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Case study

Field study evolution on a porous asphalt mixture pavement containing ladle furnace slag

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ABSTRACT

A three-year study tracking the performance of a novel, environmentally sustainable pavement, a Porous Asphalt (PA) mix incorporating Ladle Furnace (LF) slag, is presented in this paper. A thin layer of this material was applied over an existing pavement, in a pilot project of approximately 300 m^2. The main results of the research refer to the successful scaling up from laboratory design to full-scale manufacturing, laying, and compaction, validating the use of up to 10 % LF slag in the mixture. The pavement demonstrated satisfactory durability in terms of resistance to abrasion, accelerated aging, frost, and humidity. The leaching behavior of the mixture remained well below regulatory limits. Over the three-year monitoring period, skid resistance remained stable, consistently exceeding 70 BPN (British Pendulum Number), while the permeability coefficient in dust-protected areas was maintained at 10^{-1} cm/s. Moreover, visual inspections revealed no surface deficiencies throughout the study.

1. Introduction

Wearing courses of roads are undergoing significant innovations, designed to enhance durability, while also responding to demands for superior mechanical characteristics, increasing driving comfort in terms of both noise and vibration, and higher safety requirements [1]. Porous Asphalt (PA) mixes with many of the above-mentioned characteristics are at the forefront of road construction materials [2]. Firstly, their main feature, rapid infiltration of rainwater, helps reduce surface water film depth, reducing the risk of hydroplaning, and minimizing splashing between vehicles that improves visibility, significantly increasing driving safety under rainy conditions [3]. Additionally, their higher porosity levels imply less noise and quieter driving over the wearing course [4], offering high levels of driving comfort, and enhancing the quality of urban life by mitigating acoustic pollution [5].

Furthermore, the promotion of sustainability in human development now extends to all productive sectors, including the construction industry that has very high resource consumption levels [6]. The current trend is towards the recovery of by-product materials and their reuse [7,8], shifting from a linear growth model to a more sustainable circular approach [9,10]. It is an approach that harnesses the potential of what were previously considered waste materials, which often surpass the quality of conventional raw materials [11,12].

Ladle Furnace (LF) slag is a residue from the steel manufacturing industry generated in ladle furnaces during the secondary steel refining process [13,14]. It is a material that presents high difficulties for its reuse, due to its potential expansion that can generate

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undesired volumetric fluctuations [15], leach heavy metals, and other varied contaminants that may be present in the steelmaking materials [16,17]. Over the past decade, the utilization of LF slag in some applications has been explored in various lines of research: such as cement production [18], mortar manufacturing for construction [19,20], concrete production [21,22], soil stabilization [23, 24], and granular subbases [25]. However, most of those applications are still at an experimental stage, and stakeholders within the steelmaking industry are actively seeking new avenues for the recovery of waste and its reuse as co-products [26]. Meanwhile, global crude steel production continues to rise, reaching almost 1900 tonnes per year [27], with China leading the production (Table 1), which correlates with an estimated amount of around 20 million tonnes of LF slag produced annually worldwide, most of which are stockpiled [14].

Preliminary investigative results on various types of bituminous mixes have confirmed that their matrices are ideal for the incorporation of LF slag [28]. The bitumen encapsulates the slag particles, and reduces their contact with moisture, thereby minimizing any risks of expansion and leaching [29,30]. The slag-particle sizes make its potential use as a filler particularly interesting, due to the crucial role of the mastic in the performance of the asphalt mix [31]. Alternative fillers have previously been used to produce mastics of higher quality than the traditional limestone fillers [32], and some promising results for LF slag are its adhesion to bitumen [33–35], and its effectiveness as a supplementary cementitious material [36].

The main investigative results, restricted to laboratory experiences, on bituminous mixtures containing LF slag include an enhancement in Marshall stability and moisture resistance [37–39], as well as a significant improvement in resistance to permanent deformation, rutting and fatigue [38,40]. However, there are some issues to be worked on, such as uncertainties over the workability of asphalt mixtures containing LF slag [33,35], their higher brittleness [41], and excessive void content from poor compaction [42]. The above problems appear to be related to the increase in viscosity and stiffness of the mastic containing LF slag [33,34,41], which especially occur at low temperatures [42,43].

Laboratory studies on certain materials can present limitations that may only be resolved through real-scale experimental work. A limited understanding of the behavior and durability of mixtures in real-world road applications will require long-term studies. In 2021, a pilot project was therefore initiated to bridge the laboratory/real-scale knowledge gap. It was specifically designed to incorporate a PA mixture containing LF slag onto an actual road section, by overlaying a thin wearing course of the material onto an existing pavement. These trials were extensively reported in Skaf et al. [44].

Three years have now elapsed since the road section was constructed and the durability of the constructed section, its leaching of hazardous elements, the evolution of its permeability, and its skid resistance are all analysed in this paper. The aim of the study is to provide real results on the application of LF slag in porous bituminous pavements, essential to promote the use of this residue, and to transfer scientific knowledge when scaling up from laboratory to industry. To the best of our knowledge, there is no real road section where this residue has been applied, hence the utility and the novelty of this research.

2. Construction of the pilot section

2.1. Construction project

The pilot project, performed in July 2021, involved the execution of a 4 cm-PA surface layer, covering an area of around 300 m^2, installed over a dense bituminous pavement in two sections: a parking lot and a two-lane road.

2.2. Materials and mix design

The conventional materials used for the manufacture of the PA mixture were: natural siliceous aggregates, limestone filler to complement the slag filler, and an SBS-modified bitumen (PMB 45/80–60). The siliceous aggregates presented typical features regarding density, water absorption, abrasion loss and polished stone value [44], all of which complied with the standard requirements.

The LF slag can be observed in Fig. 2a; it presented a maximum particle size of 4 mm and around 20 % was filler (<0.063 mm). It had not been subjected to any chemical or thermal pretreatment. Moreover, the slag was employed in its original state neither sieved nor ground up, in order to replicate the production conditions typically encountered in a full-scale asphalt plant. The main details of the LF slag are provided in Table 2, which displays its chemical composition and main physical properties, while its particle size is illustrated in Fig. 1.

Further mix design details and material characterizations can be found in Skaf et al. [44]. In summary (see Fig. 1), the asphalt mixture was designed following the prescriptions of a Spanish standard for road construction PG-3 [45], for a mixture labeled PA-11. This fine PA has a maximum nominal size of 11 mm and a high void content (>20 %), with its envelope specifying minimal fines to maintain a high content of connected air voids that promote water infiltration (Fig. 1).

The combination of the components (81.1 % of coarse siliceous aggregate, 5.6 % fine siliceous aggregate, 10.0 % LF slag and 3.3 %

Table 1
Global steel production in 2023 [27].

Global ranking / **Country**	#1 China	#2 India	#3 Japan	#4 USA	#5 Russia	#6 S. Korea	#17 Spain	Total
Production (million tonnes)	1019.1	140.8	87.0	81.4	76.0	66.7	11.4	1890.2

Table 2
LF slag: characterization by X-ray fluorescence and physical features.

Chemical comp. wt (%)	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	F	SO_3	LOI
	51.7	29.6	6.7	3.6	2.8	2.2	1.5	4.7
Physical char.	Bulk Density		2.79 g/cm^3	Water Absorption		1.94 %	Sand Equivalent	50 %

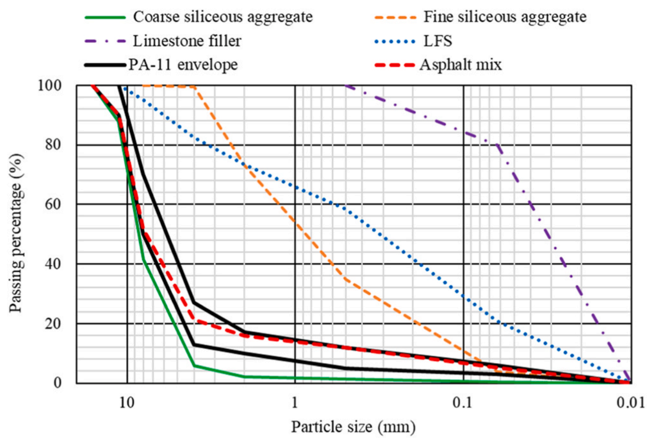

Fig. 1. Gradation of components (siliceous aggregate, LF slag, limestone filler) and mix design (envelope and final mix).

of limestone filler) was adjusted to maximize the volume of the LF slag in use, resulting in 10 % of the total aggregate volume. Following a preliminary laboratory study on PA with LF slag, an optimum bitumen content (OBC) of 5 % and a filler-to-binder ratio of 1 were selected [46].

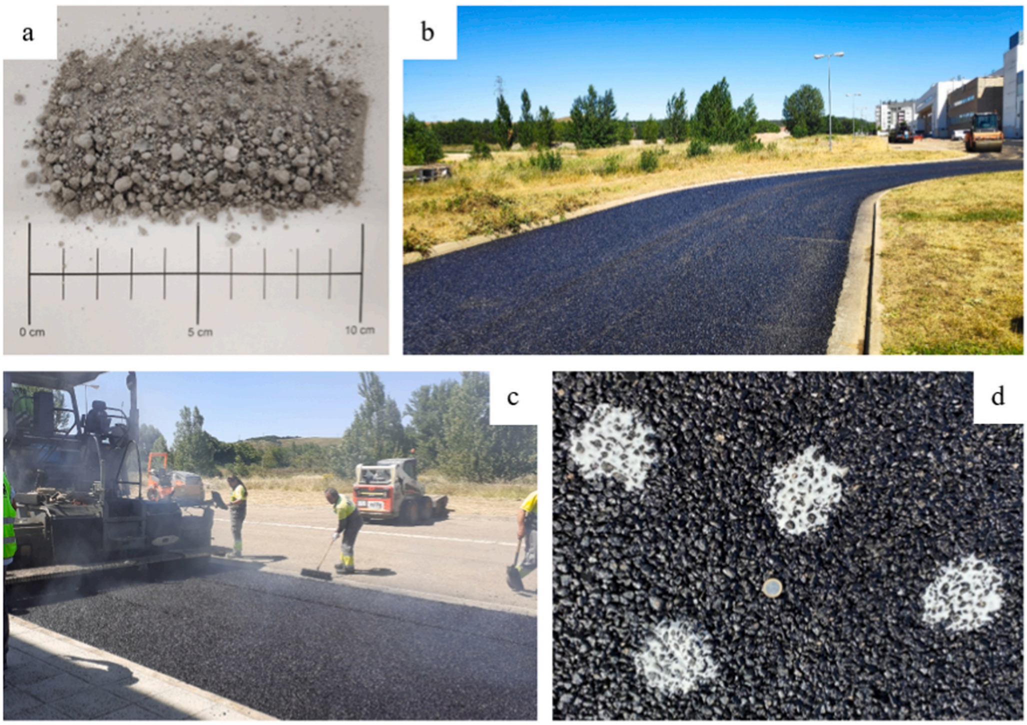

Fig. 2. (a) Ladle Furnace (LF) Slag (b) Finished roadway surface (c) Paving in the parking lot (d) Macrotexture of the Porous Asphalt (PA) with Ladle Furnace (LF) slag.

2.3. Construction

In accordance with the mix design, all the components (siliceous coarse and fine aggregate, LF slag and limestone filler) underwent drying, heating, and mixing with bitumen in a traditional full-scale asphalt plant. The resulting mixture was transported to the paving site for placement on the pre-prepared surface. The paving layer was then extended over both sections (parking and roadway), employing fixed screed height laying and vibratory roller compaction, supplemented by manual compaction at the edges (Fig. 2).

No issues related to mix design or compactability were encountered throughout the laying and compaction procedures. Neither were there instances of either binder bleeding or stripping within the mixture. Furthermore, no challenges pertaining to workability or formation of ridges were observed during the paving. In Fig. 2, the pavement construction process is depicted (c), along with the finished asphalt layer just after completion (b), and the surface texture of the newly finished pavement (d).

2.4. Testing and results

A summary of the main results of the construction phase is presented in Table 3.

First, the control tests conducted on triplicate samples from the construction site confirmed the suitability of the mixture design and the rigorous implementation of the manufacturing process: the granulometry analysis (EN 12697–2) demonstrated compliance with the specifications from the PA-11 envelope, with slight deviations due to the challenges of large-scale production; the binder content by ignition (EN 12697–39) exceeded the minimum design value (5 %), and the filler-to-binder ratio (1) was within the design parameters. No binder bleeding of the bitumen occurred during the binder drainage test (EN 12697–18), conducted on three samples using the basket method, which validated the adequacy of the laboratory design for large-scale manufacturing. Moreover, the extraction of three cores (EN 12697–27) from the constructed pavement confirmed the desired thickness (>40 mm) and target void content (20 %-23 %), so any concerns over compactability were alleviated.

Then, laboratory tests were developed on triplicate Marshall specimens fabricated from the mixture, showing satisfactory results for volumetric properties, such as air void content (EN 12697–8), which exceeded the required 20 %. The mixture also showed good abrasion resistance (EN 12697–17) which is a key property for permeable and open-graded mixtures, exhibiting an average particle loss of 24.1 %. This result complies with the established requirements for medium-heavy traffic loads, which specify less than 25 % Particle Loss (PL) for roads with average daily traffic volumes under 200 heavy goods vehicles (HGVs). The water sensitivity tests were performed following EN 12697–12, evaluating the Indirect Tensile Strength (ITS) of six specimens, by comparing three conditioned specimens with three unconditioned ones. The results pointed to excellent performance, with Indirect Tensile Strength Ratios (ITSR) over 95 %. This demonstrated the mixture's high resistance to moisture-induced damage and the good cohesion of the LFS-mastic.

Regarding surface texture, four tests were conducted for skid resistance using the TRRL pendulum (EN 13036–4), yielding satisfactory BPN results (>55). Similarly, four tests were performed to assess the macro-texture using the sand patch depth method (EN 13036–1), with measurements consistently exceeding 3 mm, far surpassing regulatory requirements.

3. Leaching

In the ladle furnace slag, calcium and silicon oxides are usually predominant, accompanied by magnesia and alumina (Table 2). Regarding hazardous elements, steel slags usually contain small amounts of toxic elements, with chromium, lead, vanadium, zinc and molybdenum, along with chlorides and fluorides, frequently mentioned in the literature [47]. Studies on this matter are diverse, yielding a range of results influenced by factors such as the slag's origin, production processes, stabilization methods, and various other considerations [48,49]. Nevertheless, concerning leachates, certain research disassociates them from production processes, stating that such variations do not present a significant effect on the leachability of individual elements [50].

Table 4 below presents the results of the tests conducted following the EN 12457–4 standard. The first and second columns show the results of the analysis of the LF slag, and the bituminous mixture manufactured with it, followed by the limits for the residue as per a Spanish standard (D64/2019) that regulates the use of steel slags. The fourth and fifth columns showcase the leachate analysis outcomes for both the slag and the bituminous mixture, along with the limits stipulated by the aforementioned regulation for the leachates of slags, as well as another national regulation for general non-hazardous landfill materials (RD646/20).

As can be observed in the first and second columns, the concentrations of hazardous elements in the slag and also in the asphalt mixture manufactured with it are minimal, well below all the legal thresholds, as it has also been found in many other studies [28,51].

Table 3
Tests and results of the construction phase.

Test (units)	Results	Requirements
Bulk density (g/cm^3)	1.93 ± 0.01	-
Air Void Content (%)	21.4 ± 0.1	> 20 %
VMA (%)	31.1 ± 0.1	-
Particle Loss -PL (%)	24.1 ± 0.4	< 25 %
Indirect tensile strength ratio- ITSR (%)	95.3	> 85 %
Thickness (mm)	46.5 ± 0.07	> 40
Skid resistance (BPN)	57 ± 2	> 55
Mean Texture Depth (mm)	3.8 ± 0.3	> 1.5

Table 4
Results and limits of the leaching tests (mg/kg).

	Solid material			Leachates			
	LFS	PA + LFS	D 64/19	LFS	PA + LFS	D 64/19	RD 646/20
Antimony				< 0.05	0.0098	0.06	0.7
Arsenic	23.6	4.05	30	< 0.05	0.00598	0.5	2
Barium				21.8	0.753	20	100
Cadmium	0.676	< 0.5	5	< 0.05	< 0.005	0.04	1
Copper	100	50.6	10,000	0.0541	< 0.005	2	50
Chromium	126	21.6	10,000	< 0.05	0.00803	0.5	10
Cr VI	< 2	< 2	8	< 0.1	< 0.1	0.1	0.4
Mercury	< 2	< 2	4	< 0.01	< 0.01	0.01	0.2
Molybdenum	8.71	4.06	75	0.123	0.0147	0.5	10
Nickel	36.3	22	110	< 0.05	< 0.005	0.4	10
Lead	30.7	8.38	120	0.817	< 0.05	0.5	10
Selenium				< 0.5	< 0.05	0.1	0.5
Vanadium	18.1	30	10,000	< 0.1	0.0282	1.5	
Zinc	388	59.1	1000	3.24	< 0.10	4	50
Chlorides				88.3	< 10	800	15,000
Fluorides				23.8	11.6	18	150
Sulfates				34.6	69.5	1000	20,000

In addition, the concentration of hazardous components of the LF slag was significantly reduced after it was prepared into asphalt mixes, as other authors have found [52].

Concerning the prescriptions for the leachates, a significant reduction in the concentration of elements is notable when comparing the original material (column 1) with its leachate (column 4). This aligns with the literature reviewed, which establishes that the effects of using LF slag as a filler are usually minimal in the surrounding groundwater, and that the presence of some elements is even undetectable in some cases [16,51]. Additionally, only a few LF slag leachate values slightly exceeded prescribed limits, specifically for barium, lead, and fluorides. It must be specified that these limits, outlined in normative D64/2019, are specifically applicable to the use of slag in unbound pavement applications, which does not apply to the current case.

Regarding the behavior of the leachates of the porous asphalt mixture incorporating LF slag, the table shows that all the elements are below the legal limits, even those not fulfilled by the LF slag leachates, which corroborates the hypothesis that suggests that the bitumen film effectively inhibits leaching phenomena of heavy metals and other toxic components [29,30,49]. These results suggest that, despite the inherent variability of LF slag due to its production processes, the bitumen cover effectively mitigates leaching, positioning LF slag as a promising option for asphalt mixtures.

The environmental behavior of the designed material, the porous asphalt mixture with ladle furnace slag, can be considered therefore safe for the designed application, and its leachates do not pose an environmental risk, with all the elements well below the stablished thresholds and most of them even falling below the detection limits. However, for a more comprehensive assessment of its long-term environmental impact, it would be important to consider the material's leaching behavior under extreme conditions, such as acid rain or freeze-thaw cycles.

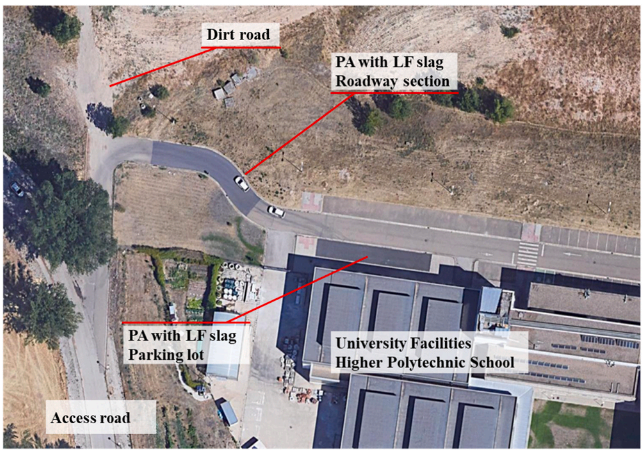

Fig. 3. Aerial view of the pilot project.

4. Evolution study of the section

4.1. Location, traffic, and weather conditions

Situated within the campus of the University of Burgos, Spain, the construction site was easily accessible, so that monitoring could be continuous. The pilot project involved the paving of two areas, as previously described: in the first place, an access road primarily utilized by local traffic, with a daily average of approximately 200 light vehicles belonging to staff and students, and minimal heavy vehicle usage; while the second area corresponded to a parking lot for lightweight vehicles (max. length 5 m) situated next to the access roadway. The aerial photo of the roadworks (Fig. 3) below is labeled to show the paved areas, also discernible due to their contrasting coloration.

The temperature and rainfall patterns of the weather in and around Burgos, Spain, throughout the study period are shown in Fig. 4, while Table 5 depicts the main climatic characteristics. As can be observed, high thermal fluctuations between day and night characterize the climate of the site, with average variations of 20 °C and, between seasons, reaching highs of 40 °C in summer, and lows of almost −10 °C in winter. Precipitation levels, concentrated mainly in winter and spring, are not very high, although summer storms, frequent throughout the summers of 2023 and 2024, can also occur. Such climatic conditions provide a suitable basis to validate a novel porous pavement at full scale, although the applicability of these findings may be limited in more extreme climates.

4.2. Durability in terms of abrasion loss

It is acknowledged that the abrasion resistance of open-graded and PA mixtures is of paramount importance in road construction and maintenance. Abrasion resistance is an assessment of the extent to which the mixture can withstand wear, due to traffic loads and abrasive forces, generated during driving and parking maneuvers, and thereby ensure the efficiency of the asphalted surface [53,54]. Moreover, it can be linked to mixture performance in the long-term, related with the ability to withstand heavy traffic and weather conditions, such as resistance to low temperatures and the effect of water [55].

The Cantabro abrasion test yields an accurate measure of the abrasion resistance of PA mixtures [55]. In this test, a Marshall specimen is subjected to 300 revolutions in the Los Angeles drum, but without steel balls. The abrasion resistance of the specimen is then evaluated by measuring the ratio of lost weight to initial weight, expressed as a percentage (EN 12697–17). In addition, thermal conditioning can be applied to evaluate the durability in terms of water sensitivity, resistance to frost, and aging.

4.2.1. Standard resistance to abrasion

In the standard abrasion test (EN 12697–17), the Cantabro test was performed after conditioning the samples at 25 ºC. The recommended maximum permitted abrasion loss for average loads of heavy traffic (HGV$<$200) is 20 % for asphalt concrete and 25 % for PA [45]. The results of the laboratory abrasion tests showed particle losses of less than 25 % in all cases (Fig. 5), which complied with the requirements of the asphalted section. The mean particle loss of the various specimens was 24.1 %, with a high degree of uniformity. The less favorable results than in the mix design phase [46] emphasized the need for the validation of the scale jump, yet the values were considered adequate for the intended usage. A next step in the research could involve field validation of the suitability of LF slag in mixture designs intended for high-intensity heavy traffic conditions.

4.2.2. Accelerated aging

A batch of specimens were then subjected to accelerated aging to evaluate specimen durability, following the specific instructions in the ASTM D-7064 standard for durability analyses of open mixes, *i.e.*, conditioned in an oven at 60 °C, for 7 days. The norm specifies that the average particle loss should be under 30 %, and no individual result should surpass 50 % (ASTM D-7064).

The aged abrasion loss results were good (Fig. 5), slightly below the ASTM requirement for average particle loss of 30 % and the individual results never exceeded 50 % in any case. The particle loss increment index, with which the test results are compared with the results for abrasion without aging, was 1.23, practically identical to the figure of 1.24 in the previous laboratory phase. Those results corroborated the observations of other researchers, who also verified that the long-term behavior of the LF slag was adequate,

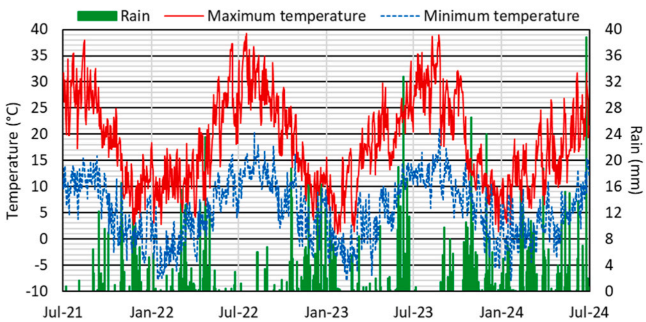

Fig. 4. Temperature and rain patterns throughout the three-year study.

Table 5
Main climatic characteristics throughout the three-year study.

Characteristic	Value	Date
Highest daily maximum temperature (°C)	39.3	07/18/2022
Lowest daily maximum temperature (°C)	1.0	01/24/2023
Highest daily minimum temperature (°C)	21.0	08/24/2023
Lowest daily minimum temperature (°C)	−8.0	02/11/2023
Highest temperature fluctuation in one day (°C)	26.1	08/09/2023
Maximum daily precipitation (mm)	38.8	26/06/2024
Total accumulated precipitation (mm)	1367.4	

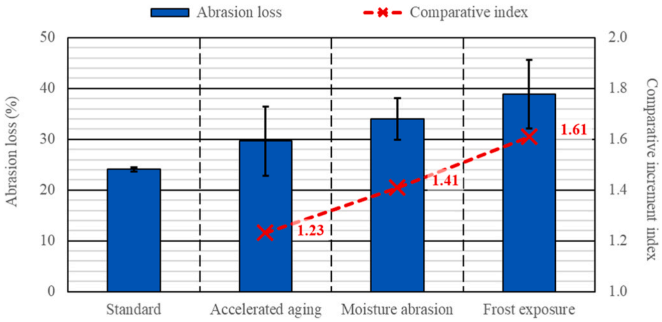

Fig. 5. Durability results in terms of abrasion loss.

with no expansivity problems affecting its raveling resistance in the long term [30,38].

4.2.3. Resistance to moisture abrasion

The wet abrasion loss test was used to assess resistance to water damage, as specified in Standard NLT-362 [56]: three specimens were submerged in a bath of hot water at 60 ºC for 24 h and then subsequently exposed to 25 °C for another 24 h. After this conditioning, the Cantabro test was performed.

The wet particle loss results were very good (Fig. 5), with a mean result of 34 % of particle loss, making the mix suitable for all heavy traffic rates (PL had to be under 35 % for the heaviest traffic category- HGV> 4000 per day following standard NLT-362). In addition, the comparative increment index (which evaluates the increase in particle loss compared to the standard results) was 1.41, an exceptional result from which it was concluded that the use of LF slag as a filler enhanced mixture cohesion and resistance to moisture, as some other researchers also found [34,41]. The results are also consistent with the laboratory results in a previous phase, which found that water sensitivity gradually improved with the incorporation of slag [46]. Moreover, visual inspections revealed no surface deficiencies in the finished layer related to moisture damage.

4.2.4. Resistance to frost exposure

In pavements located in freezing regions (see Fig. 6), a low-temperature abrasion test is used to evaluate the response of the bituminous mixture when the binder stiffens and is more prone to brittle fracture and, consequently, to particle loss [57].

Therefore, after exposure to regulated frost temperatures (1ºC for 24 h), the resistance to cold abrasion was evaluated on three

Fig. 6. Pilot project site in January 2022.

Marshall specimens [58]. The particle loss of the mixture under these conditions was high, with an average value of 38.8 %, although the comparison to the standard abrasion results showed that the increase was quite small (index 1.61), so the PA was validated for use in cold regions. The conclusion on the basis of the results was that the incorporation of LF slag yielded no problematic stiffness in the mixtures, which was also consistent with recent findings [43]. All those results together dispel a key concern over the stiffening effect of LF slag within the bituminous mix mastic.

4.3. Skid resistance

The skid resistance of permeable pavements is not directly linked to the type of filler used in the bituminous mixture, but mostly to factors relating to particle size and the binder content of the mix design. It is nevertheless of significant importance and must be monitored, as porous pavements are especially designed for regions with frequent rainfall, and their effectiveness is closely related to the friction between tires and the pavement surface, that influences vehicle control, and the potential risk of accidents during inclement weather [4,59].

The skid resistance was evaluated directly on the road section with the British Pendulum Friction Tester (EN 13036–4), which consists of a pendulum arm with a rubber slider at its lower end that moves across the wet road surface, simulating the motion of a vehicle tire. The distance the pendulum travels before stopping is recorded as the British Pendulum Number (BPN), which indicates the road's skid resistance, higher BPN values signifying higher coefficients of friction and, in consequence, increased skid resistance.

The tests were performed on the pavement of the pilot project over three years: every 4 months during the first year for detailed monitoring in the initial stages, when greater variation may occur, and subsequently at 6-month intervals as the material's behavior stabilized. The test was conducted at six different points, three on the roadway and another three within the parking area, aiming for a uniform and representative distribution across the pavement.

The findings proved that the skid resistance was very good, with high BPN values in the road area, and very high in the parking area (Table 6). The initially lower values revealed an anomaly, which was later attributed to insufficient surface curing time. The evolution of the BPN curves was logarithmic in both cases, with an ascending and critical trend in the first few days after laying, and a strong statistical fit, with R^2 values close to 0.9. The statistical relationship between BPN in the parking lot and roadway was equal to 0.938 (Fig. 7).

BPN values above 55 are suitable for all types of roads, and the maximum requirement is a BPN of 65 for traffic circles and sharp curves ($r < 150$ m) on roads with heavy traffic loads (ASTM E303). In this study, the skid resistance of the pavement with LF slag remained very stable over the three-year period, with BPN values consistently exceeding the requirements for high-traffic roads. This performance indicates excellent stability, with minimal variation over the years. In contrast to conventional asphalt pavements, this porous mixture demonstrated enhanced skid resistance, suggesting that the PA with LF slag could provide a competitive safety advantage in rainy conditions.

4.4. Permeability

Permeability is a key factor to assess, because the main function of PA is to present and maintain adequate permeability coefficients over time. A key challenge associated with these pavements is clogging, which occurs when fine particles accumulate in the pores of the porous pavement, obstructing them and reducing the pavement's ability to effectively drain water [60]. Monitoring is, therefore, essential to verify the effectiveness of the design at maintaining the permeability of the surface layer [61].

Pavement filtration in the pilot section was evaluated using the LCS permeameter (NLT-327)[62], a falling head permeameter (Fig. 9), similar to the one described in EN 12697–40 and widely employed in Spain for on-site assessment of the drainage capacity of PA pavements [63]. This *in-situ* permeability test involves placing the permeameter device on the pavement and measuring the flow rate of water through the pavement, yielding a specific result in terms of time (seconds) elapsed between the two levels of the water column (Table 7).

The test plan consisted of seven intervals within a three-year timeframe; measurements were conducted every 4 months in the first year, and every 6 months in the second and third years. These measurements were taken at critical locations within the pilot section: one in the parking area and three along the roadway. The road-based locations were strategically distributed at the starting point, the midpoint, and the endpoint (next to the dirt road) of the section (see Fig. 3).

In the NLT-327 norm [62], the following correlation between the permeability coefficient (*k, cm/s*) and the filtration time (*T, s*) for the condition of the PA and the road wearing layer in place was estimated as:

$$Ln\ k = 7.624 - 1.348\ LnT \quad (1)$$

Applying this Eq. (1) to the filtration times (Table 7) yielded the results for the permeability coefficients shown in Table 8.

Initial *in-situ* permeability coefficients proved to be exceptional throughout all points within the tested layer (Table 8). K results yielded values close to the rigorous ASCE reference of a coefficient $k > 4 \cdot 10^{-1}$ cm/s for the optimal performance of PA [64], which were also found to be very uniform at all points that were tested (interval $30–34 \cdot 10^{-2}$ cm/s).

One year after commissioning, drainage capacity worsened mainly at one end of the roadway section (final section in Table 8) as permeability coefficients fell from 34 to $12 \cdot 10^{-2}$ cm/s. This section is close to the dirt road and near a curve, which explains its early degree of clogging due to dragged fines and the low speed of traffic at that point [65]. The central section of the road, as well as the parking lot, maintained their infiltration capacity fairly well ($27–28 \cdot 10^{-2}$ cm/s).

Table 6
BPN values over three years in the pilot section.

	Jul 2021			**Nov 2021**			**Mar 2022**			**Jul 2022**			**Jan 2023**			**Jul 2023**			**Jan 2024**			**Jul 2024**		
Parking lot	62	57	58	73	75	74	73	72	74	77	78	74	78	71	77	71	75	75	78	77	78	70	73	74
	59			74			73			76			75			74			78			72		
Road	56	55	55	65	70	67	68	70	67	68	66	66	74	69	73	72	70	70	75	70	70	71	77	71
	55			67			68			67			72			71			72			73		

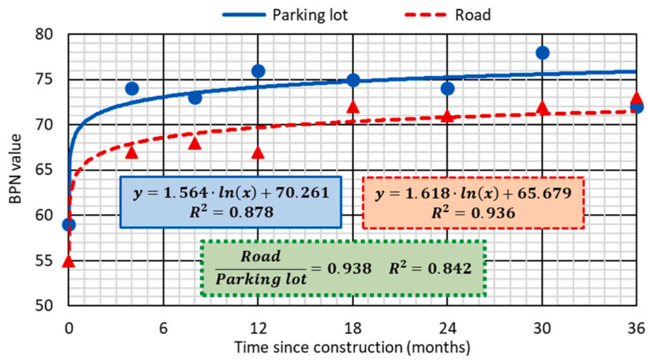

Fig. 7. Skid resistance of roadway and parking lot.

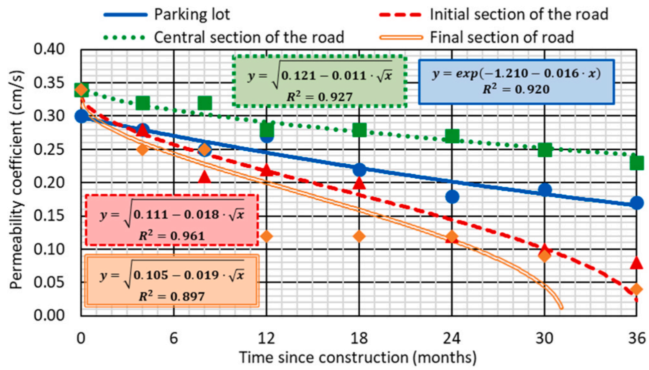

Fig. 8. Permeability coefficients of the road and parking lot.

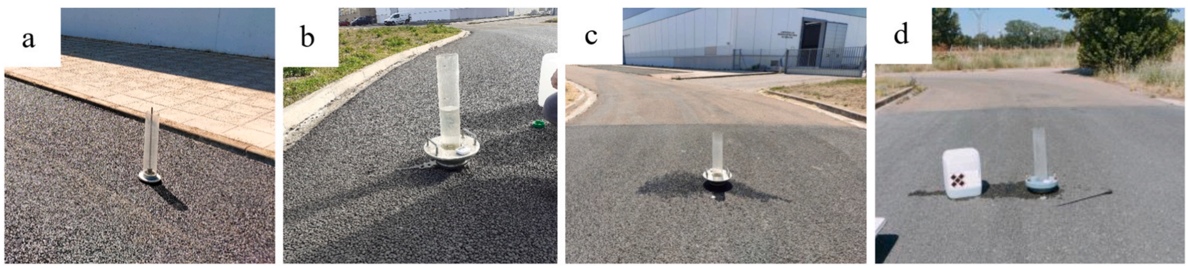

Fig. 9. Falling head permeability tests *in-situ* on roadway and parking sections (a) July 2021 (b) November 2021 (c) July 2022 (d) July 2023.

Table 7
Results of the permeability test in the pilot section (mean filtration time, s).

	Jul 2021	Nov 2021	Mar 2022	Jul 2022	Jan 2023	Jul 2023	Jan 2024	Jul 2024
Parking lot	23	24	26	25	29	34	32	35
Initial section of road	21	24	30	29	31	45	52	62
Central section of road	21	22	22	24	24	25	26	28
Final section of road	21	26	26	44	44	44	57	99

The evolution of the four control points over the subsequent two years has been varied (Fig. 8). The statistical analysis of the evolution curves for permeability indicates a strong statistical fit, with R^2 values over 0.9; both trends show non-linear decay, common in all the types of porous pavements, with a square root trend observed for the road sections and an exponential trend in the case of the parking lot. The initial and final sections of the road experimented sharper decreases in permeability with an increased level of clogging, resulting in a decline from their initial excellent permeability ratings to a classification of 'good' three years after construction (permeability coefficients above 10^{-2} cm/s). On the other hand, the permeability in the parking area and central section of

Table 8
Permeability coefficient k (cm/s) for the pilot section over three years.

	Jul 2021	Nov 2021	Mar 2022	Jul 2022	Jan 2023	Jul 2023	Jan 2024	Jul 2024
Parking lot	$30{\cdot}10^{-2}$	$28{\cdot}10^{-2}$	$25{\cdot}10^{-2}$	$27{\cdot}10^{-2}$	$22{\cdot}10^{-2}$	$18{\cdot}10^{-2}$	$19{\cdot}10^{-2}$	$17{\cdot}10^{-2}$
Initial section of road	$34{\cdot}10^{-2}$	$28{\cdot}10^{-2}$	$21{\cdot}10^{-2}$	$22{\cdot}10^{-2}$	$20{\cdot}10^{-2}$	$12{\cdot}10^{-2}$	$10{\cdot}10^{-2}$	$8{\cdot}10^{-2}$
Central section of road	$34{\cdot}10^{-2}$	$32{\cdot}10^{-2}$	$32{\cdot}10^{-2}$	$28{\cdot}10^{-2}$	$28{\cdot}10^{-2}$	$27{\cdot}10^{-2}$	$25{\cdot}10^{-2}$	$23{\cdot}10^{-2}$
Final section of road	$34{\cdot}10^{-2}$	$25{\cdot}10^{-2}$	$25{\cdot}10^{-2}$	$12{\cdot}10^{-2}$	$12{\cdot}10^{-2}$	$12{\cdot}10^{-2}$	$9{\cdot}10^{-2}$	$4{\cdot}10^{-2}$
Mean results	$\mathbf{33{\cdot}10^{-2}}$	$\mathbf{28{\cdot}10^{-2}}$	$\mathbf{26{\cdot}10^{-2}}$	$\mathbf{22{\cdot}10^{-2}}$	$\mathbf{21{\cdot}10^{-2}}$	$\mathbf{17{\cdot}10^{-2}}$	$\mathbf{16{\cdot}10^{-2}}$	$\mathbf{13{\cdot}10^{-2}}$

the road showed a more favorable evolution and a lower degree of clogging, maintaining more stable permeability coefficients, $k > 10^{-1}$ cm/s, typically ranked as 'excellent' [66]. It is worth mentioning that no direct correlation between permeability and other durability indicators, such as skid resistance, was observed in this study.

5. Conclusions

This study has evaluated a novel and sustainable porous asphalt (PA) mix containing ladle furnace (LF) slag and its evolution as a wearing course for over a period of three years.

Prior laboratory experiments [46] proved that LF slag-mixtures perform comparably to standard materials, with improvements in properties such as thermal susceptibility and water resistance. The primary advantage of this material lies in its sustainability, as it repurposes waste materials that would otherwise accumulate in landfills, while also conserving natural resources.

The laboratory design of the LF slag-PA was scaled up from laboratory to roadway tests in a pilot project in July 2021, in which a 4 cm-layer of this material was laid over an existing pavement (around 300 m^2 in two sections: roadway and parking lot).

The key findings noted in this research are as follows:

- The transition from laboratory-scale design to pilot section construction was successful, both in terms of mix design and full-scale manufacturing, laying, and compaction. No issues related to mastic stiffness were observed, and both workability and compactability were satisfactory. All tests conducted, including void content, moisture resistance, wear resistance, and binder bleeding, met regulatory requirements.
- The use of up to 10 % by volume of LF slag in the mixture with no chemical, thermal, nor mechanical treatments (neither sieving nor crushing) has been validated.
- The durability of the pavement measured as resistance to abrasion (PL<25 %) was compliant with the regulatory specifications for roads with medium-intensity traffic loads of heavy vehicles. Accelerated aging resistance (PL<30 %) and frost resistance (PL<40 %) were also satisfactory. LF slag used as a filler performed well in terms of both moisture resistance and adhesion (PL<35 %).
- The environmental performance of the material is safe, with concentrations of hazardous elements (chromium, lead, zinc, molybdenum, fluorides, etc.) in both the material and its leachates significantly below prescribed thresholds, further demonstrating that the bitumen cover effectively inhibits the leaching of toxic components from the slag.
- Initial skid resistance was very good, both in terms of macro-texture and micro-texture according to the sand patch and friction pendulum tests, respectively. Over the three years, this performance remained excellent and very stable, consistently exceeding requirements for high-traffic roads, with final BPN values above 70.
- Initial permeability coefficients yielded results of $k > 3{\cdot}10^{-1}$ cm/s, demonstrating optimal draining performance of the layer, with very uniform results at different points. The evolution pattern was irregular: the central section of the road and the parking lot maintained their infiltration capacity quite well, while the beginning and the end of the road experienced increased clogging due to loose material dragged from nearby areas. Nevertheless, permeability coefficients remained above 10^{-2} cm/s at all tested points.
- Finally, visual inspections of the pavement after three years of use have confirmed an acceptable finish with no significant road surface deficiencies.

In summary, the results of the pilot project involving the prototype section of a layer of fine PA mix with LF slag have been satisfactory. The validation of the design of the mixture at large scale and the adequate degree of compaction of the finished layer are noteworthy. Its environmental performance can be considered safe. Some mechanical properties decreased compared to the laboratory results, but all the results were considered valid at the regulatory level for urban roads with medium-intensity heavy vehicle traffic. During the first three years of use, visual inspections confirmed no surface deficiencies. Throughout their evolution, skid resistance and permeability remained above the recommendations for optimal use. Future research could focus on extended analyses of the pavement's performance, ideally encompassing a duration of 10–20 years or beyond.

Based on the positive performance and evolution of the material, it is recommended to consider using this pavement in specific applications. The proven properties of the pavement—averaging 72 BPN and permeability coefficients in the range of 10^{-1} to 10^{-2} cm/s three years after placement—make it particularly well-suited for urban areas, parking lots, and regions requiring sustainable stormwater management. Furthermore, its drainage capacity, durability, and low environmental impact make it a viable option for main roads in high-rainfall areas with medium traffic loads.

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CRediT authorship contribution statement

Vanesa Ortega-López: Writing – review & editing, Validation, Project administration, Methodology, Funding acquisition, Conceptualization. **Víctor Revilla-Cuesta:** Visualization, Software, Resources, Investigation, Formal analysis. **Juan M Manso:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Marta Skaf:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Belén Espinosa:** Writing – original draft, Resources, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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