





# Assessment of Dynamic Surface Leaching of Asphalt Mixtures Incorporating Electric Arc Furnace Steel Slag as Aggregate for Sustainable Road Construction

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**Abstract:** This study evaluated the environmental sustainability of partially replacing natural aggregates with electric arc furnace (EAF) slag in concrete and porous asphalt mixtures. Both the Equilibrium Leaching Test (EN 12457-4) and the Dynamic Surface Leaching Test (DSLT, CEN/TS 16637-2) were applied to analyse the leaching behaviour of the asphalt mixtures. The results showed that the incorporation of EAF slag led to the release of chromium (Cr), molybdenum (Mo), and vanadium (V), while the type of bitumen affected the dissolved organic carbon (DOC) release. However, when compared to EAF slag leaching, asphalt mixtures exhibited significantly reduced leaching, particularly Cr (by 70%) and V (by 60%). These results indicate that metal leaching follows a diffusion-controlled release mechanism, showing higher concentrations for the porous asphalt compared to the asphalt concrete. The cumulative leaching values at 64 days reached 2.54 mg·m<sup>-2</sup> for Cr, 3.29 mg·m<sup>-2</sup> for Mo, and 28.67 mg·m<sup>-2</sup> for V, far from the limits set by the Dutch Soil Quality Decree (SQD) of 120, 144, and 320 mg·m<sup>-2</sup>, respectively. Therefore, this study demonstrated that EAF slag is a viable alternative for sustainable road construction, reducing natural resource consumption and promoting the circular economy.

Keywords: asphalt; aggregate; EAF slag; leaching; DSLT; trace elements; DOC

# 1. Introduction

Global infrastructure needs are expected to rise significantly due to urban migration, necessitating extensive construction and maintenance [1]. Road construction is particularly resource-intensive, causing environmental impacts such as soil degradation, biodiversity loss, and greenhouse gas emissions from aggregate extraction and transport [2]. To mitigate these effects, the asphalt pavement industry promotes using waste as a secondary raw material in new asphalt, as well as recycling of old asphalt [3]. Aggregates are crucial in road construction, with 1 km of motorway requiring up to 30,000 tons (approximately 1.35 billion tons per year) [4]. Therefore, replacing natural aggregates with by-products and waste such as foundry sand, recycled aggregates, recycled glass or plastic, and various types of slags is feasible for enhancing asphalt sustainability [5]. However, before using these materials in asphalt, it is recommended that life cycle, health, and environmental risk assessments be conducted at both the service stage (e.g., road pavement) and the end-of-life stage (e.g., reuse, recycling, and disposal) [3].



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Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/ licenses/by/4.0/). Steel slags, by-products of steel production, are commonly used as aggregates in asphalt mixtures for road construction [6]. Two types of steel slag are generated: BOF slag from the basic oxygen furnace process and electric arc furnace (EAF) slag, which uses recycled metal scrap as the primary raw material in the furnace. Limestone is added as a fluxing agent to form the slag. The most common EAF slags in road construction are carbon steelmaking slag (EAFc) and stainless steel/high-alloy steelmaking slag (EAFs) due to their superior properties and availability [7,8]. The mechanical performance of asphalt mixtures that incorporate EAF slag has been widely explored, showing similar or even better results than traditional aggregates [9,10]. However, its environmental aspects have not been equally addressed. In the European Union, steel slag is classified as a by-product or waste [6], whereas the United States Environmental Protection Agency (USEPA) categorizes it as non-hazardous, based on ignitability, corrosivity, reactivity, and toxicity [11]. EAF slag can contain specific additives, such as chromium, molybdenum, and vanadium [12], which can release "dangerous substances" that contaminate soil and water, requiring compliance with leaching criteria for road construction materials [13,14].

In this context, the current European Construction Products Framework has proposed harmonized leaching test standards to assess the emission of "dangerous substances" from construction products [15]. These laboratory tests were developed to characterize the emission of "dangerous substances" in a relatively short time and to provide reproducible and meaningful results. The relationship between a test result and the expected release to the environment is established by model calculations based on knowledge of the dominant release mechanism [15,16]. Specifically, the Dynamic Surface Leaching Test (DSLT) was developed to determine the release per unit surface area as a function of time for inorganic and non-volatile organic substances from a monolithic product according to the CEN/TS 16637-2:2014 standard [17]. The DSLT and the associated requirements and mathematical modelling allow the identification of the controlling release mechanisms and, by extrapolation, the prediction of the long-term leaching behaviour [18]. Due to the lack of harmonized leaching limit values for monolithic construction materials in the European Union, the results are frequently compared to those of traditional products or reference materials. Additionally, recent studies have used leaching criteria applied directly to laboratory tests for monolithic products (unrestricted use) as proposed by the Dutch Quality Decree for Soil and Groundwater [19,20].

In the literature, the environmental feasibility of asphalt mixtures incorporating byproducts or industrial residues is usually assessed by a compliance-level leaching procedure, such as the Toxicity Characteristic Leaching Procedure (TCLP) proposed by the USEPA or the European standard Compliance Leaching Test (EN 12457-4) [21]. However, few studies have addressed the environmental risk of asphalt mixtures by simulating life-stage use scenarios based on long-term laboratory leaching behaviour [22–24] and site-specific investigations [25]. Specifically, DSLT has been used to assess road materials based on recycled concrete aggregates and activated blast furnace slags [26], asphalt paving using phosphogypsum-based foamed bitumen [27], and rubber-modified asphalt pavements [20,28].

In this way, the present study is the first to evaluate the long-term leaching behaviour of hazardous substances in bituminous mixtures containing EAF steel slag as a replacement for natural aggregates in accordance with the specifications set out in the standard DSLT (monolithic form). This approach allows the prediction of the time-dependent leaching impact of bituminous mixes based on the determined release mechanisms, thereby validating the environmental compatibility of their intended uses by different stakeholders.

The present study aimed to determine the release of chemical components of environmental concern (As, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn, chloride, fluoride, and sulphate) from EAF steel slag and the release of dissolved organic carbon (DOC) from

two types of bituminous mixtures: asphalt concrete (AC) and porous asphalt (PA). These mixtures are used on roads with high traffic densities and roads that require water drainage, respectively [29]. For this purpose, two standard procedures, the compliance leaching test (EN 12457-4) for granular form and DSLT (CEN/TS 16637-2) for monolithic form, were performed. Long-term leaching predictions of the asphalt mixtures as a wearing course for critical elements were estimated using a controlled release mechanism obtained from the mathematical modelling of the DSLT results.

## 2. Materials and Methods

# 2.1. Materials

EAF slag from a high-alloy steel manufacturing plant in northern Spain was pre-treated using the following processes: cooling, primary metal separation, crushing, screening, classification, secondary metal separation, and aging prior to use as an alternative aggregate. Two high-quality natural aggregates commonly used in the north of Spain for roads with high levels of heavy traffic were selected as the reference aggregates: ophite for the coarse fraction and limestone for the fine fraction to complete the particle size distribution of the asphalt mixtures. The EAF slag replaced the coarse and partially fine fractions of the aggregates in the mixture. The properties of these aggregates are listed in Table 1.

**Table 1.** Characteristics of coarse and fine aggregates.

Properties	Standard	Ophite Coarse	EAF Slag Coarse/Fine	Limestone Fine
Specific weight ( $g \cdot cm^{-3}$ )	EN 1097-6:2022	2.937	3.943	2.725
Los Angeles coefficient	EN 1097-2:2020	16	18	25
Flakiness index	EN 933-3: 2012	8	2	-
Water absorption (%)	EN 1097-6:2012	0.6	1.1	-
Crushed surfaces (%)	EN 933-5:2022	100	100	-
Polished stone value (BPN)	EN 1097-8:2020	57	56	-
Sand equivalent	EN 933-8:2012 +A12015	-	-	78

The EAF slag is characterized mainly by iron, calcium, silicon, magnesium, manganese and aluminium oxides, as shown in Table 2. High contents of Ba, Cr, Cu, Mo, V, and Zn were reported in the analysis of trace elements. Some studies have confirmed that the presence of Cr, Mo, and V is primarily responsible for the environmental impact of EAF slags produced from high-alloy steels [30,31].

**Table 2.** Chemical composition of the EAF slag in percent by weight (%wt.) for major elements and  $mg \cdot kg^{-1}$  for trace elements.

<b>Major Elements</b>	% wt.	<b>Trace Elements</b>	mg∙kg <sup>-1</sup>
SiO <sub>2</sub>	$10.18\pm0.47$	As	<2
$Al_2O_3$	$5.98 \pm 0.09$	Ва	$872.5\pm20.5$
Fe <sub>2</sub> O <sub>3</sub>	$45.92 \pm 1.24$	Cd	< 0.5
MnO	$6.28\pm0.27$	Cr	$17{,}700\pm1414$
MgO	$6.67\pm0.22$	Cu	$104.5\pm2.12$
CaO	$22.47 \pm 1.48$	Hg	<1
Na <sub>2</sub> O	$0.055\pm0.01$	Мо	$147\pm9.89$
TiO <sub>2</sub>	$0.41\pm0.002$	Ni	$17.5 \pm 2.12$

Major Elements	% wt.	Trace Elements	$mg\cdot kg^{-1}$
P <sub>2</sub> O <sub>5</sub>	$0.37\pm0.01$	Pb	$17\pm1.41$
S	0.077	Sb	0.4
LOI *	-1.85	Se	<3
		V	$1092.5\pm78.49$
		Zn	$197.5\pm0.71$

Table 2. Cont.

\* LOI Loss on Ignition at 1000 °C.

Two types of binders were used depending on the type of asphalt mixture: conventional B 50/70 penetration-grade bitumen PMB 45/80-65 for the asphalt concrete (AC) mixtures and polymer-modified bitumen for porous (PA) mixtures (Table 3).

Table 3. Properties of bitumen.

Properties	Standard	Bitumen B 50/70	Polymer Modified Bitumen 45/80-65
Specific weight (g·cm <sup>-3</sup> )	EN 15326:2007	1.035	1.028
Penetration (25 °C, dmm)	EN 1426:2015	57	55
Softening point (°C)	EN 1427:2015	51.6	74.1
Fraass brittle point (°C)	EN 15326:2007	-11	-13
Elastic recovery (25 °C, %)	EN 13398:2017	-	92

#### 2.2. Asphalt Mixture Design

The two types of asphalt mixtures, AC and PA, were selected because they are completely different: AC works by cohesion of the mastic with a low percentage of voids, while PA works by friction of the mineral skeleton with a high percentage of voids. Control asphalt mixtures of each type were designed (C-AC and C-PA samples) and the EAF steel slag replaced the maximum quantity of natural aggregates (S-AC and S-PA samples). The percentage replacement depended on the particle size distribution of each type of mixture. This replacement was made by volume owing to the high density of the slag to maintain the internal structure of the control asphalt mixtures. Figure 1 shows the particle size distribution according to the volume of the asphalt mixture.



**Figure 1.** Particle size distribution by volume of Asphalt Concrete, control (C-AC) and slag-based (S-AC); Porous Asphalt, control (C-PA) and slag-based (S-PA). Grey dotted lines represent Upper and Lower standard Limits.

The particle size distributions of the asphalt mixtures with slags aimed to replicate the granulometry of the control asphalt mixtures as closely as possible (Figure 1). The dosage

of the mixtures must be represented by weight to manufacture the asphalt mixtures. The high density of the slags indicates that the weights of the experimental mixtures (Table 4) differed from those of the control mixtures, although their particle size distributions are almost the same.

Materials (Particle Size, mm)				
-	C-AC	S-AC	C-PA	S-PA
EAF Slag (8/16)	-	33.4	-	63.1
EAF Slag $(4/8)$	-	24	-	9.7
EAF Slag $(0/4)$	-	20.5	-	20.4
Ophite (8/16)	31.9	-	43.5	-
Ophite $(4/8)$	21.2	-	33.9	-
Ophite $(2/4)$	10.3	-	4.5	-
Limestone $(0/2)$	31.7	17.2	10.8	-
Limestone filler	0.6	0.6	2.8	2.6
Bitumen	4.3	4.3	4.5	4.2
Type of bitumen	B 50,	/70	PMB 45	5/80-65

Table 4. Asphalt mixture dosages used in the wearing course.

The mechanical properties of the asphalt mixtures are listed in Table 5. All mixtures complied with Spanish mechanical standards. Despite the high percentage of EAF slags, the experimental mixtures can be considered similar to the control mixtures in terms of their internal structure and mechanical behaviour. More detailed information on the design and properties of the asphalt mixtures tested was provided in previous work by some of the authors of this paper [32,33].

Table 5. Mechanical properties of AC and PA mixtures.

Property	C-AC	S-AC	Limit	C-PA	S-PA	Limit						
	Voids	s test (EN 12697-	8:2003)									
Density (g · cm <sup>-3</sup> )	2.453	3.09	-	1.992	2.691	-						
Voids (%)	5.1	5.3	4–6	23.1	22.6	$\geq 20$						
Voids in aggregates (%)	15.3	17.9	$\geq 15$	16.1	16.6	-						
	Marsha	ll test (EN 12697	/-34:2020)									
Stability (kN)	15.7	16.3	>15 (*)	-	-	-						
Strain (mm)	3.8	3.2	2–3.5 (*)	-	-	-						
Cantabro particle loss test (EN 12697-17:2017)												
Particle loss (%)	-	-	-	7.1	11.1	$\leq 20$						
	Wate	er sensitivity tes	t (EN 12697-12:20	18)								
ITS Dry (kPa)	1745.7	1844.4	-	1074.2	923.6	-						
ITS Wet (kPa)	1610	1719.6	-	1034.3	859.3	-						
ITSR (%)	92	93	$\geq 85$	96	93	$\geq 85$						
	Wheel trac	king test (EN 12	697-22:2020)									
Slope (mm/1000 cycles)	0.08	0.08	$\leq 0.10$	-	-	-						
Rut (mm)	3.1	3.2	-	-	-	-						
	Binder drai	nage test (EN 12	2697-18:2017)									
Binder drainage (%)	-	-	-	0	0	$\leq 0.3$						

(\*) Limits according to the former standard NLT-159 (test not currently required).

2.3. Leaching Tests

A compliance leaching test for granular materials (EN 12457-4) [34] was performed to determine the release of inorganic species and DOC from the EAF steel slag and asphalt mixtures under chemical equilibrium conditions. According to this test, the slag sample was

crushed (particle size  $\leq 10$  mm) and asphalt samples were conventionally manufactured, but then they were cooled down without the compaction process to obtain loose mixtures. Each sample was weighed and mixed with deionized water with a liquid-to-solid ratio of  $10 \text{ L} \cdot \text{Kg}^{-1}$  in polyethylene bottles. At 10 rpm for 24 h, the bottles were shaken on a Heidolph Reax 20 rotary shaker (Figure 2a). A vacuum filtration device was used to separate the solid over a 0.45 µm nitrocellulose membrane filter. The pH and conductivity values of the leachates were measured. The tests were conducted in triplicate for each sample.



**Figure 2.** Images of the experimental developments of the leaching tests: (**a**) Compliance leaching test (EN 12457-4), (**b**) Dynamic Surface Leaching Test (DSLT, CEN/TS 16637-2).

DSLT (CEN/TS 16637-2) was performed to assess the surface-dependent release from monolithic materials as a function of time. According to the standard test procedure, specimens with a defined geometry, 101 mm in diameter and 63 mm in height (Marshall Samples), were immersed in 3 L glass vessels. The specimens were statically suspended in a nylon net to ensure contact with deionized water on all exposed surfaces, with at least 20 mm of separation from the vessel walls (Figure 2b). The water volume to surface area (L/A) ratio was  $80 \pm 10 \text{ L} \cdot \text{m}^{-2}$  (2.7 L). The long-term leaching from the monolithic asphalt mixtures was quantified by replacing the leaching solutions with deionized water at predetermined cumulative time intervals of 0.25, 1, 2.25, 4, 9, 16, 36, and 64 days. The pH and conductivity of the eluate were measured. Three replicates were performed for each sample.

# 2.3.1. Analytical Methods

The obtained leachates were acidified with HNO<sub>3</sub> and chemically analysed at the Central Analysis Service of the University of the Basque Country (Spain), in accordance with ISO quality control standards. The equipment used for chemical analysis included an Inductively Coupled Plasma Spectrometer with Mass Detector ICP-MS (Agilent, 7700x, Santa Clara, CA, USA) and a Compact Ion Chromatograph Flex 930 (Metrohm) (Herisau, Switzerland). The critical elements of Decision 2003/33/CE, which establishes the criteria and procedures for accepting waste at a landfill, were assessed. The quantification limits are as follows ( $\mu$ g·L<sup>-1</sup>): As (0.03), Ba (0.3), Cd (0.015), Cr (0.3); Cu (0.15), Hg (0.03), Mo (0.3), Ni (0.03), Pb (0.07), Se (0.03), Sb (0.015), V (0.3), Zn (0.2), Cl<sup>-</sup> (250), F<sup>-</sup> (10), and SO<sub>4</sub><sup>2-</sup> (500). The DOC concentrations were determined (EN 1484) using a Shimadzu TOC-L CPH instrument. The trace elements and DOC concentrations in the leachates were obtained in duplicate and are presented as mean values.

#### 2.3.2. Reporting of the Dynamic Surface Leaching Test Results

The analysis of the leachates provided the concentration values of the substances for different time intervals in the DSLT and the cumulative area release was calculated using Equation (1):

$$R_n = \sum_{i=1}^n c_i \cdot \frac{V_L}{A_{exp}} \tag{1}$$

where  $R_n$  is the cumulative area release of the constituent for the period n (mg·m<sup>-2</sup>),  $c_i$  is the concentration of this substance in the i step leachate ( $\mu$ g·L<sup>-1</sup>),  $V_L$  is the volume of leachate (L), and  $A_{exp}$  is the exposed area of the test specimen (m<sup>2</sup>).

The CEN/TS 16637-2 standard was utilized to determine the release mechanisms of trace elements and DOC after analysing the DSLT results. A flowchart of the steps and calculations for the mechanism identification used in this study is shown in Figure S1.

Mathematical modelling of the DSLT results allows the prediction of the long-term release of monolithic asphalt mixture specimens during their service life as a wearing course in road construction. The estimation of the area release for long-term values (greater than 64 days) was performed using formulae for extrapolation of the different release mechanisms listed in Annex B (Table B.1) of CEN/TS 16637-2:2014. In addition, the DSLT values were compared to the limits for unrestricted use of monolithic building materials set in the Dutch SQD [35].

# 3. Results and Discussion

#### 3.1. Compliance Leaching Test EN 12457-4 on Granular EAF Slag

The pH, conductivity and release of chemical components in the eluates of the granular EAF slag are presented in Table 6. These concentrations were compared with the leaching limit values established by the regulations for the use of slags in the Region of Cantabria (Spain). The EAF slag is alkaline in aqueous solution owing to its basic oxide components, with a pH value of approximately 11; after being introduced into asphalt mixtures, a significant decrease in the pH and conductivity values of the eluates was observed with respect to the slag eluates. The mobility of metals in slag is reduced due to elevated pH, and it is an important consideration for slag applications near the surface and in groundwater because carbonation decreases the pH values and causes leachability changes. However, it may have a secondary effect of changing the leaching behaviour of the soil by mobilizing constituents as DOC-bound species [36]. A similar behaviour of bituminous mixtures containing up to 40% EAF slag was reported by Sorlini et al. (2012) using the same leaching test [37].

The chromium mobility was evaluated first as it is the principal concern regarding the use of EAF slags owing to their high Cr content [30]. The Cr content in the slag (Table 1) was 17,700 mg·kg<sup>-1</sup> and this contrasts with a significantly low mobilization that does comply with the limits considered in the Region of Cantabria (Spain) Decree 100/2018 on slag valorisation. This could be due to the retention of Cr in the form of chromite,  $FeCr_2O_4$  [31], and to the cooling method of the EAF slag that favours the formation of crystalline phases that immobilize trace elements [38]. The mobility of the rest of the trace elements quantified, such as Ba, Cu, Mo, Ni, Pb, V, and Zn, presented significant retention despite their high content in the slag. Hence, the analysed EAF slag showed an overall low mobility of trace elements. However, some elements, such as Hg, Mo, and Se, slightly exceeded the established limit values. In the case of V, although low concentrations were observed in the eluate in relation to the chemical content of the EAF slag, the limit was exceeded. This can be attributed to the alkalinity derived from the slag promoting the release of V, which is usually attenuated in the long term by slag carbonation [31]. The chloride, fluoride and sulphate concentrations were well below the limits considered, and the DOC was below the limit of detection of the equipment.

However, the steel slag valorisation regulation in the Region of Cantabria (Decree 100/2018) dictates that the EAF slag does not need to comply with these limits when incorporated in asphalt mixtures, as long as the absence of a threat to the environment is demonstrated. To satisfy this requirement, it is proposed that loose asphalt mixtures should be tested with a layer of the corresponding bitumen. In Europe, waste-derived aggregates

Substances (mg∙kg <sup>-1</sup> )	EAF Slag	Limit Values *	C-AC	S-AC	C-PA	S-PA
pН	$11.46\pm0.05$	-	$9.68\pm0.07$	$10.38\pm0.03$	$10.02\pm0.05$	10.76
Conductivity (µS·cm <sup>−1</sup> )	$305.67\pm15.5$	-	$48.53 \pm 1.39$	$100.55\pm1.85$	58.03	178.27
Arsenic (As)	$0.002 \pm 0.00005$	0.5	$0.001\pm0.0004$	$0.002\pm0.0002$	$0.001\pm0.0007$	0.001
Barium (Ba)	$1.040\pm0.016$	20	$0.029\pm0.005$	$0.645\pm0.079$	$0.026 \pm 0.0029$	$0.615\pm0.026$
Cadmium (Cd)	$0.00028 \pm 0.00006$	0.04	< 0.00015	< 0.00015	< 0.00015	< 0.00015
Chromium (Cr)	$0.343\pm0.064$	0.5	$0.008 \pm 0.001$	$0.061\pm0.005$	$0.022\pm0.006$	$0.051 \pm 0.0002$
Copper (Cu)	< 0.0015	2	< 0.0015	< 0.0015	$0.006\pm0.001$	$0.004 \pm 0.001$
Mercury (Hg)	$0.011 \pm 0.00051$	0.01	< 0.0003	$0.0005 \pm 0.00007$	< 0.0003	$0.0005 \pm 0.00007$
Molybdenum (Mo)	$0.778 \pm 0.08$	0.5	$0.018\pm0.0002$	$0.106\pm0.019$	$0.016\pm0.005$	$0.081\pm0.016$
Nickel (Ni)	< 0.0003	0.4	$0.001\pm0.0004$	$0.0012\pm0.001$	$0.003\pm0.0004$	$0.001\pm0.0002$
Lead (Pb)	< 0.0007	0.5	< 0.0007	< 0.0007	< 0.0007	< 0.0007
Antimony (Sb)	$0.002\pm0.0002$	0.06	$0.0004 \pm 0.0003$	$0.0007 \pm 0.0002$	0.0003	$0.0007 \pm 0.0003$
Selenium (Se)	$0.144\pm0.0058$	0.1	$0.0036\pm0.001$	$0.019\pm0.0016$	$0.007\pm0.0004$	$0.009\pm0.005$
Vanadium (V)	$3.661\pm0.043$	1.5 **	$0.009\pm0.0008$	$0.616\pm0.060$	$0.0036\pm0.006$	$0.591\pm0.012$
Zinc (Zn)	$0.019 \pm 0.0027$	4	< 0.002	< 0.002	< 0.002	$0.001\pm0.0006$
Chloride ( $Cl^{-}$ )	$5.15\pm2.188$	800	<2.5	<2.5	<2.5	<2.5
Fluoride (F <sup>-</sup> )	$3.947 \pm 0.102$	10	< 0.1	< 0.1	< 0.1	< 0.1
Sulphate ( $[SO_4]^{2-}$ )	$230\pm14.142$	1000	<5	<5	<5	<5
Dissolved organic carbon (DOC)	<5	500	$9.0\pm0.283$	$8.5\pm0.353$	$12.5\pm0.71$	9.0

are being considered by the Commission for the development of common end-of-waste criteria [39].

**Table 6.** Concentration  $(mg \cdot kg^{-1})$  of contaminants in the leachates (EN 12457-4) of EAF slag and loose asphalt mixtures.

(\*) Decree 100/2018 of the Region of Cantabria (Spain) on slag valorisation in line with EU Inert Landfill Waste Acceptance Criteria Limits (Decision 2003/33/CE). (\*\*) Decree 64/2019 of the Basque Country (Spain) on Slag Valorization.

#### 3.2. Compliance Leaching Test EN 12457-4 on Loose Asphalt Mixtures

The pH and conductivity values and the release of critical components in the eluates from the loose asphalt mixtures are listed in Table 6. The asphalt mixtures incorporating EAF slag (S-AC and S-PA) showed considerably reduced mobilities of Hg, Mo, Se, and V with respect to the slag, and all values were below the limits set by the current environmental regulations. This leaching behaviour is supported by previous studies that used similar bituminous mixtures with different types of EAF slag [9,29,37]. On the other hand, the concentrations of trace elements were slightly higher than in the control mixtures (C-AC and C-PA) but were considerably lower compared to the release of the unbound EAF slag.

It can be concluded from the compliance leaching test results that bitumen effectively immobilized trace elements from the slag in the asphalt mixtures and there was no difference in the leaching behaviour under equilibrium conditions between the concrete and porous asphalts. However, the release of the identified elements of potential concern for slag-based mixtures should be thoroughly studied. Based on the results of this initial assessment, Cr, Hg, Mo, Se, and V were monitored in a subsequent leaching assessment of the monolithic asphalt mixtures.

Concentrations of chloride, fluoride, and sulphate asphalt mix leachates were below the limits of quantification, which is consistent with the low measured conductivity values. Therefore, anion concentrations were not considered in the leaching study of the monolithic specimens.

DOC has been detected in asphalt mixture eluates in previous studies [29,40], probably because of the corresponding bitumen layer used. Although the concentration of DOC, ranging from 9.0–12.5 mg·kg<sup>-1</sup> for all leachates, is well below the limit proposed in the

Region of Cantabria (Spain) on slag valorisation, the DOC can substantially enhance the leaching of metals and persistent organic pollutants [40]. Therefore, this parameter was also followed in the DSLT.

# 3.3. Dynamic Surface Leaching Test (CEN/TS 16637-2) on Monolithic Asphalt Mixtures

The pH and conductivity values of the eluates determined during the DSLT are depicted in Figure 3. The release of the trace elements Cr, Mo, and V is depicted in Figures 4 and 5 for the AC and PA mixtures, respectively. The release of Hg and Se was below the quantification limits for both mixtures.



Figure 3. Evolution of pH and conductivity in DSLT eluates from asphalt mixtures.



**Figure 4.** Cumulative area release of Cr, Mo, and V from asphalt concrete (AC) specimens according to the DSLT, CEN/TS 16637-2 standard.



**Figure 5.** Cumulative area release of Cr, Mo, and V from porous asphalt (PA) specimens according to the DSLT, CEN/TS 16637-2 standard.

The pH values were slightly higher in asphalt mixtures with slag than in mixtures with natural aggregates, which agrees with the granular leaching test results (Table 6). In the four samples, for the short-term stages (days 1–10), the pH values progressively increased and then reached a stable, mildly alkaline value range in the long term (days 10–64). This pH stability was also observed by Paulus et al. [26] when testing a monolithic asphalt mixture with recycled concrete aggregates. This could be related to the duration of the water renewal intervals in the leachate vessels, which was shortest in the first few days. The pH of the leachate is driven by the pH of the freshwater immediately after renewal, which favours the release of alkaline compounds from the mixtures, increasing the pH. Thus, it can be stated from the leaching characterization results that the pH is expected to be stable over the long term for slag-based mixtures, similar to conventional asphalts.

In parallel, the evolution of conductivity over time for all mixtures progressively increased, indicating the possibility of incipient depletion of total dissolved species in the long-term scenario, as the values start to stabilize at 64 days. The conductivity values were similar between the AC mixtures; however, in the PA mixtures, the values were higher for the slag-based porous asphalt specimens. This difference between the AC and PA mixtures was caused by the higher void fraction of the porous mixtures, as shown in Table 5, which promotes the dissolution of the predominant alkaline species (i.e., Ca, Mg) from the slag. This resulted in the pH and conductivity of the S-PA mixture being slightly higher than those of the S-AC.

Figure 4 shows the cumulative release of trace elements from the AC mixtures. Samples incorporating EAF slag showed higher mobilities of Cr, Mo, and V than the samples with natural aggregate. V exhibited the highest release of the considered elements, followed by Mo and Cr. The same difference was observed in the compliance leaching test results (Table 6) and by Milačič et al. [24].

Figure 5 shows the cumulative release for the PA porous mixtures, showing the same trend as for the AC concrete mixtures; the slag-based samples (S-PA) leached more than the control samples (C-PA). Although the dynamic surface leaching behaviours of both types of asphalt were similar, the difference in the mobility of all elements between the control and slag-based asphalts was greater in the PA than in the AC mixtures. This can be seen in Table 7, which shows the cumulative area release of Cr, Mo, and V at 64 days. In addition, the mobility of the S-PA sample was the highest of all the samples. The porous structure of the mixture could contribute to a higher open porosity, which greatly increases the water permeability and thus the leaching of substances [26].

**Table 7.** Cumulative area release values at 64 days of Cr, Mo, and V from asphalt mixtures according to the DSLT, CEN/TS 16637-2 standard.

Element (mg·m <sup>-2</sup> )	C-AC	S-AC	C-PA	S-PA	SQD Limit Values *
Cr	0.14	0.92	0.09	2.54	120
Мо	0.20	1.86	0.05	3.29	144
V	0.31	15.39	0.28	28.67	320

(\*) Soil Quality Decree 2007 (unrestricted use of monolithic products) [35].

In the absence of limits proposed by regulatory frameworks in the European Union on the maximum release of trace elements per unit surface area of samples, the thresholds for monolithic building materials proposed by the Dutch SQD [35] were selected to compare the cumulative area release of the trace elements Cr, Mo, and V of all mixtures in the DSLT (in mg·m<sup>-2</sup>) at 64 days. As shown in Table 7, all the asphalt mixtures investigated in this study were environmentally acceptable, as all values were below the thresholds set by the Dutch SQD.

DOC mobility was also analysed in the DSLT leachates (Figure 6). The DOC was high in the AC mixtures in the first steps of the test, decreased progressively, and approached the detection limit ( $0.5 \text{ mg-L}^{-1}$ ) in the last steps. In the PA mixtures, the DOC was close to the detection limit throughout the test.



**Figure 6.** Dissolved organic carbon: (**a**) concentration in the leachates and (**b**) cumulative area release from asphalt mixtures according to the DSLT, CEN/TS 16637-2 standard. Red dashed line in (**a**) indicates the detection limit of the apparatus.

These results indicate that while the incorporation of EAF slag did not affect the DOC release, the cumulative release differed between the two types of asphalt mixtures, which could be due to the difference in the type of bitumen used: B 50/70 bitumen in the AC mixtures and PMB 45/80-65 polymer-modified bitumen in the PA mixtures. However, this effect was not observed in the results obtained from the compliance leaching test (EN 12457-4) with the loose asphalt samples (Table 6). The non-correlation of the results

was due to the different conditions under which each leaching test was conducted. The concentrations were of the same order of magnitude as those reported by Paulus et al. [26] using similar conventional bitumen and the same leaching test. Therefore, these results suggest the need for further in-depth leaching studies of industrial waste-based construction materials to better understand the potential release of substances from the materials depending on the intended use scenario.

#### 3.4. Release Mechanisms of Cr, Mo, V, and DOC from Monolithic Asphalt Mixtures

The experimental data obtained from the application of the DSLT to monolithic specimens were used to determine the release mechanisms of trace elements and DOC according to the identification procedure proposed in CEN/TS 16637-2 Annex B. The results are listed in Table 8 and the derived calculations and mathematical conditions are listed in Table S1.

**Table 8.** Identification of Cr, Mo, V, and DOC surface release mechanisms according to the hierarchical determination proposed in the DSLT, CEN/TS 16637-2 standard and long-term release prediction from mechanisms determined, considering the service life of the wearing course for AC mixtures (15 years) and PA mixtures (10 years).

Release Mechanism		C-	AC			S-4	AC			C-	PA			<b>S-</b> ]	PA	
	Cr	Мо	V	DOC	Cr	Мо	$\mathbf{V}$	DOC	Cr	Мо	V	DOC	Cr	Мо	V	DOC
M1	-	-	-	-	-	-	-	-	$\checkmark$	$\checkmark$	-	$\checkmark$	-	-	-	$\checkmark$
M1.1	-	-	-	$\checkmark$	-	-	-	$\checkmark$	-	-	-	-	-	-	-	-
M2	-	-	$\checkmark$	-	$\checkmark$	$\checkmark$	$\checkmark$	-	-	-	$\checkmark$	-	$\checkmark$	$\checkmark$	$\checkmark$	-
M2.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
M2.2	-	-	$\checkmark$	-	-	$\checkmark$	$\checkmark$	-	-	-	-	-	-	-	-	-
M3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
M4	$\checkmark$	$\checkmark$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
M4.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
M4.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Determined mechanism	M4	M4	M2.2	M1.1	M2	M2.2	M2.2	M1.1	M1	M1	M2	M1	M2	M2	M2	M1
Long-term release prediction * (mg $\cdot$ m <sup>-2</sup> )	1.32	1.85	2.02	-	8.47	18.58	163.23	-	-	-	2.12	-	19.19	24.87	216.49	-

(\*) Dutch Soil Quality Decree limit values  $(mg \cdot m^{-2})$  for unrestricted use of monolithic products: Cr: 120; Mo: 144; V: 320. M1: Overall low concentrations; M1.1: Surface wash-off preceding M1; M2: Diffusion; M2.1: Surface wash-off preceding M2; M2.2: Depletion after M2; M3: Dissolution; M4: Unidentified mechanism; M4.1: Surface wash-off preceding M4; M4.2: Depletion after M4.

Diffusion-controlled release was the main surface release mechanism of trace elements (Cr, Mo, and V) in slag-incorporated asphalt mixtures. This means that the process is driven by a concentration gradient of a substance. In practice, the release is linear with the square root of time. Depletion of the leaching of Mo and V was identified in S-AC (substance does not release in the last stages), whereas this depletion was not observed in S-PA. This could be related to the increased cumulative concentrations detected in S-PA with respect to S-AC and attributed to the porous structure of the PA samples. The same surface release mechanisms for metal(loid)s from asphalt mixtures based on other types of slags, such as BOF slag, have been reported in previous studies [22,41].

In the control asphalt mixtures, it was not possible to correctly determine the release mechanisms of Cr and Mo because of their low concentrations, which were very close to the limit of quantification. These trace elements showed similar leaching in the EN 12457-4 test on the granular samples (Table 6). For V, diffusion-controlled release was identified as the primary mechanism.

In relation to the DOC release mechanism, in the asphalt concrete mixtures, a surface washout followed by low concentrations was identified, whereas in the porous mixtures, owing to concentrations close to the limit of detection, no mechanism of DOC leaching could be identified. The differences in DOC leaching between the two mixtures (AC and PA) are well depicted in Figure 6.

From the cumulative release data and determination of monolithic release mechanisms, it can be concluded that the substitution of natural aggregate with EAF slag in asphalt mixtures changes the leaching mechanism of trace elements but not DOC, which depends on the type of bitumen used. These results provide essential information that can be used as a basis for further environmental assessments.

#### 3.5. Long-Term Environmental Impact of the Use of EAF Slag in Asphalt Mixtures

The expected release of Cr, Mo, and V was calculated by extrapolation using the mathematical expressions contained in the CEN/TS 16637-2 document for each release mechanism identified. The predicted values considering the life expectancy of the wearing course of 15 years for AC mixtures [42] and 10 years for PA mixtures [43] are listed in Table 8. The DOC release for time values greater than 64 days was not considered because of the low concentrations obtained in the DSLT.

The estimated values of the slag-based asphalt mixtures were higher than those of the control samples, with the largest difference observed in the V release. Although the life expectancies of the PA mixtures are lower than those of the AC mixtures, the S-PA sample exhibited the highest expected release of trace elements. These predictions align with the experimental results of the DSLT described above, which detail a leaching mechanism by diffusion. As previously determined, this mechanism does not result in depletion. Instead, due to the material porosity, its contact surface with water is greater, allowing it to continue leaching for a longer period.

Table 8 shows that, during the expected lifetime of the asphalt mixtures with EAF slag, the release of trace elements Cr, Mo, and V is below the limits of the Dutch SQD for environmental assessment of monolithic construction materials.

#### 4. Conclusions

This study examined the leaching behaviour of loose and monolithic specimens of two types of asphalt mixtures, Concrete Asphalt (AC) and Porous Asphalt (PA) incorporating EAF slag as a substitute for natural aggregate.

EAF slag as an alternative aggregate is environmentally acceptable according to the Compliance leaching test (EN 12457-4) and the limit values proposed by the Region of Cantabria (Spain) Decree on steel slag valorisation in construction materials. Bitumen significantly reduced the release of critical trace elements Hg, Mo, Se, and V, which in the analysed EAF slag sample exceeded the inert waste limits.

As a monolithic, the cumulative area release of Cr, Mo, and V from asphalt mixtures using conventional aggregate showed no significant difference between the two types of matrices. However, when EAF slag-derived aggregates were used, the mobility was higher in the porous specimens due to the higher open porosity, which greatly increased the water permeability. In contrast, DOC release from polymer-modified bitumen (PMB 45/80-65) (used in PA), instead of conventional penetration grade bitumen (B 50/70) (used in AC), could considerably reduce the leaching of DOC.

Diffusion is the controlling release mechanism for Cr, Mo, and V in the EAF slag-based mixtures and for V for both types of asphalt specimens without slag. The DOC release mechanism could only be identified in AC, surface wash-off followed by low concentrations.

Considering the Dutch SQD limits, the cumulative area release of these elements during the DSLT (64 days) and long-term release over the service life of the wearing course (15 years for AC and 10 years for PA) revealed that while the values for Cr and Mo are well

below these limits, the long-term release prediction for V is 163.23 mg/m<sup>2</sup> for S-AC and 216.4 mg/m<sup>2</sup> for S-PA. These values are closer to the limit of 320 mg/m<sup>2</sup>.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17083737/s1, Figure S1. Flowchart adapted from CEN/TS 16637-2 for the hierarchical determination of release mechanisms of substances from monolithic construction materials; Table S1. Release mechanisms, mathematical criteria to be complied as noted in Annex B of CEN/TS 16637-2, and results from the calculations for each asphalt mixture.

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# References

- Basilico, A.; Botta, M.; Galli, G.; Gargani, F.; Gori, V.; Melfi, L.; Napoli, M.; Stefanucci, S. Assessment of the Unit Costs of Capital Expenditure for Investment Projects in Road Transport. Available online: https://op.europa.eu/en/publication-detail/-/publication/ e87de0f3-9e83-11eb-b85c-01aa75ed71a1/language-en/format-PDF/source-281549759 (accessed on 26 November 2024).
- International Resource Panel. Resource Efficiency for a Low-Carbon Future. Available online: https://www.resourcepanel.org/ file/1966/download?token=dNgPqfZE (accessed on 25 October 2024).
- 3. European Asphalt Pavement Association (EAPA). *The Use of Secondary Materials, by-Products and Waste in Asphalt Mixtures;* European Asphalt Pavement Association (EAPA): Bruxelles, Belgium, 2020.
- UEPG (European Aggregates Association). Annual Review 2016–2017; UEPG (European Aggregates Association): Bruxelles, Belgium, 2017.
- Poulikakos, L.D.; Papadaskalopoulou, C.; Hofko, B.; Gschösser, F.; Cannone Falchetto, A.; Bueno, M.; Arraigada, M.; Sousa, J.; Ruiz, R.; Petit, C.; et al. Harvesting the Unexplored Potential of European Waste Materials for Road Construction. *Resour. Conserv. Recycl.* 2017, 116, 32–44. [CrossRef]
- Euroslag. Statistics on Slag Production in Europe. Available online: https://www.euroslag.com/wp-content/uploads/2022/04/ Statistics-2018.pdf (accessed on 14 November 2024).
- Loureiro, C.D.A.; Moura, C.F.N.; Rodrigues, M.; Martinho, F.C.G.; Silva, H.M.R.D.; Oliveira, J.R.M. Steel Slag and Recycled Concrete Aggregates: Replacing Quarries to Supply Sustainable Materials for the Asphalt Paving Industry. *Sustainability* 2022, 14, 5022. [CrossRef]
- Liu, J.; Xu, J.; Liu, Q.; Wang, S.; Yu, B. Steel Slag for Roadway Construction: A Review of Material Characteristics and Application Mechanisms. J. Mater. Civ. Eng. 2022, 34, 03122001. [CrossRef]
- Skaf, M.; Manso, J.M.; Aragón, Á.; Fuente-alonso, J.A. EAF Slag in Asphalt Mixes: A Brief Review of Its Possible Re-Use. *Resour. Conserv. Recycl.* 2017, 120, 176–185. [CrossRef]
- 10. Fakhri, M.; Ahmadi, A. Recycling of RAP and Steel Slag Aggregates into the Warm Mix Asphalt: A Performance Evaluation. *Constr. Build. Mater.* **2017**, *147*, 630–638. [CrossRef]
- National Slag Association Iron and Steel Slags-Non Hazards. Available online: https://nationalslag.org/wp-content/uploads/ 2021/08/nsa\_194-5\_slag\_a\_non-hazard-1.pdf (accessed on 3 November 2023).

- 12. Saveyn, H.; Eder, P.; Garbarino, E.; Hjelmar, O.; Van Der Sloot, H.; Van Zomeren, A.; Hyks, J. Study on Methodological Aspects Regarding Limit Values for Pollutants in Aggregates in the Context of the Possible Development of End-of-Waste Criteria Under the EU Waste Framework Directive; Publications Office of the European Union: Luxembourg, 2014; ISBN 9789279395390.
- 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]
- 14. Yang, B.; Li, H.; Zhang, H.; Sun, L.; Harvey, J.; Tian, Y.; Zhu, Y.; Zhang, X.; Han, D.; Liu, L. Environmental Impact of Solid Waste Filler in Porous Asphalt Mixture. *Constr. Build. Mater.* **2021**, *303*, 124447. [CrossRef]
- 15. Bandow, N.; Gartiser, S.; Ilvonen, O.; Schoknecht, U. Evaluation of the Impact of Construction Products on the Environment by Leaching of Possibly Hazardous Substances. *Environ. Sci. Eur.* **2018**, *30*, 1–12. [CrossRef]
- European Union Regulation No 305/2011 of the European Parliament and the Council of 9 March 2011 Laying down Harmonised Conditions for the Marketing of Construction Products and Repealing Council Directive 89/106/EEC. *Off. J. Eur. Union* 2011, *L88*, 5–43.
- 17. *CEN* (2014). *CEN/TS* 16637-2; Construction Products—Assessment of Release of Dangerous Substances—Part 2: Horizontal Dynamic Surface Leaching Test. European Committee for Standardization: Brussels, Belgium, 2014.
- Weiler, L.; Pfingsten, J.; Eickhoff, H.; Geist, I.; Hilbig, H.; Hornig, U.; Kalbe, U.; Krause, K.; Kautetzky, D.; Linnemann, V.; et al. Improving Consistency at Testing Cementitious Materials in the Dynamic Surface Leaching Test on the Basis of the European Technical Specification CEN/TS 16637–2—Results of a Round Robin Test. J. Environ. Manag. 2022, 314, 114959. [CrossRef]
- 19. Maherzi, W.; Ennahal, I.; Bouaich, F.Z.; Benzerzour, M.; Rais, Z.; Mamindy-Pajany, Y.; Abriak, N.E. Assessment of Dynamic Surface Leaching of Monolithic Polymer Mortars Comprised of Wastes. *Materials* **2023**, *16*, 2150. [CrossRef] [PubMed]
- 20. Makoundou, C.; Fathollahi, A.; Kleiven, S.; Coupe, S.J.; Sangiorgi, C. Mechanical and Leaching Characterisation of Impact-Absorbing Rubberised Asphalts for Urban Pavements. *Mater. Struct./Mater. Constructions* **2023**, *56*, 1–19. [CrossRef]
- 21. Azadgoleh, M.A.; Mohammadi, M.M.; Ghodrati, A.; Sharifi, S.S.; Palizban, S.M.M.; Ahmadi, A.; Vahidi, E.; Ayar, P. Characterization of Contaminant Leaching from Asphalt Pavements: A Critical Review of Measurement Methods, Reclaimed Asphalt Pavement, Porous Asphalt, and Waste-Modified Asphalt Mixtures. *Water Res.* 2022, 219, 118584. [CrossRef] [PubMed]
- 22. Hu, R.; Xie, J.; Wu, S.; Yang, C.; Yang, D. Study of Toxicity Assessment of Heavy Metals from Steel Slag and Its Asphalt Mixture. *Materials* **2020**, *13*, 2768. [CrossRef]
- Mahpour, A.; Alipour, S.; Khodadadi, M.; Khodaii, A.; Absi, J. Leaching and Mechanical Performance of Rubberized Warm Mix Asphalt Modified through the Chemical Treatment of Hazardous Waste Materials. *Constr. Build. Mater.* 2023, 366, 130184. [CrossRef]
- Milačič, R.; Zuliani, T.; Oblak, T.; Mladenovič, A.; Ančar, J.Š. Environmental Impacts of Asphalt Mixes with Electric Arc Furnace Steel Slag. J. Environ. Qual. 2011, 40, 1153–1161. [CrossRef]
- 25. Xie, J.; Yang, C.; Zhang, L.; Zhou, X.; Wu, S.; Ye, Q. Investigation of the Physic-Chemical Properties and Toxic Potential of Basic Oxygen Furnace Slag (BOF) in Asphalt Pavement Constructed after 15 Years. *Constr. Build. Mater.* **2020**, *238*, 117630. [CrossRef]
- Paulus, H.; Schick, J.; Poirier, J.E. Assessment of Dynamic Surface Leaching of Monolithic Surface Road Materials. J. Environ. Manag. 2016, 176, 79–85. [CrossRef]
- 27. Cuadri, A.A.; Pérez-Moreno, S.; Altamar, C.L.; Navarro, F.J.; Bolívar, J.P. Phosphogypsum as Additive for Foamed Bitumen Manufacturing Used in Asphalt Paving. *J. Clean. Prod.* **2021**, *283*, 124661. [CrossRef]
- Fathollahi, A.; Makoundou, C.; Coupe, S.J.; Sangiorgi, C. Leaching of PAHs from Rubber Modified Asphalt Pavements. *Sci. Total Environ.* 2022, 826, 153983. [CrossRef]
- 29. Lizasoain-Arteaga, E.; Lastra-González, P.; Indacoechea-vega, I.; Flintsch, G. Comprehensive Analysis of the Environmental Impact of Electric Arc Furnace Steel Slag on Asphalt Mixtures. *J. Clean. Prod.* **2020**, 275, 123121. [CrossRef]
- Mombelli, D.; Mapelli, C.; Barella, S.; Di Cecca, C.; Le Saout, G.; Garcia-Diaz, E. The Effect of Chemical Composition on the Leaching Behaviour of Electric Arc Furnace (EAF) Carbon Steel Slag during a Standard Leaching Test. *J. Environ. Chem. Eng.* 2016, 4, 1050–1060. [CrossRef]
- 31. Neuhold, S.; van Zomeren, A.; Dijkstra, J.J.; van der Sloot, H.A.; Drissen, P.; Algermissen, D.; Mudersbach, D.; Schüler, S.; Griessacher, T.; Raith, J.G.; et al. Investigation of Possible Leaching Control Mechanisms for Chromium and Vanadium in Electric Arc Furnace (EAF) Slags Using Combined Experimental and Modeling Approaches. *Minerals* **2019**, *9*, 525. [CrossRef]
- Lastra-González, P.; Calzada-Pérez, M.; Castro-Fresno, D.; Vega-Zamanillo, Á.; Indacoechea-Vega, I. Porous Asphalt Mixture with Alternative Aggregates and Crumb-Rubber Modified Binder at Reduced Temperature. *Constr. Build. Mater.* 2017, 150, 260–267. [CrossRef]
- Lastra-González, P.; Calzada-Pérez, M.A.; Castro-Fresno, D.; Indacoechea-Vega, I. Asphalt Mixtures with High Rates of Recycled Aggregates and Modified Bitumen with Rubber at Reduced Temperature. *Road Mater. Pavement Des.* 2018, 19, 1489–1498.
   [CrossRef]

- 34. CEN (2003) EN 12457-4; Characterisation of Waste—Leaching—Compliance Test for Leaching of Granular Waste Materials and Sludges—Part 4: One Stage Batch Test at a Liquid to Solid Ratio of 10 L/Kg for Materials with Particle Size below 10 Mm (Without or with Size). European Committee for Standardization: Brussels, Belgium, 2003.
- 35. Soil Quality Decree. Available online: https://wetten.overheid.nl/BWBR0023085/2020-06-09 (accessed on 24 October 2023).
- 36. Van Zomeren, A. On the Nature of Organic Matter from Natural and Contaminated Materials. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 2008.
- Sorlini, S.; Sanzeni, A.; Rondi, L. Reuse of Steel Slag in Bituminous Paving Mixtures. J. Hazard. Mater. 2012, 209–210, 84–91. [CrossRef]
- 38. Mombelli, D.; Gruttadauria, A.; Barella, S.; Mapelli, C. The Influence of Slag Tapping Method on the Efficiency of Stabilization Treatment of Electric Arc Furnace Carbon Steel Slag (EAF-C). *Minerals* **2019**, *9*, 706. [CrossRef]
- Tecnalia End of Waste Criteria Protocol for Waste Used as Aggregates. Available online: https://www.cinderela.eu/The-project/ Reports/D5.5-End-of-waste-criteria-protocol-for-waste-used-as-aggregates (accessed on 17 January 2025).
- 40. Xue, Y.; Hu, Z.; Wang, C.; Xiao, Y. Evaluation of Dissolved Organic Carbon Released from Aged Asphalt Binder in Aqueous Solution. *Constr. Build. Mater.* **2019**, *218*, 465–476. [CrossRef]
- Van der Sloot, H.A.; Dijkstra, J.J. Development of Horizontally Standardized Leaching Tests for Construction Materials: A Material Leaching Mechanisms for Different Materials? *Identical Leaching Mechanisms for Different Materials*. Available online: https://publications.tno.nl/publication/34628440/P1kb20/c04060.pdf (accessed on 16 September 2024).
- 42. Lizasoain-Arteaga, E.; Indacoechea-Vega, I.; Alonso, B.; Castro-Fresno, D. Influence of Traffic Delay Produced during Maintenance Activities on the Life Cycle Assessment of a Road. *J. Clean. Prod.* **2020**, 253, 120050. [CrossRef]
- 43. Lizasoain-Arteaga, E.; Indacoechea-Vega, I.; Pascual-Muñoz, P.; Castro-Fresno, D. Environmental Impact Assessment of Induction-Healed Asphalt Mixtures. J. Clean. Prod. 2019, 208, 1546–1556. [CrossRef]

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