Ladle furnace slag in asphalt mixes

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Abstract

Ladle Furnace Slag (LFS) may be used in substitution of fine aggregate (2-0.063 mm), and filler (<0.063 mm) in bituminous mixtures, considering its suitable particle size and hydraulic properties. From among the range of bituminous mixtures, this research is conducted on Porous Asphalt mixes (PA). Their high void ratio means they can absorb any eventual expansion of the LFS.

Mechanical behavior, moisture susceptibility and durability are all tested. The results report the performance of the LFS mixtures, which showed compliance with the specifications of the relevant standards and no significant differences from those made of natural aggregates and cement.

Keywords: Ladle Furnace Slag (LFS), Porous Asphalt Mix, Bituminous Permeable Course, Open Graded Asphalt Concrete, Steel slag, Refining slag, steelmaking reducing slag, filler substitution, fine aggregate replacement, waste management.

1. Introduction

Rational use of natural resources within the construction industry, as in other productive processes, is becoming a high priority. This trend is reflected in efforts to reuse by-products and waste and to reduce landfilling. “Sustainable construction” has an inherent need for scientific support to facilitate the reuse of these by-products, combining sustainability and compliance with technical requirements.

In its continuous expansion, the global steel industry produced 1.6 billion tons of steel in 2014. There is plenty of previous experience, backed by extensive research, in the reuse of certain byproducts from iron and steelmaking, basically Blast Furnace Slag (BFS), Electric Arc Furnace Slag (EAFS) and converter slag (Basic Oxygen Furnaces Slag- BOFS) [1-7]. However, the reuse of Ladle Furnace Slag (basic slag, reducing slag, white slag or refining slag), a by-product of steelmaking from secondary metallurgy processes, is less widespread.

Approximately 60-80 kg of LFS are recovered for each ton of steel that is refined. Varying amounts of LFS are usually reintroduced into the steel production process, in both electric arc furnaces [8-10] and basic oxygen furnaces [11, 12]. This practice is reported to produce beneficial effects on the characteristics of the new steels that are produced and in the black slag that is generated, as well as a reduction in production costs [8].

Despite the above-mentioned process, an important amount of LF slag is dumped at landfill sites close to production centers, with its consequent environmental and visual impacts. In Spain, LFS landfill dumping is in excess of 400,000 tons annually, prompting a search for alternative uses to reduce this volume of waste and excessive land filling.

One of the main properties of LFS is its hydraulicity, resulting from its chemical composition, which provides it with cementitious properties [13, 14]. Hydration may also provoke the dissolution of some elements and volumetric expansion. LFS usually contains certain unstable minerals (mainly in the form of free lime and periclase). These minerals are transformed into $Ca(OH)_2$ and/or $Mg(OH)_2$ in the presence of moisture, which occupy a larger volume than the primary components [15]. As sufficient volumetric stability is essential in construction, it is required to study the behavior of the LFS in the composite [15, 16].

Based on the aforementioned cementitious properties, one modern-day application for LFS would be as an active or inert addition in the preparation of Portland cement clinker [17, 18]. In fact, cement production is the only use of LFS that is currently approved in Spanish regulations [19].

Within the construction industry, these cementitious properties and their initial possibilities are explored, so that the application of LFS would be (complete or partial) replacement of cement and lime in their varied applications. Other investigations include its suitability as a substitute of fine natural aggregate, in view of its particle size.

The most highly developed LFS applications in construction are: in replacement of cement and/or sand in the manufacture of mortars [13, 20-24] and concrete [25-27], and even self-compacting concrete [28, 29], soil stabilization for road platforms and rural road pavements [15, 16, 30], and several uses related to environmental engineering such as water treatment [31-33], agronomic correctors and supplements [34], and as a fine element for landfill covers [35].

Road construction requires various different materials; among these materials, bituminous mixes are mainly composed of aggregates, traditionally extracted from quarries and gravel pits. Along with the exploitation of limited natural resources, mining, crushing, sieving, washing and transporting natural aggregates expend significant amounts of energy. Global consumption of natural aggregates is estimated to exceed 30,000 million tons/year.

Numerous lines of research have investigated substitution of the fine fraction and the filler of bituminous mixes by recycled materials: quarry by-products and mine tailings [36-38], foundry sand [39, 40], coal fly ash [41-43], municipal solid waste incineration ash [44-46], cement bypass dust [43, 47], waste glass [48-50], recycled concrete and mortar [51, 52], waste ceramic materials (bricks, tiles…) [53, 54], asphalt shingles [55], crushed steel slags [56-60] and nonferrous slags (copper, nickel, zinc). However, the Authors are unaware of the existence of a line of investigation that introduces LFS into bituminous mixtures.

Porous Asphalt (PA) mixes, also known as Permeable Friction Courses (PFC) are special types of hot bituminous mixtures that have a coarse granular skeleton that develops stone-on-stone contact, and a high content of connected air voids, meaning that these mixtures have good drainage properties [61].

The main advantages of these kinds of mixtures are related to safety in wet-weather driving, owing to the reduction of splash and spray, the risk of hydroplaning and wet skidding; effective drainage also improves the visibility of pavement markings in wet weather [61]. Improvements to water quality after drainage have also been demonstrated [62]. In addition to this, they also contribute to noise abatement, reportedly between 4 to 6 dB(A) when compared to a concrete pavement or dense-graded asphalt concrete [63, 64].

The object of this article is to demonstrate the suitability of Ladle Furnace Slag (LFS) for use in manufacturing porous bituminous mixtures. The following observations were made in this research when using LFS, due to its volumetric instability:

- Its proportion in the total asphalt mixture was never in excess of 15%.
- The use of slag wrapped in a bituminous matrix is less problematic than its use as an unbound material, as its surrounding binder protects it from moisture and prevents hydration reactions. This protection is more noticeable in the case of fine materials, such as LFS.

- Its use in flexible and porous matrices, such as porous bituminous mixtures (with an approximate void ratio of 20%) means any eventual expansion will be absorbed into the mix voids.

The research followed two approaches. Firstly, the LFS was used as filler, to replace the cement that is usually employed as quality filler. Then, whole-particle-size LFS was used in substitution of the fine natural aggregate and the filler. All the bituminous mixtures were tested in terms of mechanical behavior, moisture susceptibility and durability, comparing their results with the standard mix. The final aim was to demonstrate that porous bituminous mixtures manufactured with ladle slag presented a strong, stable, durable and environmentally efficient behavior.

2. Materials and Methodology

2.1. Natural aggregates, cement and binder

Asphalt mixes are composed of a combination of coarse aggregates (16/2 mm), fine aggregates (2/0.063 mm), filler (<0.063 mm), and binder.

The following materials were used in this research: a natural siliceous aggregate from a nearby quarry, the characteristics of which are summarized in Table 1. It was used as coarse aggregate in all of the samples and as fine aggregate in the control samples. Ordinary Portland cement, CEM I/42.5 R was used as filler in the control samples.

Every specimen was manufactured using a Polymer Modified Bitumen complying with EN 14023 [65] and obtained by a chemical reaction between a hydrocarbon binder and an elastomeric polymer; penetration 45/80 and softening point 60ºC (PMB 45/80-60 [65]).

2.2. Ladle Furnace Slag (LFS)

The LFS used in this research was provided by a Spanish company which produces carbon steel pipes by melting scrap in an Electric Arc Furnace and then refining it in a Ladle Furnace.

The LFS, obtained after spontaneous cooling, is a grayish-white powdery material, with a particle size of 0/2 mm. Its physical properties and chemical composition are detailed in tables 1 and 2, respectively.

Table 1. Physical properties of the siliceous aggregate and the LFS

Feature	Standard	Siliceous aggregate	LFS
Bulk Density	EN 1097-6	2.74 g/cm^3	2.83 g/cm^3
Fineness modulus	EN 933-1	2.9	4.2
Blaine specific surface	EN 196-6	-	2654-3091 cm^2/g
Sand Equivalent	EN 933-8	78%	50 %
Water Absorption	EN 1097-6	1.5 %	-
Los Angeles coefficient	EN 1097-2	20%	-
Polished Stone Value (PSV)	EN 1097-8	52%	-
Flakiness index	EN 933-3	18%	-
Crushability index	EN 933-5	100%	-
Plasticity	UNE 103103 / UNE 103104	Non Plastic	Non Plastic

Table 2. Chemical composition of the LFS used

Component	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	TiO_2	SO_3	CO_2	Others	LOI
wt.-%	56.7	17.7	9.6	6.6	2.2	0.3	0.9	1.3	4.7	4.0

The complete mineralogical and morphological microstructural characterization of this slag, labeled as slag E, can be found in previous papers of the research group of the Authors [15, 16]. It presents medium amounts of periclase and portlandite, calcium-olivine silicates and reactive aluminates such as mayenite, as may be observed in figures 1a and 1b.

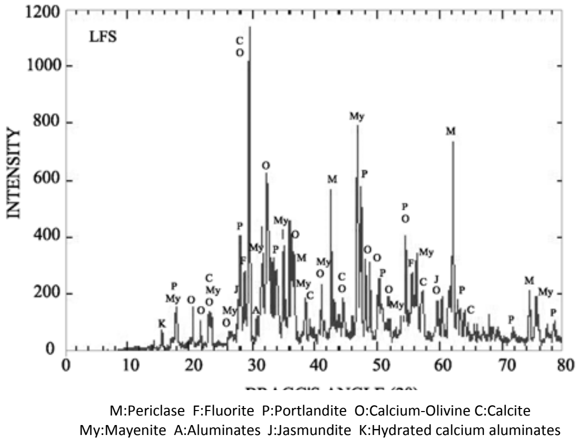


Figure 1a. LFS Diffraction Pattern.

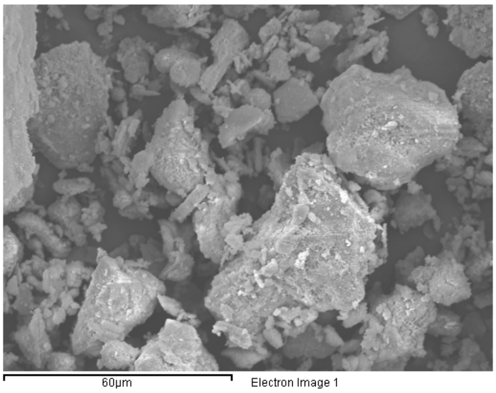


Figure 1b. LFS Scanning Electron Microscopy

This research group also subjected this LFS to a potential expansion test in previous studies [15]. The main conclusion was that, although complying with the requirements of potential expansion after a week, according to ASTM-2940 (<0.5%), delayed swelling registered higher values (>18%). This behavior leads us to advise caution, as previously noted, in the use of LFS.

2.3. Specimen preparation

Each specimen was manufactured according to EN 12697-35 [65] specifications on materials, preparation and mixing. Polymer-modified bitumen was applied according to the manufacturer’s recommended temperatures: 160ºC for mixing and 155ºC for compaction. Specimens of 101.6 mm in diameter and approximately 63.5 mm in height were prepared for the Marshall compaction, by applying 50 blows on each face, as described in EN 12697-30 [65]. Binder draindown tests were conducted on uncompacted samples.

2.4. Mix-design procedure

In a preliminary phase of the research, two types of mixes were designed: a mixture named PA-SC, made with the standard components (siliceous sand and cement as filler) and a mixture named PA-LL, with the ladle furnace slag as both fine aggregate and filler.

The particle size distribution of the mixture was chosen for the grading envelope named PA-11 in the Spanish Standard PG-3 [66], reflected in table 3. It is a porous asphalt mix, with a nominal maximum size of 11 mm and a thick mineral skeleton, with a large void ratio (>20%).

Table 3. Grading envelope PA-11 from Spanish Standard PG-3 [66]

Sieve size (mm)	16	11.2	8	4	2	0.5	0.063
Mass percent passing	100	90-100	50-70	13-27	10-17	5-12	3-6

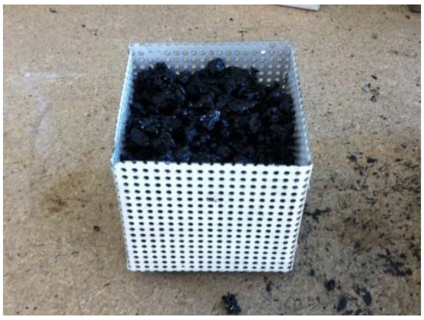
In this preliminary phase of the research, a series of initial tests were established to choose the optimum bitumen content (OBC). Some series of samples were manufactured with bitumen contents varying from 4.5% to 6%. Slight differences in particle distribution were accommodated to maintain the filler/asphalt ratio under the established limits.

The choice of OBC was taken on the basis of the results of two tests: the Cantabro test, which provides information on minimum bitumen content, and the binder drainage test, which limits the maximum content.

In the **Cantabro test**, each Marshall specimen is placed inside the Los Angeles abrasion drum without steel balls. Then, the drum is operated for 300 revolutions, at 30 revolutions/min, as described in EN 12697-17 [65]. Particle loss, PL (%) is expressed as a ratio of the weight of the disintegrated particles, W_1-W_2, over the initial weight of the specimen, W_1.

$$PL = 100(W_1 - W_2)\ /W_1 \qquad (1)$$

The **binder drainage** or draindown test prescribed by EN 12697-18 [65] consists in preparing a loose asphalt mixture sample at the designed asphalt binder content and then placing it in a perforated basket (see figure 2a.) in an oven at 170ºC for 3 hours; so that the mastic that flows through the perforations can be weighed, as shown in figure 2b.



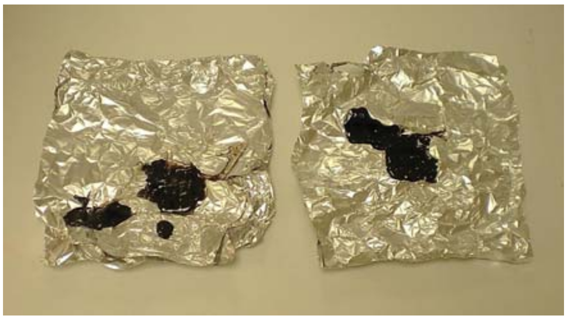


Figure 2a. Binder drainage basket containing the asphalt mixture

Figure 2b. Mastic flow from the basket after the test

The percentage of the drained mastic to the original sample weight is referred to as its draindown value, D (%).

2.5. Testing program

Volumetric properties, mechanical behavior, durability and moisture susceptibility were tested. Tests were conducted in triplicate on each mixture.

2.5.1. Volumetric properties

For each sample, and prior to testing, the **air void content (AVC)** of the specimen was determined according to EN 12697-8 [65], from the **maximum density** of the mixture (determined by the mathematical procedure defined in EN 12697-5 [65]) and the **bulk density** (according to the geometrical procedure defined in EN 12697-6 [65]).

This procedure is essential to verify the success of the sample design and preparation and to establish the air void content of the mixtures, which is a key characteristic of the bituminous mix [67]. Samples had in all cases to be discarded, if not within a set range of values (21% ± 3%).

The **permeability** coefficient (K) of the mixtures was also assessed, using the constant head permeameter, according to the vertical permeability test described in EN 12697-19 [65].

2.5.2. Mechanical behavior

There is wide agreement over the critical parameter that determines the performance of mixtures with a high content of voids: resistance to raveling or abrasion [68]. The Cantabro test, as described in 2.4., is commonly used to evaluate resistance to wear and particle losses in porous asphalt mixtures, because of its better correlation with the performance and durability of such mixtures [69].

Basic wear resistance of the mixtures, **Basic Abrasion Loss (BAL)**, has to be determined by the Cantabro test, performed at 25ºC in accordance with Spanish regulation PG-3 [66]. However, the drum was not placed in a thermostatic room and the actual temperature at which each test took place was recorded. Nevertheless, particle losses of specimens at lower temperatures (15-20 °C) are known to be higher than those obtained at 25 °C [70], so the results are expected to be on the safe side.

Indirect Tensile Strength (ITS) was tested as described in EN 12697-23 [65], where the cylindrical cross-section of the specimen is subjected to diametric compressive loading until breakage. As in the Marshall test, the load is applied at a constant strain rate of 50 ± 2 mm/min.

The ITS (N/mm^2) is obtained from the maximum tensile strength calculation, based on the maximum load applied at the moment of breakage, P (N) and the dimensions of the specimen, h (height) and R (radius), (mm).

$$ITS = P/(\pi \ h \ R) \tag{2}$$

2.5.3. Durability

A frequently evaluated feature in the literature is resistance to wear abrasion on aged specimens: **Aged Abrasion Loss (AAL)**. The accelerated aging process is regulated by the ASTM D-7064 [71] and consists in keeping the specimens for 7 days in a forced draft oven at 60°C.

They are then conditioned at the test temperature for 4 hours, after which the Cantabro test is performed.

Likewise, to investigate the potential effect of binder aging on the cohesion loss of the mixtures, the samples were subjected to controlled aging, in which they were held in a regulated environment (humid chamber 23°C and 96% humidity) for 6 months. Thereafter, their **Long term performance (LTP)** in terms of wear resistance was evaluated and compared to the fresh samples.

Bituminous mixtures stiffen at low temperatures and are more susceptible to brittle fracture and cracking. Although not a regulatory requirement, a mechanical test after conditioning the samples at low temperatures is recommended. Sample conditioning was done by placing the specimens in a freezing temperature of 1ºC for 24h, after which their particle loss was tested, with the **Cold Abrasion Loss (CAL)** test, as described by Álvarez et al. [69].

The former three mean durability results are expressed, both in absolute and relative terms with the fresh test results (PL_b, Particle Loss in basic conditions), through "loss increment indexes": Aged Abrasion Loss index (AAL index), Long Term Performance index (LTP index) and Cold Abrasion Loss index (CAL index), which are defined as follows:

$$AAL\ index = PL_a/PL_b \quad (3)$$

$$LTP\ index = PL_l/PL_b \quad (4)$$

$$CAL\ index = PL_c/PL_b \quad (5)$$

2.5.4. Moisture susceptibility

Moisture produces the loss of adhesion between the asphalt binder and the aggregate surface, and accelerates deterioration in the form of potholes, cracking and raveling [72].

Moisture susceptibility or resistance to moisture damage in the PA mixes was assessed through two approaches: retained tensile strength or the **tensile strength ratio (TSR)** as specified by EN 12697-12 [65], and **wet abrasion loss (WAL)**, in accordance with Spanish regulation NLT-362/92. In both cases, six Marshall specimens were divided into two groups: the control subset, which remains dry at room temperature, and the conditioned subset, which is saturated and submerged in hot water for a period of time (40ºC for about 72h in the TSR and 60ºC for 24h in the WAL). Both performance indexes are the result of comparing the conditioned results (ITS_w, PL_w) against the dry results (ITS_d, PL_d).

$$TSR\ (\%) = 100\ \times\ ITS_w/ITS_d \tag{6}$$

$$WAL\ index = PL_w/PL_d \tag{7}$$

In this case, the standard procedure was followed, except for sample saturation, as no vacuum machine is available at the laboratory facilities. Nonetheless, non-saturation of voids through a vacuum machine is common in research on porous mixtures [73], because their high content of connected voids fill with water when left submerged in water [74]. Other authors maintain that this procedure is designed for bituminous concrete and is too aggressive for mixtures with a high void content, so they propose alternative non-saturation procedures [75].

3. Results and discussion

3.1. Mix design

Table 4 shows the gradation and composition of the bituminous mixtures and the results from the tests conducted in this preliminary phase.

Table 4. Mix design results

Sample	Filler 0/0.063 mm	Fine aggregate 0.063/2 mm	Coarse aggregate 2/16 mm	Asphalt Binder	Air Void Content, AVC	Cantabro abrasion loss, PL	Draindown test, D
PA-SC 4.5	4.5 % cement	8.4 % Silic.	82.6 % Silic.	4.5 % PMB	22.03 %	14.19 %	0.00 %
PA-SC 5.0	5.0 % cement	7.8 % Silic.	82.2 % Silic.	5.0 % PMB	19.71 %	8.89 %	0.00 %
PA-SC 5.5	5.5 % cement	7.3 % Silic.	81.7 % Silic.	5.5 % PMB	21.68 %	9.69 %	0.12 %
PA-SC 6.0	5.6 % cement	7.1 % Silic.	81.3 % Silic.	6.0 % PMB	21.24 %	9.74 %	0.99 %
PA-LL 4.5	4.5 % LFS	8.4 % LFS	82.6 % Silic.	4.5 % PMB	19.83 %	11.33 %	0.00 %
PA-LL 5.0	5.0 % LFS	7.8 % LFS	82.2 % Silic.	5.0 % PMB	19.96 %	10.60 %	0.00 %
PA-LL 5.5	5.5 % LFS	7.3 % LFS	81.7 % Silic.	5.5 % PMB	17.67 %	10.18 %	0.09 %
PA-LL 6.0	5.6 % LFS	7.1 % LFS	81.3 % Silic.	6.0 % PMB	18.70 %	8.49 %	0.24 %

As shown in table 4, particle losses tend to increase as the binder content decreases, because the bitumen film that covers the aggregates protects them from wear and enhances cohesion and adhesion. Although the abrasion loss results were excellent for all the tested mixes, the performance of the mixtures designed with 4.5% binder was perceivably worse.

Moreover, binder drainage usually occurs in asphalt mixtures lacking fine aggregate and filler that maintain the binder in place, so as to create appropriate mastics. In general, drainage control leads to an upper limitation of the bitumen content. Spanish regulations [66] are very strict and allow no draindown, hence binder contents over 5% must be discarded.

Finally, given the similar behavior of the two types of mixtures, it was decided to adopt the same particle size and the same OBC. Samples containing 5% of bitumen were considered to be balanced in durability, strength and potential draindown.

Additional information can be extracted from the draindown test. First of all, the test demonstrates that LFS functions properly as filler, presenting good adhesion with the bitumen and forming quality mastic. Otherwise, binder drainage would occur for all bitumen contents and not only for the higher ones. Secondly, as may be observed in table 4, it appears that for high bitumen contents, the samples made with LFS produced less binder drainage than the control mixtures, which suggests that LFS has higher asphalt absorption than the conventional components. This may be related to the higher porosity or rougher texture of the slag.

In the following phase of the research, three types of mixtures were manufactured with the selected particle size distribution and OBC as described in table 5. Their components varied to observe the influence of the LFS in the mix behavior. PA-SL mix incorporated the LFS only as filler, while the PA-LL used it in its whole particle size, as filler and fine aggregate. Their results will always be compared with the control mix, PA-SC.

Table 5. Final mix design

	Content	**Materials used**		
		PA-SC	**PA-SL**	**PA-LL**
Coarse aggregate	82.2 %	Siliceous	Siliceous	Siliceous
Fine aggregate	7.8 %	Siliceous	Siliceous	LFS
Filler	5.0 %	Cement	LFS	LFS
Binder	5.0 %	PMB 45/80-60	PMB 45/80-60	PMB 45/80-60

3.2. Volumetric properties

The average volumetric properties of all the specimens that were tested appear in table 6.

Table 6. Volumetric properties

	PA-SC	**PA-SL**	**PA-LL**
Bulk density (g/cm^3) EN 12697-6	2.000	1.999	1.986
Maximum density (g/cm^3) EN 12697-5	2.537	2.531	2.536
Air voids (%) EN 12697-8	21.1%	21.0%	21.7%
Permeability (cm/s) EN 12697-19	$9.07 \cdot 10^{-2}$	$9.01 \cdot 10^{-2}$	$9.04 \cdot 10^{-2}$

The calculated maximum **density** of the three types of mixture is similar, as the siliceous aggregate and the LFS share very similar densities.

A slight increase in the **void content** of the mixtures may be inferred when introducing the LFS in the range of the fine material. This increase may be due to the superior angularity of LFS compared to the siliceous sands. It should be remembered that the siliceous sands are particularly rounded fine materials, used sometimes in bituminous mixtures to improve their compaction.

Some studies, in relation to the use of black slags (EAFS, BOFS) in the manufacture of bituminous mixtures, reported that the void content of the mixes increased, because of the greater sharpness of the slag particles. This increment was noted even when the slag was only used as fine aggregate [58].

Permeability tests yielded very similar mean results, as expected with similar air void contents, demonstrating that the introduction of LFS has no effect on the permeability of the mixtures. The values provided an acceptable and durable permeable behavior.

3.3. Mechanical behavior

Wear resistance of both the PA-SL and the control mixtures was very similar, as shown in table 7. In fact, a slight improvement could be detected in the PA-SL mixtures, although that might also be attributed to the higher test temperature, which was favorable [70]. However, when using LFS as fine and filler replacement (PA-LL mixes), an increase in particle loss was noticeable. These losses might be due to the higher bitumen absorption of the LFS detected in the "binder drainage test", which would produce thinness in the binder film that covers the particles, decreasing their resistance to raveling.

Table 7. Mechanical behavior

		PA-SC	**PA-SL**	**PA-LL**
Basic Abrasion Loss (BAL)	Void Content (%)	19.79	21.92	19.97
	Test Temperature (ºC)	20	25	20
	Particle loss, PL_b (%)	8.06	7.12	10.57
Indirect Tensile Strength (ITS)	Void Content (%)	22.10	18.53	22.30
	Maximum load (N)	12.96	12.95	13.53
	ITS (N/mm^2)	1.26	1.30	1.31

In any event, every mixture greatly exceeded the standard requirements, which have to be under 20% of Particle Loss, as required by the Spanish standards [66] for the most demanding applications. Regulations in other countries required values from 15% to 30% of maximum loss, depending on the type of traffic and the test temperature [76].

The **indirect tensile strength** values were very good. A good cohesion of the mixtures may be inferred as well as high resistance to cracking and fine performance under shear stress. Furthermore, the results were very close in the different mixtures; hence, the introduction of LFS as filler or fines will neither worsen the performance of pavements under tensile stress nor produce a loss of cohesion in the bituminous mix.

3.4. Durability

The average results of the different durability tests made to the asphalt mixes appear in table 8, below.

Table 8. Mixture Durability

		PA-SC	PA-SL	PA-LL
Aged Abrasion Loss (AAL)	Void Content (%)	19.14	21.62	21.06
	Particle loss, PL_a (%)	12.07	8.83	13.06
	AAL Index	1.50	1.24	1.24
Long-Term Performance (LTP)	Void Content (%)	21.37	20.17	23.58
	Particle loss, PL_l (%)	8.52	8.05	10.44
	LTP Index	1.06	1.13	0.99
Cold Abrasion Loss (CAL)	Void Content (%)	22.70	20.62	22.7
	Particle loss, PL_c (%)	23.84	17.90	26.57
	CAL Index	2.96	2.51	2.51

Following the fresh trend, **aged abrasion loss** of the samples made with LFS as filler (PA-SL) were the best, while the results of the PA-LL mixes were slightly worse than those of the conventional components (PA-SC).

Standard ASTM D-7064 [71] imposes a particle-loss limit of 50% on the values of individual samples and a limit of 30% on the overall average results. All of the specimens that were tested more than complied with those requirements.

It was also observed that the effect of time on specimen wear resistance (**Long-Term Performance**) was practically non-existent. The behavior of the specimens after six months was very similar to the behavior of the fresh samples, such that the aging of the designed pavement was successful.

Again following the fresh trend, the samples with LFS as filler showed the best low-temperature performance (**Cold Abrasion Loss)**, followed by the PA-SC and the PA-LL mixes. However, regarding the loss increment index under cold conditions, it may be noted that introducing LFS as filler improves the thermal susceptibility of the mixtures.

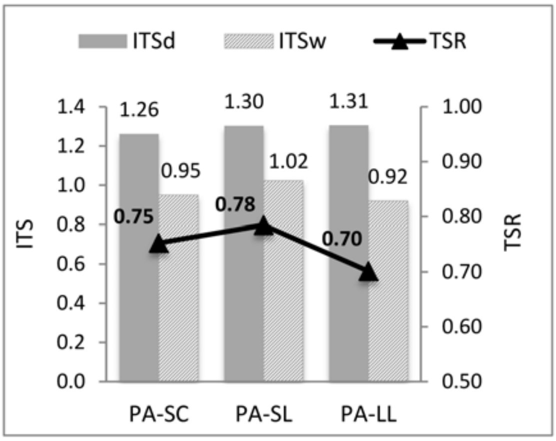
3.5. Moisture susceptibility

In terms of the **Tensile Strength Ratio** of the samples, the performance of all three types of mixes was similar, as can be observed in Figure 3a. Regulations in the U.S. require TSR values of between 70% and 80%, depending on each State Administration [71, 75], so the mixtures may not comply with some of those requirements.

Anyway, some researchers consider that this method may not be appropriate to evaluate moisture sensitivity in high air void content mixtures and propose a search for an alternative approach [61, 75], such as the Wet Abrasion Loss, described below.

Beyond these preliminary considerations, it may be observed that the mixtures incorporating LF slag provide results that are in line with those of the standard mixture. This happens in both indirect tensile strength after wet conditioning (ITS_w), as in the tensile strength ratio (TSR). Therefore, it may at the very least be stated that the slag in no way worsens the performance of materials that are commonly used for manufacturing quality porous asphalt (cement and silica).

In addition, the resistance of the slag mixes to raveling under wet conditions **(Wet Abrasion Loss)** was better than the performance of the control mix, both in absolute terms (PL_w) and in comparison with the fresh samples (WAL index), as reflected in figure 3b. In fact, water sensitivity gradually improved with the incorporation of slag. Unlike with the TSR, each mix exceeded the requirements of PL_w, which should be below 30%.



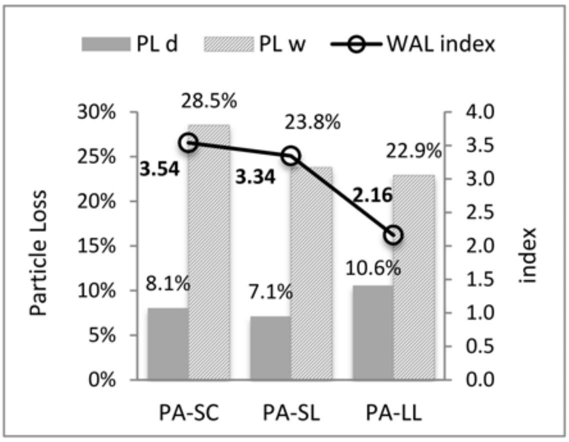


Figure 3a. Moisture susceptibility through TSR

Figure 3b. Moisture susceptibility through WAL

From the results of this test, it could be inferred that the LFS showed good affinity with the binder, forming quality mastic, and giving good cohesion to the mix. This could be due to the basicity of the slag, which has better adhesion with the binder than the silica, which is an "acid" aggregate, forming a more cohesive mixture. Furthermore, the slag texture is rougher, which also favors the passive adherence of bitumen.

4. Conclusions

1. Mix design and OBC in slag mixes can be assimilated to the control mixes. The void content of the mixtures with LFS sand was slightly higher, which may be due to the

superior angularity of the slag. Mean permeability results were also very close to those of the control mixes.

2. The binder drainage test demonstrated that the LFS works properly as filler, presenting good adhesion with the bitumen and forming good quality mastic. It was also noted that white slag had superior bitumen absorption than the conventional materials.
3. The mechanical behavior of the mixes (abrasion, tensile strength) was excellent for every mixture designed, which enables these mixtures to be used even in the most demanding applications. Mixtures manufactured with slag sand showed a slightly worse performance, which could be attributed to the higher bitumen absorption of the slag.
4. Aging produced similar effects on every mixture, far exceeding the regulatory recommendations.
5. Thermal susceptibility of the mixtures improved with the incorporation of ladle slag.
6. Moisture sensitivity in terms of TSR hardly met the regulatory requirements, although this may not be significant for the porous asphalt mixes. Water resistance evaluated by the Wet Abrasion Loss exceeded the prescriptions and showed a good cohesive performance that, in fact, increased with the incorporation of slag. The rougher texture of the slag and its better adhesion to the binder are favorable for the moisture susceptibility of the mixes.

These results will hopefully encourage further research on the viability of replacing sand and cement with ladle furnace slag in porous asphalt mixtures.

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