infrastructures

Article

Preliminary Validation of Steel Slag-Aggregate Concrete for Rigid Pavements: A Full-Scale Study

Víctor Revilla-Cuesta [1], Vanesa Ortega-López [1], Marta Skaf [2], Emiliano Pasquini [3,*] and Marco Pasetto [3]

[1] Department of Civil Engineering, University of Burgos, 09001 Burgos, Spain; vrevilla@ubu.es (V.R.-C.); vortega@ubu.es (V.O.-L.)
[2] Department of Construction, University of Burgos, 09001 Burgos, Spain; mskaf@ubu.es
[3] Department of Civil, Environmental and Architectural Engineering (ICEA), University of Padua, 35131 Padua, Italy; marco.pasetto@unipd.it
* Correspondence: emiliano.pasquini@unipd.it

Abstract: The high wear resistance and toughness of electric arc furnace slag (EAFS) means that this industrial by-product can successfully replace natural aggregate in hydraulic or bituminous concretes that withstand vehicle traffic. This article validates the use of concrete made with large amounts of EAFS for rigid pavements. Accordingly, three EAFS–concrete mixes made with metallic or synthetic fibers were designed. Their performance was studied through laboratory tests (compressive strength, modulus of elasticity, splitting tensile strength, and abrasion resistance) and field observations on full-scale slabs made with each of the studied mixes. All mechanical properties yielded adequate results for concrete for rigid pavements. The metallic fibers increased the strength and elastic stiffness by 7–10%, while the addition of synthetic fibers slowed the development of these properties over time. On the other hand, all the mixes allowed for a successful implementation of full-scale slabs, with none of them showing excessive deterioration after five years of exposure to the outdoor environment. Only minor cracking and some chips in the surface-treatment layer were detected. The strength development of the slabs and their slipperiness were adequate for use in high-speed pavements. The overall analysis of the results shows that concrete made with EAFS can be used in real rigid pavements.

Keywords: circular economy; sustainability; electric arc furnace slag; concrete for rigid pavements; siderurgic concrete; fiber-reinforced concrete; abrasion resistance; full-scale slab; outdoor environment; skid resistance

check for updates

Citation: Revilla-Cuesta, V.; Ortega-López, V.; Skaf, M.; Pasquini, E.; Pasetto, M. Preliminary Validation of Steel Slag-Aggregate Concrete for Rigid Pavements: A Full-Scale Study. *Infrastructures* **2021**, *6*, 64. https://doi.org/10.3390/infrastructures6050064

Academic Editor: Chris Goodier

Received: 2 April 2021
Accepted: 20 April 2021
Published: 22 April 2021

1. Introduction

Currently, the concept of circular economy is of particular relevance in all productive sectors, such as the construction industry. This is due to the fact that sustainable-development objectives include the sustainable use of resources and the conservation of the environment [1]. Since the consumption of natural aggregates is very high, 3000 million tons of natural aggregates are consumed every year in the European Union alone [2], it is crucial to look for alternative materials that can replace them and reduce the great environmental impact caused by their extraction [3]. These alternative materials can be wastes and industrial by-products [4]. In this way, it is possible not only to reduce the over-exploitation of quarries and gravel pits, but also the deposit of waste in landfills [3]. As a result, in recent years, numerous research lines have addressed the use of different wastes in both hydraulic [5] and bituminous concretes [6,7]. Their use has been tested not only in conventional concretes but has also been extended to concretes with improved performance in the fresh or hardened state [8].

Among the different alternative materials that can be employed, the use of by-products from the metallurgical industry stands out [9–11]. The emphasis on giving a second life to the waste materials derived from steelmaking is due to the continuous growth of this industry, whose production exceeded 1.8 million tons in 2019 [12].

In the last decades, the steel industry in Europe has been transformed towards the electric arc furnace (EAF) steelmaking technology. EAF technology is used for approximately 30% of European steel production. The EU steel sector, in 2018, produced a total of 47.8 Mt of slag, of which 7.9 Mt are electric arc furnace slags (EAFS), according to data from the latest available report from EUROSLAG (European association representing metallurgical slag producers and processors) [13].

The EAFS is produced during the melting of scrap in electric arc furnaces to obtain steel [14]. After solidification, it is a brownish-black granular material, with a very high density, around 3.5 Mg/m^3, high micro-porosity, an angular shape, and excellent wear resistance [15]. It is especially suitable for wearing courses where skid resistance and durability are critical functional requirements [16] and for the production of asphalt mixes subjected to heavy traffic [17].

It is widely accepted that the use of the coarse fraction of EAFS can produce hydraulic concrete with adequate mechanical [18] and durability properties [19], increasing the sustainability of the resulting product [20]. The use of the fine fraction without any fine natural aggregate is also suitable for concretes that do not require high workability, due to the scarcity of fine particles in EAFS [14]. This, along with the high density of EAFS, makes the use of this aggregate particularly useful for the production of hydraulic concrete works where a greater weight is desirable [21]. In fact, there are several examples of real constructions of these characteristics manufactured with EAFS concrete. As recent examples, both the foundation and the basement walls of the Kubik building, in Derio (Spain), were built in 2008 with concrete in which 80% of its volume was EAFS [21]; in 2015, heavy-weight concrete blocks destined to protect two docks in the Port of Bilbao (Spain) were produced with EAFS [22]. The use of this waste in the last concrete elements was noticeable due to the marine environment in which they were located, because the durability properties of concrete in this critical environment must be optimal [23].

If the aspects of high density, wear resistance, and polishing stone value [24] are jointly considered, it seems clear that the use of EAFS can be extended to the production of concrete for rigid pavements [25]. This type of concrete works by weight, does not require a very high workability since it is placed by pouring and vibration, and must present a high resistance to abrasion to withstand the continuous traffic of vehicles [26]. In this type of concrete, using fibers is quite common due to the low amount of structural steel that it incorporates [27]. Furthermore, the addition of fibers reduces cracking, which allows for a more comfortable and pleasant travelling of vehicles, increases stiffness, facilitates the surface cleaning of concrete, and reduces its absorption of liquids [23]. The use of hydraulic concrete that simultaneously incorporates EAFS and fibers is not widespread, mainly due to the reduced workability of concrete mixes that incorporate both materials [28]. Generally, fibers lead to a decrease of workability in addition to that caused by EAFS [29]. However, concrete mixes manufactured with both fibers and EAFS and that have an adequate workability have been developed in some studies through a precise and careful mix design [25].

In view of the above, this study aims to preliminarily validate the use of EAFS for the production of real-scale pavements. For this purpose, three mixes were designed with a high EAFS content in addition to metallic or synthetic fibers. The behavior of the mixes was studied through laboratory tests, and then a full-scale slab was produced with each mixture of EAFS concrete to evaluate their placement conditions and durability behavior in the outdoor environment. The main novelty of this study is the analysis of full-scale slabs manufactured with EAFS concrete for pavements, as the existing studies mainly analyzed the performance of this type of concrete through laboratory tests. All the results obtained showed that hydraulic concrete made with both large volumes of EAFS and fibers is suitable for the construction of rigid pavements.

2. Materials and Methods

2.1. Raw Materials

Six different raw materials were used to produce the concrete mixes, which can be divided into three groups: (i) cement, water, and admixtures; (ii) aggregates; and (iii) fibers.

2.1.1. Cement, Water, and Admixture

CEM I 42.5 R class ordinary Portland cement was used in accordance with standard EN 197-1 [30]. According to this standard, its specific gravity was approximately 3.1 Mg/m^3 and its clinker content was over 95%.

The addition of EAFS usually reduces the workability of concrete due to its higher density (weight) and angularity, which prevents it from being successfully dragged by the cement paste [31]. Therefore, a plasticizer admixture was used to improve the workability of concrete.

Finally, water was taken from the water supply network of Burgos, the Spanish city where the research was performed. During previous chemical tests, no compound was detected that could negatively affect the behavior of concrete [25].

2.1.2. Aggregates

Two different types of aggregates were used: a siliceous sand and electric arc furnace slag (EAFS). The latter aggregate represented the largest volume of the mixes.

- Siliceous sand had a continuous gradation 0/4 mm, as shown in Figure 1, and a rounded shape. Its oven-dried density and water absorption exhibited usual values (Table 1).
- EAFS was supplied by a recycling plant that usually manages waste from the metallurgical industry. It was received in the laboratory in 3 different sizes, 10/20 mm, 4/10 mm, and 0/4 mm, all of which were used in the preparation of concrete (Figure 2).

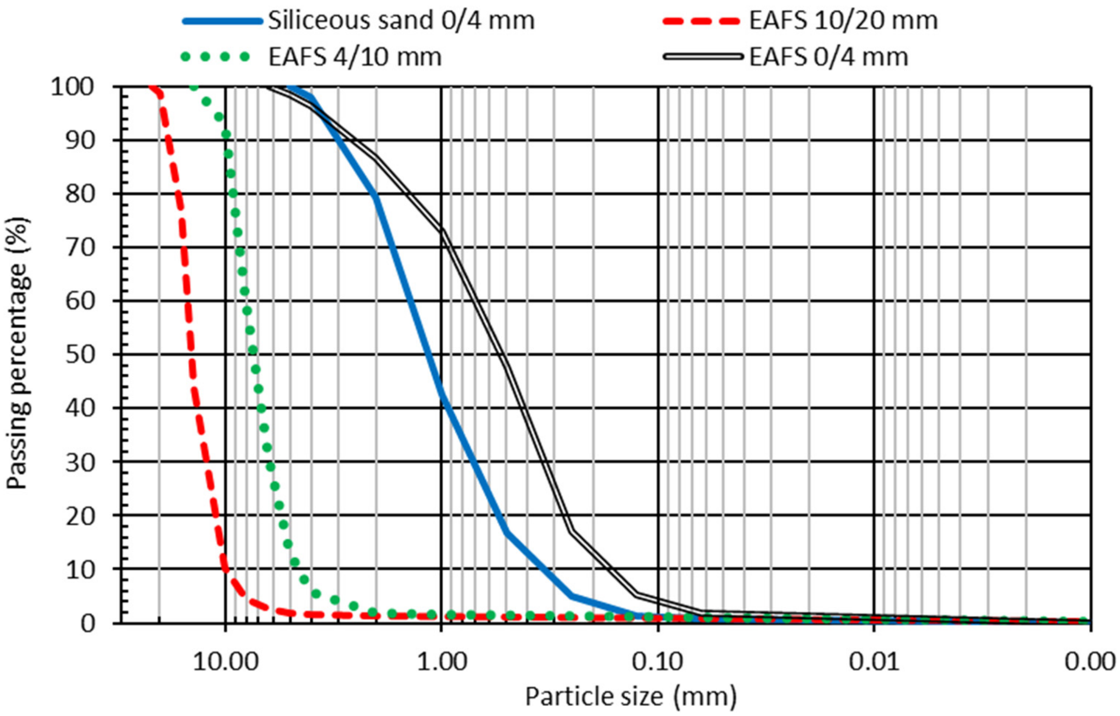

Figure 1. Gradation of aggregates.

Figure 2. EAFS used in the study, provided in three grading sizes.

Table 1. Physical properties of aggregates.

Aggregate	Oven-Dried Density (Mg/m^3)	Water Absorption (% wt.)	Sand Equivalent (%)	Los Angeles Coefficient (%)
Siliceous sand 0/4 mm	2.65	1.41	89	–
EAFS 10/20 mm	3.51	3.55	–	23
EAFS 4/10 mm	3.49	2.87	–	24
EAFS 0/4 mm	3.64	1.12	98	–

The gradation of all the EAFS fractions is shown in Figure 1, in which its low fines content (<0.063 mm) can be distinguished. This is a common problem of EAFS and it reduces the concrete workability [10].

Its oven-dried density was around 30% higher than that of the natural aggregates traditionally used in concrete, while its water absorption was slightly higher. Its sand equivalent and resistance to abrasion are also appropriate, as shown in Table 1.

Finally, regarding its chemical composition (XRD analysis), the content of expansive compounds, such as free lime or magnesia, were lower than 0.5% and 0.1% respectively, thus suggesting a correct dimensional stability [32].

2.1.3. Fibers

Both metallic and synthetic (polypropylene) fibers were used in order to compare their behavior (Figure 3). Their characteristics are collected in Table 2, which shows the higher strength and stiffness of metallic fibers. These characteristics usually cause metallic fibers to improve the mechanical behavior of concrete.

Figure 3. Metallic (**left**) and synthetic (**right**) fibers.

Table 2. Properties of fibers.

Fiber Type	Length (mm)	Equal Diameter (mm)	Aspect Ratio	Tensile Strength (MPa)	Young's Modulus (GPa)
Metallic fibers (RL-45)	50	1.05	45	>1000	210
Polypropylene fibers (M-48)	48	0.93	50	>400	6

2.2. Mix Design

First, a mix without fibers was designed, in which the EAFS content was maximized, but at the same time an adequate workability for concrete for rigid pavements (S2 or S3 slump class according to EN 206 [30]) was established as the main objective. Through various preliminary mixes, a water-to-cement (w/c) ratio of 0.55 was defined, which allowed us to obtain an adequate balance between workability and strength. In addition, the optimum EAFS content was determined as 78% of the total mass of aggregate added. The remaining 22% of aggregate was siliceous sand 0/4 mm. Due to the different density of the aggregates, EAFS and siliceous sand represented 73% and 27% of the total aggregate volume, respectively. The rounded shape of the sand partially compensated for the higher surface roughness and the higher density of EAFS. The total aggregate content of the mixes was defined by fitting to the Fuller curve, as shown in Figure 4.

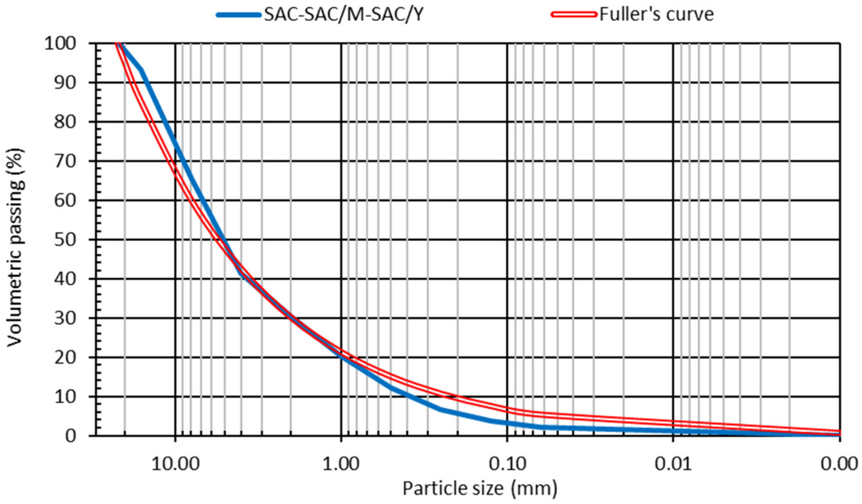

Figure 4. Joint gradation of the mixes.

Subsequently, two other mixes were prepared, one with each type of fibers: metallic or synthetic. The use of fibers is common in concrete pavements to reduce cracking [27]. The amount of fiber, 0.5% of the total concrete mix volume, was also defined through preliminary mixes in which it was determined that the fibers would not greatly reduce the workability of concrete that is already highly conditioned by the use of large quantities of EAFS. In addition, it was not desirable to increase the w/c ratio in order not to reduce the strength of the concrete.

The reference mix was labelled SAC (slag-aggregate concrete), while the mixes with metallic and synthetic fibers were labelled SAC/M and SAC/Y, respectively. Their composition is shown in Table 3.

Table 3. Composition of the mixes (kg/m^3).

Component	Mix		
	SAC	SAC/M	SAC/Y
Cement	360	360	360
Water	200	200	200
EAFS 10/20 mm	550	550	550
EAFS 4/10 mm	670	670	670
EAFS 0/4 mm	515	515	515
Siliceous sand 0/4 mm	500	500	500
Admixture	5.4	5.4	5.4
Fibers	0	45 (metallic)	3.5 (synthetic)

2.3. Experimental Plan

The experimental plan was divided into two different parts: laboratory tests, in which test specimens were used, and full-scale tests, in which full-scale slabs were manufactured. In both cases, the mixing process was the same, which was performed continuously, and during which the aggregates (both EAFS and siliceous sand), cement, water, and the plasticizer admixture were added in that order. Once the concrete mix was homogeneous, then the fibers were poured.

2.3.1. Laboratory Tests

To perform the characterization tests, both in fresh and hardened state, batches of 60 liters were produced in a concrete mixer with a capacity of 80 liters. After finishing the mixing process, the fresh properties were determined: slump (consistency) by the Abrams-cone test (EN 12350-2 [30]) and fresh-density test (EN 12350-6 [30]).

Subsequently, specimens were prepared to measure the hardened properties. Table 4 shows, for each hardened-state test, the age of concrete when the test was performed, the standard followed, and the type of specimen used. The specimens were stored in a wet chamber with a humidity of 95 ± 5% and a temperature of 20 ± 2 °C until the time of testing. The results of all the tests were calculated as the arithmetic mean of the values obtained in three different specimens.

Table 4. Hardened tests.

Test	Age (Days)	Standard [30]	Specimen
Hardened density	28	EN 12390-7	10 × 10 × 10-cm cubic specimens
Compressive strength	7, 28, 90	EN 12390-3	15 × 30-cm cylindrical specimens
Modulus of elasticity	60	EN 12390-13	15 × 30-cm cylindrical specimens
Splitting tensile strength	60	EN 12390-6	15 × 30-cm cylindrical specimens
Abrasion	60	EN 1340	Cut cylindrical specimens (see Figure 5 right)

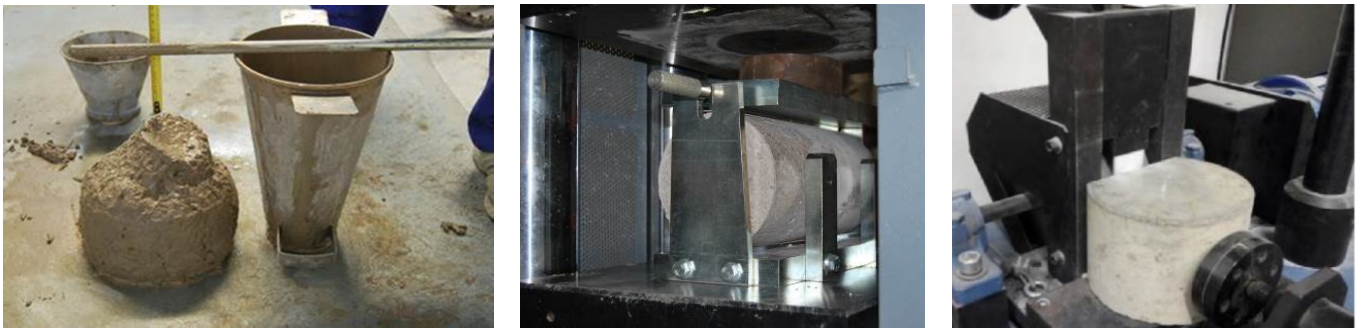

Figure 5. Consistency of the SAC/M mix (**left**); splitting-tensile-strength test (**middle**); abrasion-resistance test (**right**).

2.3.2. Full-Scale Tests

To test the suitability of the mixes for use in the construction of real infrastructures, more specifically in concrete pavements, three slabs were produced, one with each EAFS–concrete mix developed. Those slabs had a square shape with a side of 2.5 m and a depth of 0.15 m, and for their laying, it was necessary to produce batches of concrete of 1 m^3 of volume. The most relevant aspects related to their implementation are explained in detail in Section 4. They were then exposed to the outdoor environment of Burgos, Spain, for five years to monitor their degradation. After this period of time, the compressive strength (EN 12390-3 [30]) of the mixes was analyzed, as well as their skid, according to EN 13036-4 [30]. The measurement of skid resistance in all the slabs was intended to check whether the use of fibers had any effect on this property even though the same surface treatment was applied to all the slabs.

3. Results and Discussion: Laboratory Tests

This section presents the results obtained in the laboratory tests performed on the concrete specimens to characterize both the fresh and hardened behavior of the mixes.

3.1. Fresh Performance

The fresh behavior of the mixes was evaluated by determining their consistency (Abrams-cone test, EN 12350-2 [30], see Figure 5 left) and their fresh density (EN 12350-6 [30]). The results of each test are shown in Table 5.

Table 5. Fresh properties.

Mix	Slump (mm)	Slump class (EN 206 [30])	Fresh density (Mg/m^3)
SAC	140	S3	2.86
SAC/M	130	S3	2.87
SAC/Y	60	S2	2.85

3.1.1. Consistency

Traditional concrete for rigid pavements usually presents an intermediate or low workability, so it generally never reaches an S4 slump class (slump between 160 and 210 mm) [33]. Therefore, all the mixes had an adequate workability for a concrete of those characteristics, which was set as an objective during the design of the mixes (see Section 2.2). Thus, the SAC and SAC/M mixes were of the S3 slump class (slump between 100 and 150 mm), while the SAC/Y mix was of the S2 slump class (slump between 50 and 90 mm). The use of EAFS in concrete usually reduces its workability due to its angular shape and its high density, which hinder its dragging by the cement paste [10]. These aspects were compensated for in this study by the partial use of siliceous sand 0/4 mm of rounded shape, as well as by the addition of a plasticizer.

Concerning the effect of fibers, their use led to a decrease in workability, as expected [34]. The addition of metallic fibers resulted in a decrease of the slump of 10 mm, so the cement paste did not exhibit a greater difficulty in dragging the fibers in addition to the large amount of EAFS used. However, the SAC/Y mix manufactured with synthetic fibers experienced a large decrease of workability (slump decrease of 57%), which is explained by the lower efficiency of the plasticizer due to the rougher surface of synthetic fibers.

3.1.2. Fresh Density

The fresh density was similar in all mixes (around 2.85–2.90 Mg/m^3, Table 5), and significantly higher than that obtained in conventional concrete (around 2.4–2.5 Mg/m^3) due to the high density of EAFS compared to natural aggregate.

Theoretically, the addition of fibers leads to an increase of the mass of concrete with a negligible increase in volume, which results in an increase of the fresh density if the quantities of the other components remain constant [35]. This situation can be observed in the SAC/M mix, with a fresh density 0.01 Mg/m^3 higher than that of the reference mix. However, the addition of synthetic fibers caused a decrease in the fresh density, which was attributed to an increase in the air content of concrete as a consequence of the poor interaction between the admixture and this type of fiber [23].

3.2. Hardened Performance

The values of the hardened density, modulus of elasticity, and splitting tensile strength are shown in Table 6.

Table 6. Hardened properties (mean value and standard deviation).

Mix	Hardened Density (Mg/m^3)	Modulus of Elasticity (GPa)	Splitting Tensile Strength (MPa)
SAC	2.46 ± 0.02	36 ± 1.2	4.20 ± 0.9
SAC/M	2.53 ± 0.01	40 ± 1.5	6.94 ± 0.8
SAC/Y	2.45± 0.02	34 ± 1.4	5.42 ± 1.1

3.2.1. Hardened Density

The values of hardened density (Table 6) were higher than those commonly found in concrete made with natural aggregate due to the high density of EAFS. Moreover, they were 12–14% lower than the values of the fresh density (Table 5). This notable decrease of density is explained by the evaporation of water from the mix during setting [36]. This phenomenon is especially noticeable when EAFS is used as an aggregate, because, although it generally has a high water absorption, its high micro-porosity leads the water it absorbs to be quickly released, which in turn usually results in a high density change from the fresh to the hardened state [10].

The effect of the fibers was the same as that observed regarding fresh density: while the use of metallic fibers increased the density, the addition of synthetic fibers decreased the value of this property. The higher density of metallic fibers [27], as well as the inadequate interaction between the plasticizer and the synthetic fibers [23], could explain this behavior.

3.2.2. Compressive Strength

The compressive strength was measured at 7, 28, and 90 days on 15 × 30 cm cylindrical specimens that were stored in a wet chamber until the testing time. The evolution of this strength over time is shown in Figure 6. It can be noted that the strength of all the mixes was higher than 45 MPa, regardless of the age, showing all the mixes had an optimum compressive-strength development [37].

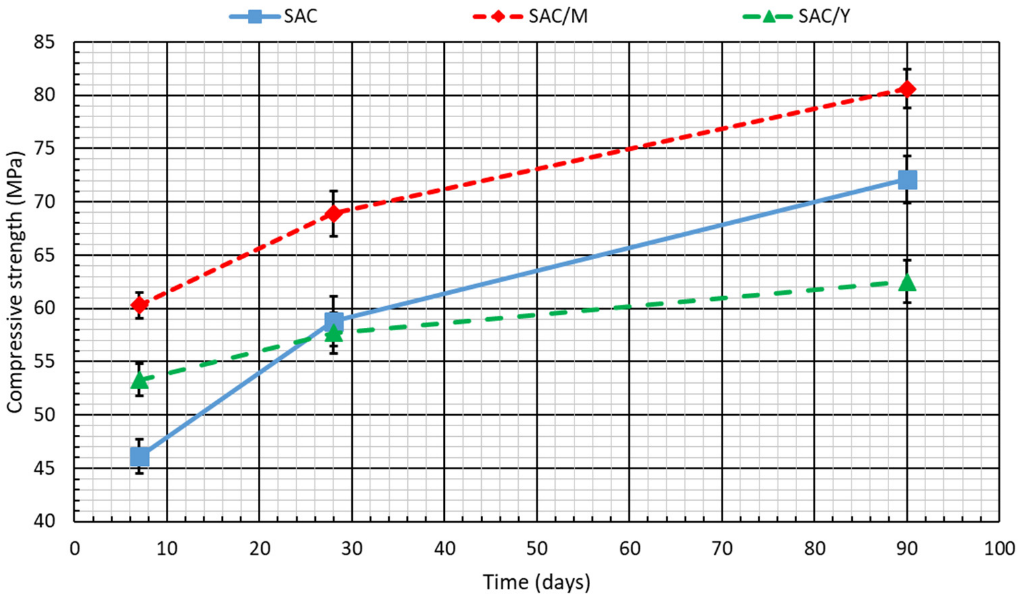

Figure 6. Compressive strength over time.

As expected, the SAC/M mix, manufactured with metallic fibers, had the highest compressive strength, exceeding 80 MPa at 90 days. The SAC mix presented a lower strength, with a value of around 72 MPa at 90 days, in line with similar studies [31]. Finally, the SAC/Y mix exhibited a worse strength development (62 MPa at 90 days), so that the addition of synthetic fibers had a negative effect on the compressive strength of concrete.

A similar behavior can be observed in relation to the temporal evolution of compressive strength over time. Although the increase of strength between the different testing points was high in all mixes, the use of synthetic fibers had a noticeable effect. Thus, the SAC and SAC/M mixes had at 7 days 65–75% of the 90-day compressive strength, while this percentage was 85% for the SAC/Y mix. At 28 days, this percentage was 82–85% for the SAC and SAC/M mixes, and 92% for the SAC/Y mix.

The phenomenon observed in the SAC/Y mix can be explained due to the interaction between the admixture and the polyolefin of the synthetic fibers [23]. This may cause an increase of porosity, addressed above in relation to the fresh density, which could reduce the compressive strength [5]. On the other hand, this interaction could also cause chemical reactions that delayed the effective hydration of the cement and, therefore, the development of strength in the medium term [25]. Thus, the compressive strength of the SAC/Y mix after longer curing times (e.g., 180 or 360 days) may be higher than that of the SAC mix. The results collected for the full-scale slabs (Section 4) could corroborate this aspect.

3.2.3. Modulus of Elasticity

The modulus of elasticity at 60 days (mechanical property shown in Table 6) mirrored the behavior observed regarding compressive strength, so the SAC/M mix had the highest modulus of elasticity (40 GPa), followed by the SAC mix (36 GPa). The SAC/Y mix presented the lowest value, although in this case the difference regarding the result obtained for the SAC mix was not as high as that for the compressive strength, only 6%.

The modulus of elasticity reflects the elastic stiffness of concrete when subjected to compressive stresses, so its behavior is closely linked to that obtained in relation to compressive strength [10], as shown in the previous paragraph. In addition, it is common to find expressions in the different international standards that correlate both properties; usually, the higher the modulus of elasticity, the higher the strength [37]. Therefore, the behavior obtained can be explained by the same aspects as those described for compressive strength: the interaction between the chemical admixture and the synthetic fibers led the SAC/Y mix to develop its stiffness over a longer period.

3.2.4. Splitting Tensile Strength

One of the great advantages of the use of fibers in concrete is that they inhibit or delay the opening of cracks [27]. This makes their use in concrete pavements highly recommended, since they can significantly reduce cracking, resulting in a better durability of the pavement [23], as well as greater comfort for the travelling of vehicles [38]. In addition, the use of fibers also improves the behavior of concrete when it is subjected to tensile stresses (Figure 5 middle).

As expected, the lowest splitting tensile strength was obtained in the reference mix that was made without fibers. The addition of synthetic fibers increased the splitting tensile strength by 29%, while the use of metallic fibers resulted in an increase of the splitting tensile strength of 65%. The higher strength increase provided by the use of metallic fibers was expected due to their higher tensile strength and Young's modulus compared to synthetic ones (Table 2). Fibers, under tensile stresses, were able to compensate for the negative effects observed in the compressive-strength and modulus-of-elasticity tests, in which compressive stresses are applied.

3.2.5. Abrasion Resistance

Any concrete pavement must have a high abrasion resistance, so that the traffic does not cause quick deterioration of the material [26]. EAFS is an alternative aggregate with a high surface hardness that has a higher wear resistance and polishing stone value (PSV) than those of natural aggregates [15]. Therefore, its use would allow for the improvement of the abrasion resistance of concrete and its evolution over time, which can be especially useful when concrete is used for pavements manufacturing. The abrasion resistance of any concrete can be measured by adapting the EN 1340 standard [30], as performed in this study (Figure 5 right).

According to a previous study by the authors, the abrasion-resistance test of a concrete for rigid pavements made with 100% natural siliceous aggregate showed that the footprint obtained had a length of 82 ± 3 mm and a width of 14 ± 0.5 mm [25]. The three mixes made with EAFS in this study had a similar width (Table 7), although there was a noticeable improvement in the length of the footprint in all the mixes except the SAC/Y mix, possibly due to its unexpected slower strength development, as indicated in previous sections. The footprint length was 66 mm for the SAC mix and 68.5 mm for the SAC/M mix, and it can be observed that the metallic fibers did not show a clear beneficial effect.

Table 7. Abrasion resistance (mean value and standard deviation).

Mix	Abrasion Resistance	
	Footprint Width (mm)	Footprint Length (mm)
SAC	66 ± 2	13 ± 0.5
SAC/M	68.5 ± 1	13.5 ± 0.5
SAC/Y	84 ± 4	14 ± 1

4. Results and Discussion: Full-Scale Tests

This section describes the results obtained in the tests carried out on full-scale slabs manufactured with the three mixes designed in this study. After an explanation of the process of placement, the results of exposure to the outdoor environment, compressive strength, and resistance to slipping and skidding are discussed.

4.1. Placement and Casting

The production of the slabs was performed outside the laboratories of construction and civil engineering of the University of Burgos, Spain. Since the objective was to evaluate the behavior of the designed mixes in real conditions, the manufactured slabs had dimensions of 2.5 × 2.5 × 0.15 m, so that concrete had to be produced industrially for their manufacture (1 m^3 of concrete was needed for each slab). The slabs made with the fiber-reinforced mixes (SAC/M and SAC/Y) did not incorporate any structural reinforcement, while the slab manufactured with the reference mix (SAC mix) incorporated two ϕ6 mm steel grids placed on the upper and lower faces, respectively. These steel grids had the same mission as the fibers: minimizing cracking from shrinkage during concrete setting and cracking that flexural stresses can cause over its useful life. The construction process is shown in Figure 7.

The first step in the execution of the slabs was the construction of the formwork over the existing soil pavement and the placement of a polyethylene sheet in the lower area to separate the existing pavement from the slabs to be manufactured. Next, the concrete was cast. Concrete casting consisted in the manufacturing of the mixes (1 m^3) according to the mix design explained in Section 2.2, concreting and, finally, concrete vibration with a needle vibrator to expel the trapped air. Concrete was also vibrated with a vibrating screed to smooth the surface.

Once the slabs were finished, a surface treatment was applied, similar to that used in real concrete pavements, with the aim of facilitating the cleaning of the pavement and giving it a more regular surface. For this purpose, 6 kg/m^2 of a fluid mortar manufactured with type-I PC cement was applied with a cement-to-aggregate ratio of 1:2, and in which the aggregate used was crushed and subsequently milled quartz-corundum aggregate 0/0.6 mm. After the application and spreading of this mortar, the upper surface was treated by mechanical scrubbing.

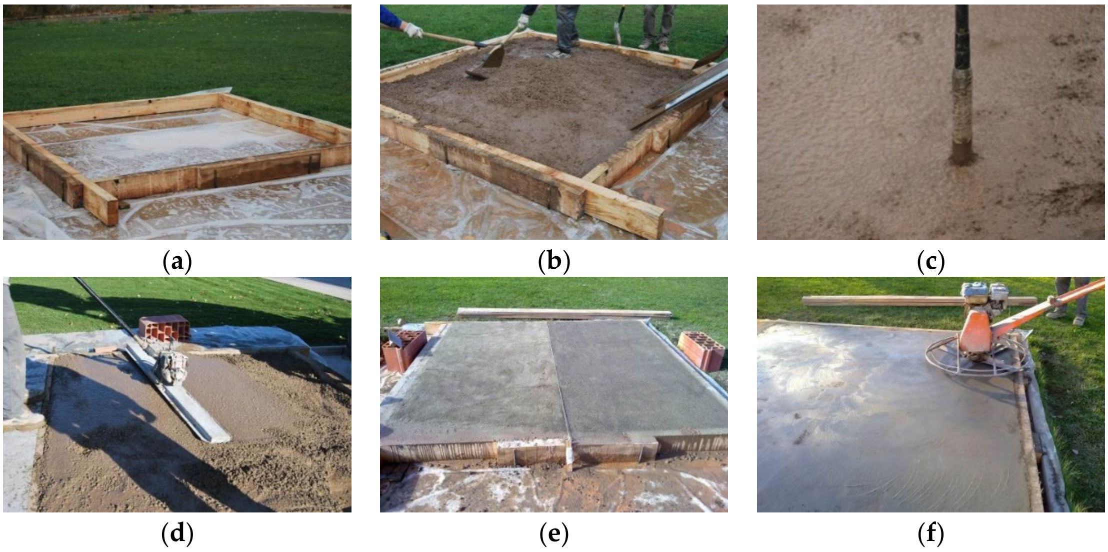
(**a**) (**b**) (**c**)
(**d**) (**e**) (**f**)

Figure 7. Construction process of the slabs: (**a**) construction of the formwork; (**b**) concrete casting; (**c**) concrete vibration with a needle vibrator; (**d**) surface smoothing with a vibrating screed; (**e**) slabs finished without surface treatment; (**f**) mechanical scrubbing of surface slabs.

Once the slabs were produced, they were exposed for 5 years to the outdoor environment of the city of Burgos, Spain. After this period of time, the deterioration experienced by the slabs due to the climate was studied, as was their compressive strength and resistance to slipping and skidding.

4.2. Degradation Due to Outdoor Exposure

Burgos is one of the cities in Spain with a more adverse climatology due to its location in the north of the country and its high altitude (856 m). Although it has a relatively dry climate, it has large thermal oscillations between night and day, which result in frosts, and between the different seasons. This means that an outdoor exposure test performed in this location is extremely demanding for any type of material that will be directly exposed to the elements (sun, water, ice . . .) during its service life [39]. The main characteristics of the climatology of Burgos are shown in Figure 8.

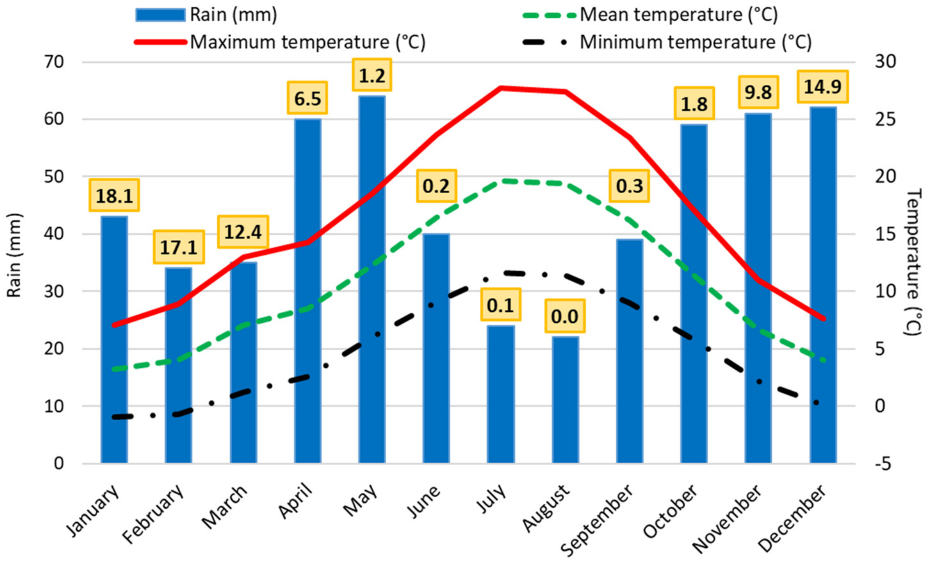

Figure 8. Climatology of Burgos, Spain (adapted from [40]). Frosty days in yellow rectangles.

After 5 years of exposure to the outdoor environment, no major deterioration of any slab was observed, and the defects that appeared mainly affected the surface treatment. Therefore, it can be concluded that the developed mixes presented an adequate durability for their exposure to an extreme climate such as that of Burgos. The main defects observed in the surface treatment after 5 years of outdoor exposure were as follows:

- A cracking appeared on the upper face of the slab made with the SAC mix, without fibers, as shown in Figure 9a. It is thought that the absence of fibers, which inhibit the cracks [35], could explain the appearance of this defect, which may have been caused by the numerous frosts that occur in Burgos. This phenomenon could also have been caused by differences in ambient temperature and humidity during laying.
- There were some chips in the slab made with the SAC/Y mix, which covered approximately 20% of the slab surface. It is believed that this phenomenon was due to an inadequate interaction between the synthetic fibers and the applied surface treatment since the presence of some fibers was observed in most of the chips (Figure 9b). This degradation process was caused by both the frosts typical of this climate and by the absorption of water by the synthetic fibers and its subsequent evaporation due to sunlight.

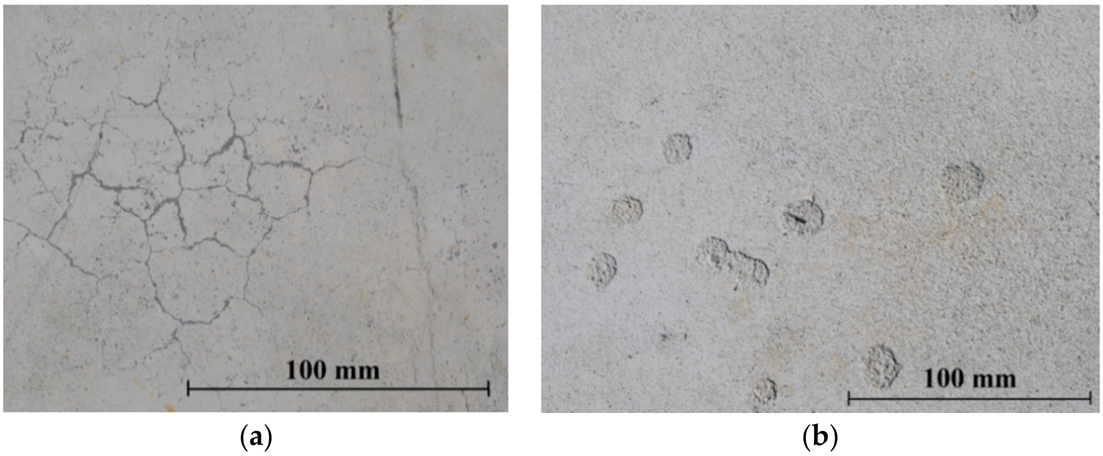

Figure 9. Surface-treatment defects: (**a**) cracks (SAC-mix slab); (**b**) chips (SAC/Y-mix slab) (adapted from [23]).

4.3. Compressive Strength: Core Drilling

After five years of exposure to the outdoor environment, three 75 × 150-mm cores (height-to-diameter ratio equal to 2) were extracted from each slab to evaluate the development of compressive strength (EN 12390-3 [30]) under real conditions (large volume of concrete manufactured and no storage in a wet chamber). The results obtained are shown in Table 8.

Table 8. Compressive strength on 75 × 150 mm cores (mean value and standard deviation).

Mix	Compressive Strength (MPa)
SAC	70.2 ± 2.3
SAC/M	76.4 ± 2.8
SAC/Y	69.6 ± 2.1

The values of compressive strength obtained show that the slabs exhibited the same behavior as that observed in lab specimens (Figure 6): the mix with the highest compressive strength was the SAC/M mix, while the SAC mix showed the second highest value. The SAC/Y mix had the lowest compressive strength, although the difference with the compressive strength of the SAC mix was only 0.6 MPa. This non-significant difference between the compressive strength of SAC and SAC/Y mixes supports the previously stated hypothesis that the SAC/Y mix did not have a much lower compressive strength than the SAC mix, but that the interaction between the admixture and the synthetic fibers led to a more delayed increase of compressive strength over time [23]. Finally, it should be noted that the compressive strength obtained at 90 days in lab specimens was slightly higher than that obtained on cores in those mixtures that had a strength development at a normal rate (SAC and SAC/M mixes). Wet curing clearly favors a higher strength development of concrete, as other studies have concluded [41].

4.4. Skid Resistance

The skid resistance (slipperiness) of each slab was measured after five years of exposure to the outdoor environment. The purpose was to determine whether the climatic conditions caused too much deterioration in the surface treatment to lead the slabs to exhibit inadequate skid resistance [42].

This property was measured using the friction pendulum, also known as the TRRL (Transport Road Research Laboratory) pendulum, according to EN 13036-4 [30], which is shown in Figure 10. The test was performed in two different surface conditions (wet and dry surface) and at three different points on each slab for each surface condition (wet or dry). The result of this test is the so-called "British Pendulum Number" (BPN).

Figure 10. Friction pendulum (TRRL pendulum).

The average BPN obtained for each slab in each surface condition is shown in Table 9. In general, a BPN between 50 and 55 is required to ensure safe driving on high-speed roads [43], so the slabs developed would be suitable for this type of routes, since in all cases the BPN was higher than 65. As expected, BPN was lower for a wet surface.

Table 9. BPN of each slab (mean value and standard deviation).

Slab	Dry Surface	Wet Surface
SAC	71 ± 3	68 ± 3
SAC/M	80 ± 4	72 ± 4
SAC/Y	77 ± 3	73 ± 4

Concerning the composition of the mixes, slipperiness was slightly lower in those slabs that incorporated fibers, especially metallic ones. The presence of fibers leads to the appearance of a slightly rougher surface that favors greater skid resistance of the pavement [42].

5. Conclusions

The high wear resistance of electric arc furnace slag (EAFS) makes it a material that can be successfully used as a substitute for natural aggregate in concrete pavement. Throughout this article, the behavior of concrete for rigid pavements made with large quantities of EAFS has been studied in addition to its interaction with both metallic and synthetic fibers. The behavior of these mixtures was evaluated through laboratory tests performed on test specimens and through the elaboration of full-scale slabs. The following conclusions can be drawn:

- The use of EAFS produced concrete with an adequate workability (S3 or S4 slump class) despite the high density and rough shape of this aggregate.
- The interactions between EAFS and metallic and synthetic fibers in the fresh state were different. While metallic fibers maintained the workability, synthetic fibers reduced it. It is thought that this phenomenon was due to the inadequate interaction between synthetic fibers and the plasticizer admixture.
- All the mixes exhibited adequate mechanical properties, which proved the suitability of EAFS for developing concrete pavements of adequate strength. The use of metallic fibers improved all properties, while the use of synthetic fibers delayed the temporal development of compressive strength and elastic stiffness. The interaction between the admixture and the synthetic fibers again explains this phenomenon.
- The use of EAFS as aggregate increased the abrasion resistance of the concrete for rigid pavements compared to the use of natural siliceous aggregate.
- All mixes allowed for the successful production of full-scale slabs with a good appearance and finish by a conventional surface treatment.
- The exposure of the slabs to the outdoor environment for 5 years did not cause major deterioration of the concrete, and only a slight degradation of the surface-treatment layer of the slabs was observed. This degradation consisted of the appearance of cracks, a phenomenon that did not occur with the addition of fibers, and the appearance of chips due to the absorption of water by the synthetic fibers. Throughout these five years, the compressive-strength development was adequate.
- All the slabs had a "British Pendulum Number" (BPN) suitable for high-speed roads. The use of fibers increased the roughness of the surface treatment and, therefore, the skid resistance.

The results obtained are encouraging for promoting the use of EAFS in concrete for real rigid pavements. The use of this waste would increase the sustainability of this type of infrastructure and, with it, that of the construction sector.

Author Contributions: Conceptualization, V.O.-L. and M.S.; methodology, V.O.-L., E.P., and M.P.; software, V.R.-C.; validation, V.R.-C., M.S. and E.P.; formal analysis, V.R.-C. and M.S.; investigation, V.R.-C., V.O.-L. and M.P.; resources, V.O.-L., M.S. and M.P.; data curation, V.R.-C., V.O.-L. and E.P.; writing—original draft preparation, V.R.-C.; writing—review and editing, V.O.-L., M.S., E.P. and M.P.; visualization, M.S. and M.P.; supervision, V.O.-L. and E.P.; project administration, M.S. and M.P.; funding acquisition, V.O.-L. and E.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded through the following entities and grants: Spanish Ministry MCI, AEI, EU, and ERDF, grants BIA2014-55576-C2-1-R and FPU17/03374; the Junta de Castilla y León and ERDF, grant BU119P17 awarded to research group UIC-231; Youth Employment Initiative (JCyL) and ESF, grant UBU05B_1274; the University of Burgos, grant Y.135 GI awarded to the SUCONS group; and the University of Padova, through grant BIRD182754.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available because they are a part of ongoing research.

Acknowledgments: The authors would like to thank the staff of the Construction and Large Structures laboratories of the University of Burgos for their involvement and help in the performance of this research work. The support of the administrative staff of the University of Padua in project administration and interuniversity collaboration management is also gratefully acknowledged.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Hák, T.; Janoušková, S.; Moldan, B.; Dahl, A.L. Closing the sustainability gap: 30 years after "Our Common Future" society lacks meaningful stories and relevant indicators to make the right decisions and build public support. *Ecol. Indic.* **2018**, *87*, 193–195. [CrossRef]
2. European Aggregates Association (UEPG). Available online: https://uepg.eu/ (accessed on 20 February 2021).
3. Maghool, F.; Arulrajah, A.; Du, Y.J.; Horpibulsuk, S.; Chinkulkijniwat, A. Environmental impacts of utilizing waste steel slag aggregates as recycled road construction materials. *Clean. Technol. Environ. Policy* **2017**, *19*, 949–958. [CrossRef]
4. Branca, T.A.; Colla, V.; Algermissen, D.; Granbom, H.; Martini, U.; Morillon, A.; Pietruck, R.; Rosendahl, S. Reuse and recycling of by-products in the steel sector: Recent achievements paving the way to circular economy and industrial symbiosis in europe. *Metals* **2020**, *10*, 345. [CrossRef]
5. Silva, R.V.; De Brito, J.; Dhir, R.K. The influence of the use of recycled aggregates on the compressive strength of concrete: A review. *Eur. J. Environ. Civ. Eng.* **2015**, *19*, 825–849. [CrossRef]
6. Terrones-Saeta, J.M.; Suárez-Macías, J.; Moreno-López, E.R.; Corpas-Iglesias, F.A. Determination of the chemical, physical and mechanical characteristics of electric arc furnace slags and environmental evaluation of the process for their utilization as an aggregate in bituminous mixtures. *Materials* **2021**, *14*, 782. [CrossRef]
7. Pasetto, M.; Baliello, A.; Pasquini, E.; Skaf, M.; Ortega-López, V. Performance-based characterization of bituminous mortars prepared with ladle furnace steel slag. *Sustainability* **2020**, *12*, 1777. [CrossRef]
8. Gupta, N.; Siddique, R.; Belarbi, R. Sustainable and greener self-compacting concrete incorporating industrial by-products: A review. *J. Clean. Prod.* **2020**, *284*, 124803. [CrossRef]
9. Yüksel, İ. A review of steel slag usage in construction industry for sustainable development. *Environ. Dev. Sustain.* **2017**, *19*, 369–384. [CrossRef]
10. Brand, A.S.; Fanijo, E.O. A review of the influence of steel furnace slag type on the properties of cementitious composites. *Appl. Sci.* **2020**, *10*, 8210. [CrossRef]
11. Pasetto, M.; Baliello, A.; Giacomello, G.; Pasquini, E. Sustainable solutions for road pavements: A multi-scale characterization of warm mix asphalts containing steel slags. *J. Clean. Prod.* **2017**, *166*, 835–843. [CrossRef]
12. World Steel Association. Steel Statistical Yearbook. 2019. Available online: https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html (accessed on 20 February 2021).
13. European Association Representing Metallurgical SLAG Producers and Processors (EUROSLAG). Available online: https://www.euroslag.com/ (accessed on 1 November 2020).
14. Yildirim, I.Z.; Prezzi, M. Chemical, mineralogical, and morphological properties of steel slag. *Adv. Civ. Eng.* **2011**, *2011*, 463638. [CrossRef]
15. Skaf, M.; Pasquini, E.; Revilla-Cuesta, V.; Ortega-López, V. Performance and durability of porous asphalt mixtures manufactured exclusively with electric steel slags. *Materials* **2019**, *12*, 3306. [CrossRef]
16. Autelitano, F.; Giuliani, F. Optimization of electric arc furnace aggregates replacement in dense-graded asphalt wearing courses. *Int. J. Pavement Res. Technol.* **2021**, *14*, 309–317. [CrossRef]
17. Pasetto, M.; Baldo, N. Fatigue performance of asphalt concretes made with steel slags and modified bituminous binders. *Int. J. Pavement Res. Technol.* **2013**, *6*, 294–303. [CrossRef]
18. Yu, F.; Fang, Y.; Zhang, Y.; Xu, L.; Bai, R. Mechanical behavior of self-stressing steel slag aggregate concrete filled steel tubular stub columns. *Struct. Concr.* **2020**, *21*, 1597–1611. [CrossRef]
19. Faleschini, F.; Zanini, M.A.; Toska, K. Seismic reliability assessment of code-conforming reinforced concrete buildings made with electric arc furnace slag aggregates. *Eng. Struct.* **2019**, *195*, 324–339. [CrossRef]
20. Václavík, V.; Ondová, M.; Dvorský, T.; Eštoková, A.; Fabiánová, M.; Gola, L. Sustainability potential evaluation of concrete with steel slag aggregates by the LCA method. *Sustainability* **2020**, *12*, 9873. [CrossRef]
21. Arribas, I.; San-José, J.; Vegas, I.; Hurtado, J.; Chica, J. Application of steel slag concrete in the foundation slab and basement wall of the Tecnalia kubik building. In Proceedings of the 6th European Slag Conference (EUROSLAG), Madrid, Spain, 20–22 October 2010; pp. 251–264.
22. Unión de Empresas Siderúrgicas (UNESID). Available online: http://www.unesid.org (accessed on 20 February 2021). (In Spanish).
23. Ortega-López, V.; Fuente-Alonso, J.A.; Santamaría, A.; San-José, J.T.; Aragón, Á. Durability studies on fiber-reinforced EAF slag concrete for pavements. *Constr. Build. Mater.* **2018**, *163*, 471–481. [CrossRef]
24. Li, S.; Xiong, R.; Zhai, J.; Zhang, K.; Jiang, W.; Yang, F.; Yang, X.; Zhao, H. Research progress on skid resistance of basic oxygen furnace (BOF) slag asphalt mixtures. *Materials* **2020**, *13*, 2169. [CrossRef]
25. Fuente-Alonso, J.A.; Ortega-López, V.; Skaf, M.; Aragón, Á.; San-José, J.T. Performance of fiber-reinforced EAF slag concrete for use in pavements. *Constr. Build. Mater.* **2017**, *149*, 629–638. [CrossRef]
26. Kalhori, M.; Ramezanianpour, A.A. Innovative air entraining and air content measurement methods for roller compacted concrete in pavement applications. *Constr. Build. Mater.* **2021**, *279*, 122495. [CrossRef]
27. Awolusi, T.F.; Oke, O.L.; Atoyebi, O.D.; Akinkurolere, O.O.; Sojobi, A.O. Waste tires steel fiber in concrete: A review. *Innov. Infrastruct. Solut.* **2021**, *6*, 34. [CrossRef]

28. Bosela, P.; Delatte, N.; Obratil, R.; Patel, A. Fresh and hardened properties of paving concrete with steel slag aggregate. Propiedades para firmes del hormigón fabricado con áridos siderúrgicos. *Carreteras* **2009**, *4*, 55–66.
29. Bharath, V.; Rao, P. Study on the fibre reinforced concrete using steel slag as the coarse aggregate replacement. *Int. J. Eng. Res.* **2015**, *2*, 1322–1326.
30. EN-Euronorm. *Rue de Stassart 36*; European Committee for Standardization: Brussels, Belgium.
31. Santamaría, A.; Ortega-López, V.; Skaf, M.; Chica, J.A.; Manso, J.M. The study of properties and behavior of self compacting concrete containing Electric Arc Furnace Slag (EAFS) as aggregate. *Ain Shams Eng. J.* **2020**, *11*, 231–243. [CrossRef]
32. Wang, G.; Wang, Y.; Gao, Z. Use of steel slag as a granular material: Volume expansion prediction and usability criteria. *J. Hazard. Mater.* **2010**, *184*, 555–560. [CrossRef]
33. Zhao, Z.; Guan, X.; Xiao, F.; Xie, Z.; Xia, P.; Zhou, Q. Applications of asphalt concrete overlay on Portland cement concrete pavement. *Constr. Build. Mater.* **2020**, *264*, 120045. [CrossRef]
34. Golpasand, G.B.; Farzam, M.; Shishvan, S.S. Behavior of recycled steel fiber reinforced concrete under uniaxial cyclic compression and biaxial tests. *Constr. Build. Mater.* **2020**, *263*, 120664. [CrossRef]
35. Papachristoforou, M.; Anastasiou, E.K.; Papayianni, I. Durability of steel fiber reinforced concrete with coarse steel slag aggregates including performance at elevated temperatures. *Constr. Build. Mater.* **2020**, *262*, 120569. [CrossRef]
36. Silva, R.V.; de Brito, J.; Dhir, R.K. Fresh-state performance of recycled aggregate concrete: A review. *Constr. Build. Mater.* **2018**, *178*, 19–31. [CrossRef]
37. EC-2. *Eurocode 2: Design of Concrete Structures. Part 1–1: General Rules and Rules for Buildings*; CEN (European Committee for Standardization): Brussels, Belgium, 2010.
38. Zhao, Z.M.; Liu, K.D.; Chai, J.Y.; Lei, L.L.; Wang, Q.; Qi, X.S.; Liu, R.X. Safety evaluation of reinforced concrete girder bridge after strengthened with pasting technology. In Proceedings of the 4th International Conference on Structures and Building Materials (ICSBM), Guangzhou, China, 15–16 March 2014. [CrossRef]
39. Liu, H.; Zhu, B.; Wei, H.; Chai, C.; Chen, Y. Laboratory evaluation on the performance of porous asphalt mixture with steel slag for seasonal frozen regions. *Sustainability* **2019**, *11*, 6924. [CrossRef]
40. Agencia Estatal de Meteorología (AEMET). Available online: http://www.aemet.es/es/portada (accessed on 22 February 2021). (In Spanish).
41. Nematollahzade, M.; Tajadini, A.; Afshoon, I.; Aslani, F. Influence of different curing conditions and water to cement ratio on properties of self-compacting concretes. *Constr. Build. Mater.* **2020**, *237*, 117570. [CrossRef]
42. Wasilewska, M.; Gardziejczyk, W.; Gierasimiuk, P. Evaluation of skid resistance of exposed aggregate concrete pavement in the initial exploitation period. *Roads Bridges Drogi Mosty* **2017**, *16*, 295–308. [CrossRef]
43. Donbavand, J. *Skidding Resistance of Road Surfaces-Implications for New Zealand*; National Roads Board: Wellington, New Zealand, 1989; Volume 81.