# Bituminous Pavement Overlay of a Porous Asphalt Mixture with Ladle Furnace Slag: A Pilot Project.

Marta Skaf[a*], V. Ortega-López[b], V. Revilla-Cuesta[b] and J. M. Manso[b]

*[a] Department of Construction, University of Burgos, Burgos, Spain; [b] Department of Civil Engineering, University of Burgos, Burgos, Spain.*

*Marta Skaf Revenga. Escuela Politécnica Superior. Calle Villadiego s/n. 09001 Burgos. Spain.

**Acknowledgements**

This work was supported by [MICINN, AEI and ERDF] under grant [PID2020-113837RB-I00; 10.13039/501100011033; FPU17/03374]; and [Junta de Castilla y León and ERDF] under grant [Plan TCUE, VIIIPC_05].

Word count: 6530 words

# Bituminous Pavement Overlay of a Porous Asphalt Mixture with Ladle Furnace Slag: A Pilot Project.

The step from the laboratory design of green pavement materials to their implementation in the field is key to promote more sustainable roads. This paper presents a pilot experience of applying a novel, high-performance and sustainable material for pavements: a Porous Asphalt (PA) mixture that incorporates Ladle Furnace Slag (LFS), a residue from the steel refining industry. The overlay of a thin surface layer of this material was applied to an existing bituminous pavement. The main investigative results included the validation of the laboratory mix design through large-scale mixing, laying, and compacting, followed by extensive laboratory and field tests. The results showed that the incorporation of up to 10% LFS in porous asphalt mixtures was feasible, with no need for preliminary physical or chemical treatments. The tests on the sustainable PA mixture revealed that its voids content, wear resistance, moisture susceptibility, and skid resistance were within regulatory limits. Neither workability nor compactability issues were observed in the execution of the pavement, and no ridging, rutting, cracking, or stripping were visible on the surface during the first months of use.

Keywords: pilot project; porous asphalt; permeable pavement; ladle furnace slag; field testing; sustainable construction.

## Introduction

There is an undeniable need to preserve natural resources and to reduce the unsustainable levels of raw material consumption and waste disposal of the 21st century. In the road construction sector, with increasing volumes of material consumption and among the highest emission levels of other sectors (Russo *et al.* 2021), the investment of resources to research the application of alternative products linked to the circular economy is essential (Branca *et al.* 2021). These products are of high added value as raw materials and reduce the impact of unrelenting human and technological development (Georgiou and Loizos 2021, Pasetto *et al.* 2022). The use of residues in construction must also be supported by scientific research based on multi-criteria studies, integrating mechanical, environmental, and economic aspects (Varma *et al.* 2019, Oreto *et al.* 2021).

Ladle Furnace Slag (LFS) is a by-product of the steel industry, a residue recovered from the transport and refining ladles used in the secondary metallurgical processes of basic oxygen furnaces and electric arc furnaces (Piemonti *et al.* 2021). Although the steel industry is striving to minimize its production and to promote its reuse within its production processes (Matino *et al.* 2018, Sheshukov *et al.* 2021), it is estimated that over one million tonnes of Secondary Metallurgical Slags (SECS) are deposited in landfills every year (EUROSLAG) in the European Union alone.

Also called reducing slag or basic slag, LFS from carbon steel presents a fine greyish aggregate, has a maximum size of around 2-to-4 mm, and a significant percentage of powdery particles. Its main chemical components are CaO, $SiO_2$, $Al_2O_3$, and MgO (Jiang *et al.* 2018, Piemonti *et al.* 2021). LFS demonstrates slight hydraulicity because of its chemical structure (Fang *et al.* 2022), especially in the cases of elevated CaO contents, which means it has some soft binding properties (Vlček *et al.* 2016). Nevertheless, the effect may be activated through mechanical or thermal treatment when the slag is intended to be used as supplementary cementitious material (Jiang *et al.* 2018, Fang *et al.* 2021). The potential utilization of LFS is still limited, mainly due to its fine size, potential expansion, and contaminating leachates, with some applications being developed in the construction field (Serjun *et al.* 2013, Najm *et al.* 2021, Li *et al.* 2022). In road construction, due to its particle size, powder components, and low hydraulicity, most of the experimental uses of this type of slag include its application in granular bases and for soil stabilization (Montenegro-Cooper *et al.* 2019, Brand *et al.* 2020, Lopes *et al.* 2022).

Permeable pavements on roads have some obvious benefits, such as the reduction of accidents during rainfall, due to reduced aquaplaning, and decreased visibility loss produced by splash and spray (Sambito *et al.* 2021). Moreover, their higher porosity and absorption levels also contribute to traffic noise reduction (Mikhailenko *et al.* 2020): around 3-5dB for fine porous asphalt (Vaitkus *et al.* 2017). Defined as Sustainable Urban Drainage Systems (SUDS) when used in cities, these road materials mitigate the urban 'heat island effect' (Guan *et al.* 2021), and improve traditional storm-water management (Ahmad *et al.* 2017, Abellán García *et al.* 2021).

In addition to those benefits, permeable bituminous mixtures provide an optimal matrix for the application of LFS. Firstly, bituminous mixes are an ideal substrate for the use of slag, since the encapsulation of the slag by the bitumen favours its protection from moisture, thus preventing its hydration and potential expansion, as well as reducing the amount of leachates (Oluwasola *et al.* 2016, Hu *et al.* 2020). Secondly, the porous and open-graded mixes, with a very high volume of voids, could accommodate an eventual expansion of the slag particles (Pisciotta 2020), by fitting the voids of the viscoelastic matrix (Wang and Thompson 2011). Finally, because of their low fines content, it is possible to replace most of the natural sands and the filler, reducing $CO_2$ equivalent emissions by as much as 60% (Terrones-Saeta *et al.* 2021b).

In a preliminary study restricted to the laboratory on the use of LFS in asphalt mixtures, Skaf *et al.* (2016) found that LFS complied with the main characteristics for use as filler: suitable grading sizes, appropriate adhesion with bitumen, and cohesion of the mixtures, although higher amounts of bitumen were absorbed within the LFS than within either the limestone filler or the cement. In another laboratory-based study, Bocci (2018) postulated that LFS application in hot bituminous concrete was possible and that the mixes complied with regulations on mechanical behaviour, moisture damage, and resistance to fatigue. Subsequently, in recent experiments, Nebreda-Rodrigo *et al.* (2021) and Terrones-Saeta *et al.* (2021a) found that different asphalt mixtures that incorporated

LFS presented higher voids, and enhanced Marshall stability and deformation. Moreover, both the compressive strength and the moisture resistance were better in the slag-mixes.

From the results described above, it can generally be inferred that asphalt mixtures with LFS behave properly. However, the main problem with its application appears to be its mastic stiffening effect, which critically reduces mix workability. This has been observed both in cementitious matrices (Santamaria *et al.* 2019) and in bituminous matrices at mortar and mastic scale (Pasetto *et al.* 2020). A stiffening effect may be positive for certain characteristics of the bituminous mixes and thus, for example, it has been observed that the introduction of LFS improves Marshall stability, resistance to permanent deformation and rutting (Terrones-Saeta *et al.* 2021a). The resulting problem may be poor workability, especially when the LFS is used as filler and in the fine aggregate fraction, which produces mixes that are more difficult to compact (Pasquini *et al.* 2020). It increases the content of voids, which impairs the performance of the mixture in terms of abrasion and moisture resistance (Skaf *et al.* 2018). Moreover, this effect increases the brittleness and impairs the deformability of the asphalt mixtures manufactured with LFS (Roberto *et al.* 2022).

It is essential to address this issue through scaled up experiments, to verify that the laboratory mix design works as foreseen when real pavements are built. The main objective is to check that there is no poor compactability and excessively porous mixes due to the stiffening effect of the LFS, as well as checking any other issues related to the mechanical behaviour or durability of the pavement. To date, no full-scale project has been carried out to introduce bituminous mixes with ladle furnace slag outside the laboratory, on real roads. Thus, the high novelty and interest of this experiment that advances the application of this by-product and the transfer of scientific knowledge from research laboratories to industry.

In this paper, the results of the laboratory design are applied to a pilot pavement construction project (porous asphalt mixture with ladle furnace slag) on a real road section, through the overlay of a thin surface layer of this sustainable material on top of an existing dense bituminous pavement.

## Materials and Methods

### ***Natural aggregates and Bitumen***

Natural siliceous aggregates from a quarry in northern Spain were used. These aggregates are commonly applied to wearing layers, with excellent characteristics in terms of abrasion and polishing, as can be seen in Table 1. Their appearance is shown in Figure 1.

The filler employed to complement the slag was of limestone origin, which usually has good binder adhesion proper to quality mastics.

Table 1. Physical features of the different aggregates.

| Characteristic | Siliceous aggregate (12/0 mm) | Limestone filler (0.0063/0 mm) | Ladle Furnace Slag (4/0 mm) |
|---|---|---|---|
| Bulk Density EN 1097-6 | 2.65 g/cm$^3$ | 2.69 g/cm$^3$ | 2.79 g/cm$^3$ |
| Water Absorption EN 1097-6 | 0.55 % | 1.82 % | 1.94 % |
| Apparent density of filler in kerosene EN 933-8 Annex A | - | 0.67 g/cm$^3$ | 0.75 g/cm$^3$ |
| Sand Equivalent EN 933-8 | 77 % | 68 % | 50 % |
| Los Angeles Abrasion Loss EN 1097-2 | 18 % | - | - |
| Flakiness Index (FI) EN 933-3 | 16 % | - | - |
| Polished Stone Value (PSV) EN 1097-8 | 50 % | - | - |


Figure 1. (a) Coarse siliceous aggregate. (b) Fine siliceous aggregate. (c) Limestone filler. (d) Ladle furnace slag.

A conventional elastomeric Polymer Modified Bitumen was used, type PMB 45/80-60, according to EN-14023.

***Ladle Furnace Slag (LFS)***

The LFS was recovered from a Spanish steelwork where steel is refined in ladle furnaces for the production of steel rebars. It was then acquired by a manufacturer of building materials that supplied it previously sieved and free from impurities for this study.

The appearance of the slag is shown in Figure 1, which shows a fine greyish material, with a maximum particle size of 4 mm, and a percentage of filler (<0.063 mm) of around 20%. It was subjected to no treatment, neither in the steelworks nor in the asphalt mixing plant, although it underwent spontaneous weathering and air-drying to remove moisture prior to use in the mix.

The main outcomes of the physical analysis of the LFS are detailed in Table 1. Its slightly higher density than that of natural aggregates can be observed and likewise implies volumetric adjustment of the mix design. The usual predominance of calcium and silicon oxides, as well as magnesia and alumina can be observed in the chemical analysis performed by X-ray fluorescence (XRF) (Table 2). The crystalline composition of ladle furnace slag is usually dominated by dicalcium silicate. (Jiang *et al.* 2018), as well as mayenite, periclase, portlandite, and merwinite (Brand and Fanijo 2020).

Table 2. XRD analysis of Ladle Furnace Slag.

| **Component** | CaO | $SiO_2$ | MgO | $Al_2O_3$ | $Fe_2O_3$ | $SO_3$ | $TiO_2$ | MnO | Others | LOI |
|---|---|---|---|---|---|---|---|---|---|---|
| **Weight content (%)** | 51.7 | 29.6 | 6.7 | 3.6 | 2.8 | 1.4 | 0.6 | 0.4 | 3.2 | 4.7 |

***Mix design***

The mixture was designed according to Spanish technical instructions for roads and highways materials, PG-3 (2014), following the prescriptions for mixture PA-11, whose grading is shown in Table 3. That is a fine Porous Asphalt (PA) mix, intended for thin permeable wearing layers, with 11 mm of maximum nominal size and a coarse skeleton with few fines, which results in mixtures with high (over 20%) void ratios and very high contents of interconnected voids that facilitate water permeation.

The combination of the different components was adapted to meet the requirements of the PA-11 envelope, by maximizing the proportion of the LFS in use and adapting the rest of the components to the grading size of the slag, *i.e.*, complementing the missing slag fractions with the available natural aggregates and filler. The slag was used as received (no sieving or grinding), in order to maximise its potential use and to reproduce conventional full-scale conditions on asphalt-plant production.

The combination of the components resulted in 81.1% of coarse siliceous aggregate, 5.6% fine siliceous aggregate, 10.0% LFS and 3.3% of limestone filler (weight percent over total amount of aggregates). No fibres were added. The volumetric grading sizes of the components and the resulting mixture are reflected in Table 3. The results of the design were then converted into weights, to adjust to the different LFS densities at the production plant.

Table 3. Particle size (% passing vol. over total aggregates) for the components, the mixture, and the standard envelope (PA-11).

| | Size EN 931-1 (mm) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Material** | **16** | **11.2** | **8** | **4** | **2** | **0.5** | **0.063** |
| **Coarse siliceous** | 100.0 | 87.7 | 41.6 | 5.9 | 2.0 | 1.4 | 0.5 |
| **Fine siliceous** | 100.0 | 100.0 | 100.0 | 99.4 | 73.3 | 34.8 | 3.9 |
| **LFS** | 100.0 | 100.0 | 95.1 | 82.4 | 73.2 | 58.4 | 20.7 |
| **Limestone filler** | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 80.0 |
| **Mix design** | 100.0 | 90.0 | 51.8 | 21.4 | 15.9 | 11.8 | 5.2 |
| **PA-11 envelope** | 100 | 90-100 | 50-70 | 13-27 | 10-17 | 5-12 | 3-6 |

Prior laboratory research was focused on selecting the optimum binder content (OBC) from among four batches of specimens with different bitumen contents. The result was that the mixtures with 5% bitumen and a filler/bitumen ratio equal to one were balanced in volumetric properties, mechanical performance, risk of bleeding, and durability (Skaf *et al.* 2016). The main conclusions of that slag-mix design phase included slightly higher binder absorption than the natural aggregates and volumetric correction of the grading sizes due to the density differences.

One of the main steps in this research was to verify that the performance achieved in the laboratory design could be replicated on a large scale where particle size control with fraction-by-fraction sieving is not an option. It was also verified that the bitumen content was adequate for the full-scale mix design, achieving an adequate degree of compactability of the mixture and no bleeding of the binder.

### *Construction Project*

The project consisted of the field laying of the wearing course of about 320 $m^2$, by applying the sustainable PA to a thickness of 4 cm, over a dense bituminous pavement in good conditions. The project covered two separate areas (Fig. 2): a parking lot of 4.5 m x

30 m and a two-lane 6.0 m wide road of approximately 30 m in length.

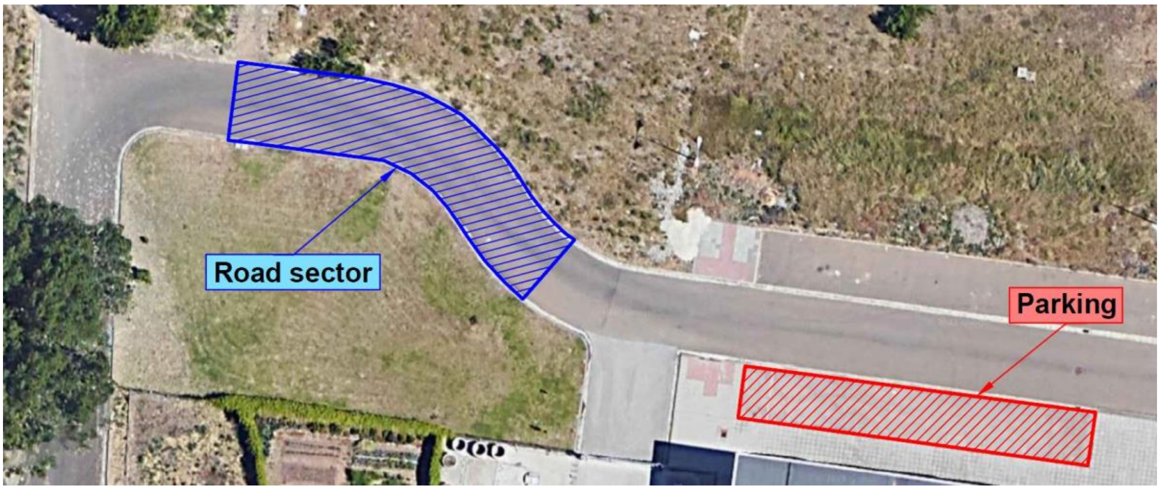


Figure 2. Construction project. Two separate areas for laying the PA over the existing pavement.

***Test methods***

The assessment of the project performance was conducted at two levels: mix and field testing.

First, from samples taken from the truck, the manufactured mixture was tested for grading (EN 12697-2), binder content by ignition (EN 12697-39), and the binder drainage test (EN 12697-18). Then, Marshall specimens were manufactured in the laboratory from that mixture and were compacted by applying 50 blows per face. The following tests were then performed:

- Air Void Content (AVC) and voids in the mineral aggregates (VMA), following EN 12697-8. Maximum density and bulk density according to EN 12697-5 procedure C and EN 12697-6 procedure D, respectively.
- Abrasion resistance through the Cantabro test (EN 12697-17), where each specimen is located inside the Los Angeles drum and operated for 300 revolutions without steel balls, and their Particle Loss is then calculated.

- Moisture resistance through the Indirect Tensile Strength Ratio (ITSR) described in EN 12697-12 and calculated as the proportion between the Indirect Tensile Strength of wet (submerged at 40 °C for 72 hours) and dry specimens.

In second place, the following field tests were performed:

- The thicknesses of core samples extracted from the pavement (EN 12697-27) were measured (EN 12697-29) and the corresponding volumetric study was performed – bulk density and AVC as described for the laboratory samples (EN 12697-8).
- Pavement skid resistance in relation to microtexture as specified in EN 13036-4, which uses the British Pendulum from the TRRL to measure the friction of a standard rubber slider over a wet surface.
- Macrotexture by a volumetric patch test, as specified in EN 13036-1, where a standardised volume of sand is spread out in a circle, filling all the superficial voids, in such a way that the diameter of the circle of sand is linked to the Mean Texture Depth (MTD) of the pavement.
- *In situ* permeability test, with a falling head permeameter (EN 12697-40), on different places of the road and parking sections.

## Results and discussion

### *Construction of the sustainable porous layer*

In the bituminous-mixing plant, the slag was used as received from the steel producer and neither sieving nor grinding was performed. All the components (siliceous gravel and sand, ladle furnace slag and limestone filler) were dried, heated and then mixed, following the mix design supplied, with 5% PMB and the gradation shown in Table 3.

Around 28 tonnes of PA mixture were produced, and the mixing temperature was established at 160ºC, as recommended by the manufacturer of the binder.

The mix was transported from the plant to the paving site (about 18 km) in a heat-treated truck and was then placed over the existing, previously prepared surface. The existing pavement consists of dense asphalt concrete in good condition. Surface preparation included sweeping, kerb protection, milling of transverse joints, and the application of tack coats. As a permeable mixture, it was placed over the dense layer, protruding above the channel kerbs, without longitudinal milling. The ambient temperature during paving was between 26 and 22 ºC with wind speeds of 22 km/h.

The paving was performed on two sections, both with a minimum layer thickness of 4 cm. Firstly, a 30 m long, 90º parking lot was paved through fixed screed height laying and vibrating roller compactor. Laying and compacting of the mixture against the kerbs was completed manually using a plate compactor. Secondly, the road traffic area, which consisted of a single two-way carriageway, with low heavy-traffic intensity, that provides access to the parking lot. Approximately 6 m wide and 30 m long, it was paved through fixed screed height laying with a longitudinal joint, followed by two passes of a vibratory roller compactor.


Figure 3. (a) Surface preparation. (b) Paving the parking area. (c) Manual border compaction. (d) Laying and compacting on the roadway section.

There were neither mix design nor compactability issues during laying and compaction. No binder drainage nor stripping was observed in the mixture and neither workability issues nor ridging during paving were detected (Fig. 4).

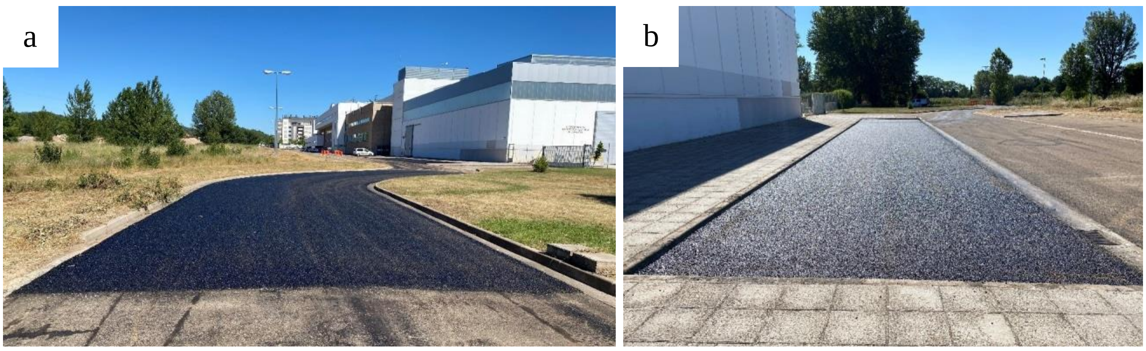


Figure 4. (a) Finished pavement of the road section. (b) Finished pavement of the parking lot.

***Laboratory tests***

The mix samples taken from the truck were tested for grading, binder content by ignition, and binder drainage, to check that the manufactured mixture met the design requirements. The aggregate particle size analysis was within the ranges prescribed for the PA-11 mix and the bitumen content and the filler/binder ratio complied with the mix design. There was no bleeding of the binder (see Fig. 5).

*Wear resistance*

Abrasion loss is the main feature to be controlled in porous pavements, which are susceptible to ravelling and cracking and that reduce their lifespan (James *et al.* 2017). Moreover, fine materials and, above all, fillers play a fundamental role in the performance of PA pavements (Liu *et al.* 2021, Awed *et al.* 2022), so this test is essential to verify the suitability of LFS in the manufacture of open-graded mixes.

The results of the laboratory tests presented particle losses below 25%, in all cases; suitable for medium intensities of heavy traffic (with average daily traffic under 200 heavy goods vehicles), which the road section fulfils. The average particle loss of the different test specimens was 24.1%, with very homogeneous individual results, as can be observed in Table 4.

Furthermore, visual inspections of the constructed pavement have so far revealed no signs of traffic wear, nor particle loss in the form of ravelling or stripping after six months of use.

It has previously been proposed in other studies that filler materials with high contents of CaO can improve the wear resistance of porous asphalt pavements (Du *et al.* 2021), and in preliminary laboratory studies, open-graded mixtures with ladle furnace slag have previously shown good abrasion resistance (Skaf *et al.* 2016).

Table 4. Individual results of the volumetric and mechanical laboratory tests performed with the porous asphalt with LFS specimens.

| **Test** | **Standard** | **Units** | **Individual results** |
|---|---|---|---|
| Bulk density | EN 12697-6 | $g/cm^3$ | 1.93 / 1.92 / 1.93 / 1.93 / 1.93 |
| Air Void Content (AVC) | EN 12697-8 | % | 21.3 / 21.5 / 21.4 / 21.3 / 21.4 |
| Voids in the Mineral Agg. (VMA) | EN 12697-8 | % | 31.0 / 31.2 / 31.1 / 31.0 / 31.1 |
| Particle Loss (PL) | EN 12697-17 | % | 23.5 / 24.1 / 24.4 / 24.3 |
| Indirect tensile strength ratio (ITSR) | EN 12697-12 | % | 88.7 / 97.6 / 99.6 |

*Moisture resistance*

Resistance to water damage is crucial for porous friction courses, as some studies have found that the effect of moisture exposure is even more severe than ageing on PA mix performance (Chen and Wong 2018), so it is essential to verify the moisture susceptibility of the mixes manufactured with LFS.

The results of the moisture resistance tests performed on the slag-mixture were excellent, as shown in Table 4. The average results for the ITSR, above 95%, met the most demanding regulatory requirements for the roads with the highest levels of heavy traffic.

This test confirmed the excellent resistance of mastic formed with the LFS to the action of water, even exceeding that of natural fillers, as demonstrated in other studies (Nebreda-Rodrigo *et al.* 2021).

### ***Field testing***

Core samples (see Fig. 5) were taken at four locations on the pavement, and the results met the technical specifications: an average sample thickness of 46±2 mm. and a mean void content of 21.4%.

*Skid resistance*

The macro and the micro-textures of the pavement are primarily related to the coarse aggregate characteristics and to the mix design, rather than to any additions of LFS. However, it is always key to assess the skid resistance of permeable pavements, which are especially designed for rainy climates, as their performance is directly linked to tire-pavement friction, vehicle control, and the risk of crashing during wet weather conditions (Najafi *et al.* 2017, Chu and Fwa 2018).

The results showed that the skid resistance measured by the TRRL pendulum (see Fig. 5) was adequate, with mean BPN (British Pendulum Number) values of 57±2. The higher the BPN, the rougher the surface (increased friction), and the higher its slipping resistance. Although no normative values restrict this parameter, it is generally recognised that values above BPN 55 are appropriate for medium intensity roads (Adamu *et al.* 2018).

The macro-texture far exceeded the regulatory requirements, which require the mean texture depth (MTD) to be > 1.5 mm for the PA mixtures (PG-3). All results are shown in Table 5.

Table 5. Individual results of the field testing over the PA with LFS pavement.

| **Feature tested** | **Standard** | **Units** | **Individual results** |
|---|---|---|---|
| Thickness | EN 12697-29 | mm | 44.8 / 45.2 / 47.2 / 48.7 |
| British Pendulum Number (BPN)* | EN 13036-4 | | 62 / 57 / 58 / 55 / 56 / 56 |
| Mean Texture Depth (MTD) | EN 13036-1 | mm | 3.8 / 3.5 / 3.7 / 3.6 / 3.9 / 4.3 |
| Permeability | EN 12697-40 | cm/s | $30\cdot10^{-2}$ / $34\cdot10^{-2}$ / $34\cdot10^{-2}$ |

* Results include the temperature correction factor.

*Permeability*

Permeability is basically related to mix porosity (Vardanega 2014), so it is linked to a proper mix design and compaction and, in this case, it must be monitored as a sign of proper placement (adequate laying and compacting of the PA, and correct volumetry of the resulting pavement). Besides, permeability is the main advantage of these pavements over common dense wearing layers, so it is important to check the permeable layer behaviour for its classification.

There are usually no requirements in the construction standards for the permeability of pavements, as the limits are usually specified in terms of their void content. In scientific research, permeability coefficients (k) > $10^{-1}$ cm/s are usually classified as ‘excellent’ (Alvarez *et al.* 2010).

The in-situ permeability results were excellent at all points in the tested layer, producing values that were close to the very demanding ASCE recommendation of $4*10^{-1}$ cm/s for optimum performance of porous asphalt pavements (Eisenberg *et al.* 2015). These results are particularly relevant, given that this is a very fine permeable layer, as it has been shown that permeability increases with the maximum size of the aggregate used (Król *et al.* 2018).

The combination of excellent permeability and resistance to slipping and skidding makes these pavements particularly suitable for use on roads with medium traffic intensities in very rainy areas.

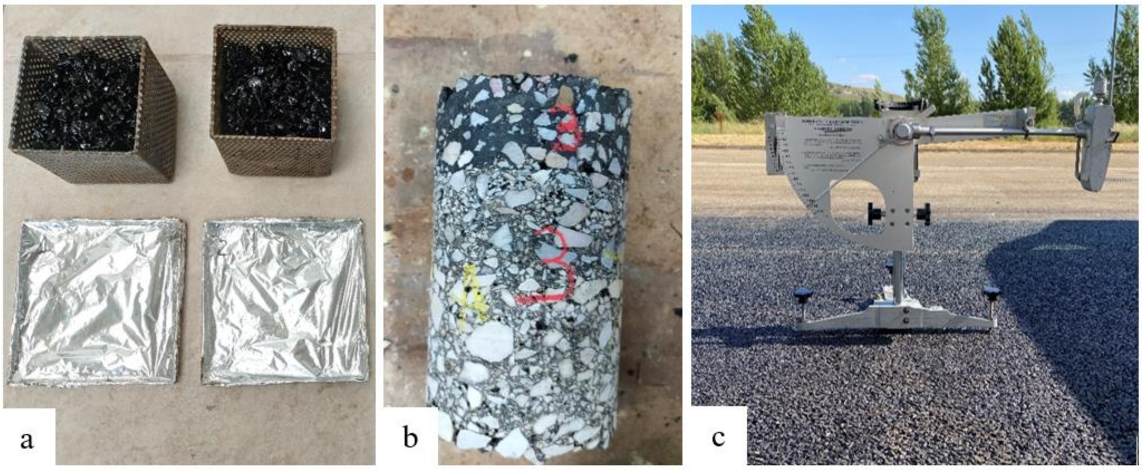


Figure 5. Laboratory and field tests. (a) Binder-drainage test. (b) Core samples. (c) Skid-resistance test.

***Summary of requirements complying and overview of results***

The 95% confidence intervals of the results for each property that was tested against the regulatory requirements are shown below (Table 6) and, subsequently, the degree to which the confidence intervals of the results comply with those requirements (Figure 6).

Table 6. Confidence interval and test requirements.

| **Property** | **Confidence Interval (95%)** | **Requirements** |
|---|---|---|
| Air Void Content (AVC) | 21.3 % – 21.4 % | > 20 % |
| Thickness | 44.7 mm – 48.3 mm | > 40 mm |
| Particle Loss (PL) | 23.7 % – 24.5 % | < 25 % |
| Indirect Tensile Strength Ratio (ITSR) | 88.7 % – 101.7 % | > 85 % |
| British Pendulum Number (BPN) | 55.3 – 59.3 | > 55 |
| Mean Texture Depth (MTD) | 3.5 mm – 4.0 mm | > 1.5 mm |
| Permeability | $30 \cdot 10^{-2}$ cm/s – $35 \cdot 10^{-2}$ cm/s | > $10 \cdot 10^{-2}$ cm/s |

From the above results, it can be inferred that not only the mean values, but the 95% confidence intervals of all the properties were compliant with the regulatory requirements, some presenting large margins. Figure 6 graphically plots the margins of compliance; in graph a) it can be seen that all properties comply with the requirements, some of them, such as macrotexture (MTD) and permeability, far over the required minimum standards. The rest of the properties are displayed in Figure 6b, in which the 95% confidence intervals of their margins of compliance are represented.

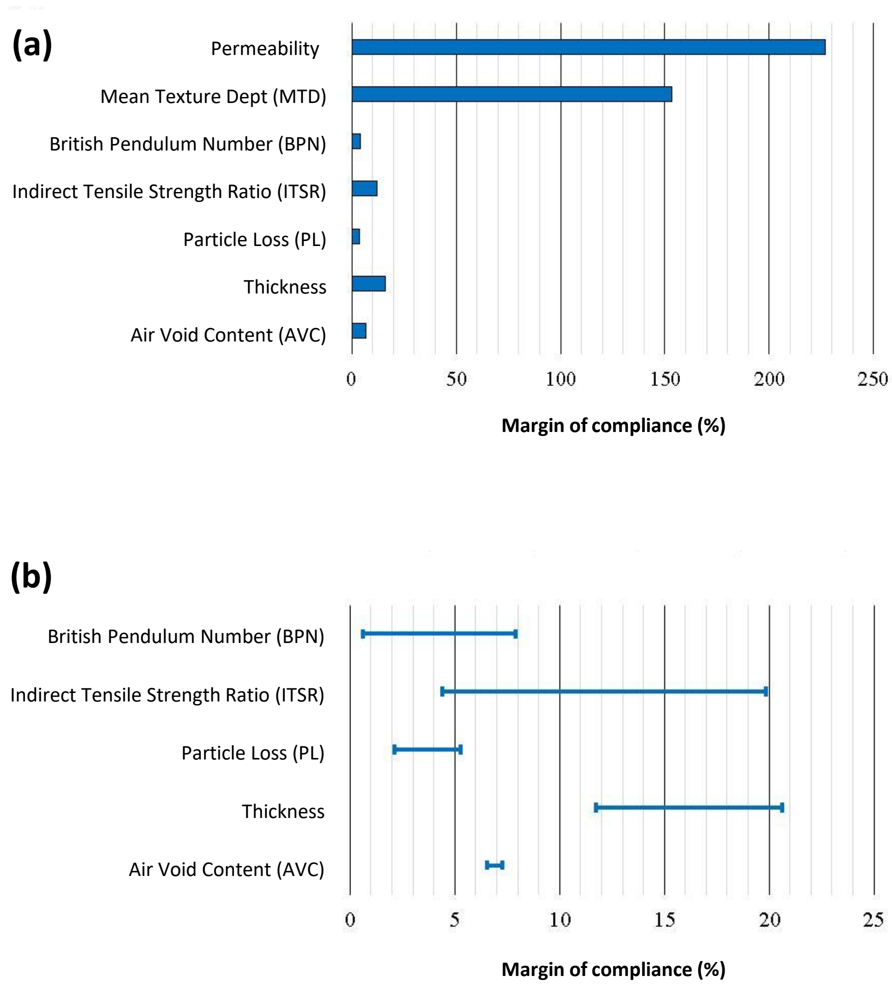


Figure 6. Compliance margins. (a) Mean results (b) 95% confidence interval.

From the statistical analysis, it can be inferred that special attention should be paid to the evolution of skid and abrasion resistance, as they are statistically closest to the limit. To that end, a research programme to study abrasion resistance on aged specimens, and a monitoring campaign of the evolution of the skid resistance are planned every three months.

## Conclusions

The following main conclusions can be drawn from the pilot project of the overlay of a thin layer of Porous Asphalt with Ladle Furnace Slag (LFS):

- The design of the mixture, which had been performed in the laboratory, is adequate for full-scale road construction, including large scale mixing at an asphalt plant, and laying and compacting with heavy machinery. Higher bitumen absorption and volumetric mix design must be considered. The employment of LFS without any prior (chemical or mechanical) treatment has been validated for up to 10% of the mixture.
- Compactability, in terms of void content of the on-site mixture, was within the appropriate limits for a porous asphalt. No bitumen leakage was observed in the tests or during laying, and the general performance of slag as a filler, in terms of adhesion, was correct.
- The visual inspection of the pavement concluded that the final finish was acceptable and no road surface deficiencies were detected. Neither ridging, rutting, cracking, nor stripping were observed on the pavement during the first months of use.
- The mechanical behaviour of the specimens manufactured from samples of the mixture was correct. The main feature, particle loss, met the normative limits for roads with medium intensity HGV traffic. Sensitivity to water gave excellent results.
- The results of the tests on the macro and microtexture of the coating layer were very good. The permeability tests scored top on the classification, proving the good sustainability of this material (PA with LFS) and its highly suitable properties for areas of high rainfall.

The results of the field experience of the porous mixture with ladle furnace slag have proved satisfactory and the products comply with the regulatory requirements. It is now necessary to study the durability of the constructed pavement in the long term, with special regard to abrasion and skid resistance, as well as to analyse the differences in behaviour between the two pavemented areas that withstand different stresses.

## Declaration of interest

The authors report there are no competing interests to declare

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