arc furnace slag would have masked the results and the detailed conclusions could not have been obtained.

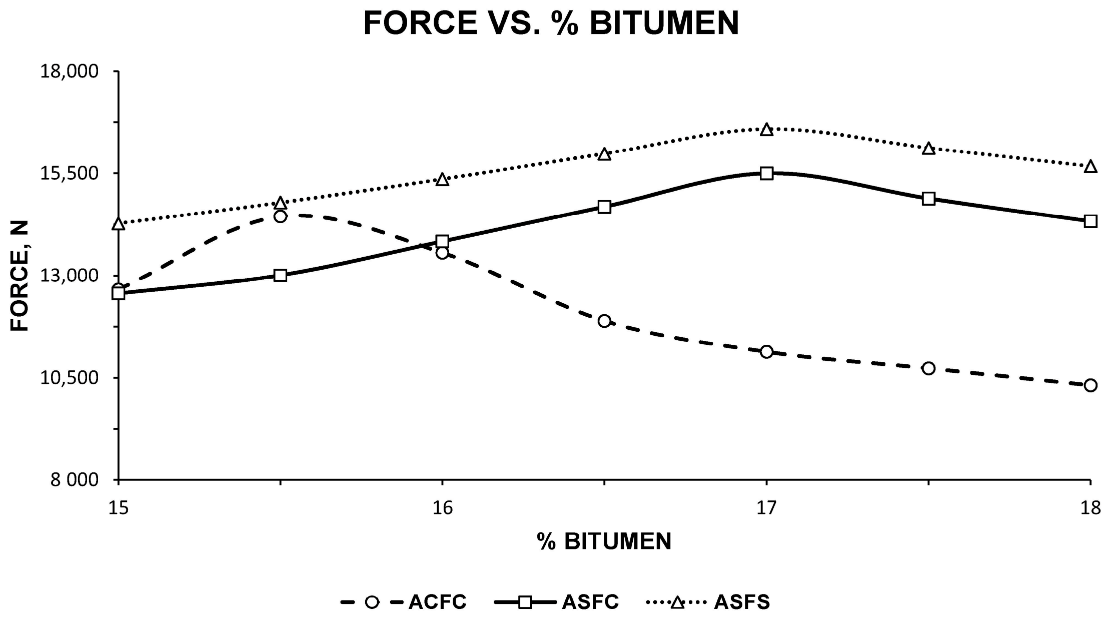

Figure 6. Marshall stability of the families of bituminous mixtures ACFC, ASFC and ASFS with different percentages of bitumen in volume of aggregate.

In addition, the Marshall test reflects the possibility of assessing the plastic deformations that may occur in the pavement. Therefore, it is essential to represent and evaluate the deformation of each family of bituminous mixtures. Marshall deformation is shown in Figure 7.

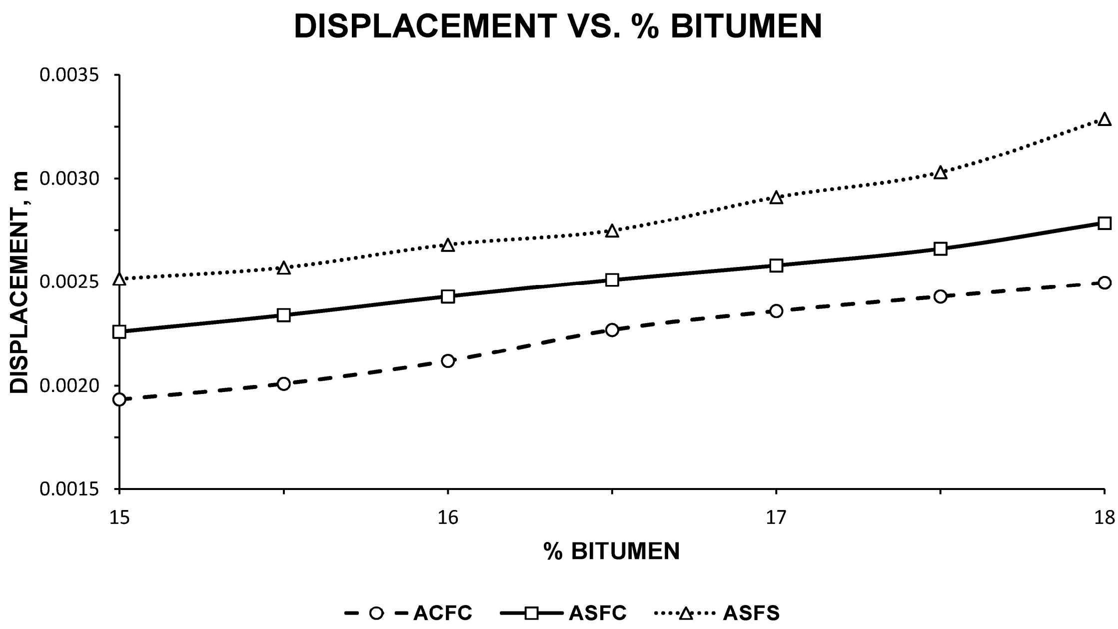

Figure 7. Marshall deformation of the families of bituminous mixtures ACFC, ASFC and ASFS with different percentages of bitumen in volume of aggregate.

Marshall deformation, or displacement during the test, is limited by the Spanish regulations for this type of bituminous mixture. The acceptable range of Marshall deformation results is 2 to 3 mm. Therefore, the ACFC family of bituminous mixtures has valid deformation percentages from 15.5% onwards. The ASFC family has acceptable bitumen percentages throughout its range to obtain adequate Marshall deformations. Finally, the ASFS family has adequate deformations, according to the regulations, in the percentages of bitumen from 15% to 17.5%. It is worth noting the greater deformation of the bituminous mixtures conformed with electric furnace slag and, in particular, of the mixtures that incorporate ladle furnace slag filler. This greater deformation is mainly due to the higher percentage of bitumen; however, the variations between the different families are small.

3.3. Determination of Optimal Material Combinations and Comparison of Results

Once the families of bituminous mixtures (ACFC, ASFC and ASFS) had been physically and mechanically analyzed, the optimum combination of materials was obtained. For this purpose, the Marshall test was taken as the reference test, since the aim is to obtain a resistant bituminous mixture without problems of plastic deformation. Therefore, the percentage of bitumen that provided the greatest Marshall stability was selected, provided that the other physical properties were acceptable according to the regulations.

With this optimal combination of materials for each family, the previous tests were again carried out to corroborate the quality of the mixtures, as well as the binder drainage test (standard UNE-EN 12697-18) [65] and the wheel-tracking tests (standard UNE-EN 12697-22) [66]. The results of all the tests carried out for the optimum combination of materials in each family are detailed in Table 10.

Table 10. Test results for the optimal combination of materials of the different families of bituminous mixtures ACFC, ASFC and ASFS.

Test	Standard	ACFC	ASFC	ASFS
Optimal percentage of bitumen (in volume and of aggregate)	-	15.50%	17%	17%
Bulk density	UNE-EN 12697-6 [62]	2291 ± 46 t/m^3	2716 ± 53 t/m^3	2721 ± 54 t/m^3
Maximum density	UNE-EN 12697-5 [61]	2436 ± 49 t/m^3	2857 ± 57 t/m^3	2887 ± 58 t/m^3
Void content	UNE-EN 12697-8 [63]	5.9 ± 0.1%	4.9 ± 0.1%	5.8 ± 0.1%
Stability Marshall	UNE-EN 12697-14 [64]	14586 ± 287 N	15524 ± 307 N	16658 ± 331 N
Marshall Deformation	UNE-EN 12697-14 [64]	0.0020 ± 0.0001 mm	0.0026 ± 0.0001 mm	0.0028 ± 0.0001 mm
Binder drainage	UNE-EN 12697-18 [65]	0 ± 0%	0 ± 0%	0 ± 0%
Wheel tracking (10,000 cycles; 60 °C)	UNE-EN 12697-22 [66]	0.07 ± 0.01 mm	0.05 ± 0.01 mm	0.04 ± 0.01%

As can be seen in Table 10, the results reflected from the previous tests for the optimum combination of materials from the three families of bituminous mixtures are acceptable according to the Spanish standard ORDER OC 3/2019. In addition, the three detailed mixtures reflect excellent results in comparison with other types of bituminous mixtures and can all be used for important traffic roads.

Nevertheless, and with the aim of evaluating the influence that the incorporation of waste has on the bituminous mixture, the best results obtained by the ASFS family, the conform made up of electric arc furnace slag and ladle furnace slag, should be highlighted. With similar but slightly lower results, there is the ASFC bituminous mixture and, finally, with important differences in terms of resistance and bitumen percentages, there is the ACFC mixture.

More specifically, the densities of the three families differ because of the higher density of the slags used. However, the percentage of voids obtained is similar even if a higher percentage of bitumen is used in the mixtures with electric arc furnace slag. This higher percentage of bitumen, without producing bleeding problems as confirmed by the binder drainage test, implies a higher resistance of the mix to withstand the repeated traction loads of traffic. This fact is reflected by the wheel tracking test, with the best values being achieved in the ASFS and ASFC mixes. The Marshall stability of the bituminous mixtures reflects the excellent behavior of the use of electric arc furnace slag and ladle furnace slag, being the family with the highest resistance. Finally, we should comment on the correct functioning of cellulose fibers from the paper industry as an additive in the mixtures, since it has allowed the incorporation of higher percentages of bitumen in all the families without the production of bleeding.

4. Conclusions

The research methodology followed and the results of the tests, as well as the discussions held, reflect a series of partial conclusions that will lead to the final conclusion. In turn, it should be mentioned that the initial hypothesis was the aptitude of electric arc furnace slag, ladle furnace slag and cellulose fibers from the papermaking industry for the conformation of Stone Mastic Asphalt type bituminous mixtures. The partial conclusions obtained are described below:

- The cellulose fibers discarded from the papermaking industry have a mainly organic composition, without the presence of chemical elements such as sulfur in large proportions that could cause environmental pollution problems. The size of the fibers is millimetric, and there are no agglomerations of the same after their treatment.
- Ladle furnace slag has an inorganic composition, being composed mainly of calcium, magnesium and silicon oxides. These oxides are mainly responsible for the cementitious characteristics. At the same time, it has a particle density that is slightly higher than that of a conventional aggregate, as well as a reduced particle size as demonstrated by its apparent density. However, the ladle furnace slag does not possess any plasticity.
- Electric arc furnace slag has an inorganic composition consisting mainly of metal element oxides. The density of these slags is high, not reflecting the existence of a high percentage of colloidal particles. In turn, the shape of the particles makes them suitable for use in high traffic bituminous mixtures, since, together with their mechanical resistance, they are capable of withstanding the compressive loads of traffic without problems of fractures or deformations. The resistance to abrasion, by contact with the tire, is another of the particularities that it possesses.
- Bituminous mixtures conformed with cellulose fibers from the paper industry are suitable for retention of a higher percentage of bitumen without causing bleeding problems. This fact has been corroborated by the binder drainage test of the mixtures made with the optimum combination of materials.
- Bituminous mixtures conformed with electric arc furnace slag provide greater Marshall stability, with similar deformation values. In addition, they are capable of absorbing a higher percentage of bitumen than a conventional aggregate, forming a mastic of suitable quality for the repeated traction loads of traffic. This fact has been corroborated with the wheel tracking test.
- The ladle furnace slag gives the mix greater Marshall stability, even being used in a low proportion and as a filler in the bituminous mixes.
- The optimum combination of materials in the ACFC, ASFC and ASFS mixtures reflects a similar percentage of void index. However, the maximum and bulk density of the slag mixtures is higher than that of hornfels aggregate.

Based on the partial conclusions derived from the methodology presented in this investigation and according to the tests carried out, it can be stated that the incorporation of electric arc furnace slag, ladle furnace slag and cellulose fibers from the paper industry, creates Stone Mastic Asphalt type bituminous mixtures with a higher percentage of bitumen, greater Marshall stability, better behavior towards permanents deformations and with a similar content of voids or deformations. The quality of these materials is therefore assured for use in bituminous mixtures dedicated to roads for important traffic. It is important to highlight the importance of using unused waste to conformed materials, not only of similar but superior quality, as it reduces their disposal in landfills and avoids the extraction of new raw materials.

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