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DURABILITY IN ABRASION TERMS OF A FULL-SCALE POROUS BITUMINOUS MIXTURE MANUFACTURED WITH LADLE FURNACE SLAG

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ABSTRACT

A research experience on the construction of a pilot road section with a porous asphalt mixture incorporating Ladle Furnace Slag (LFS) as fine aggregate in its composition is reported. The pilot section consisted of overlaying this mixture on existing bituminous pavement and was intended to simulate a real application of this sustainable construction material. Along with the paving, quality control was conducted to ensure that this mixture complied with the requirements of the current regulations for its use. This quality control included a durability-performance study. Thus, water-sensitivity, accelerated-aging and frost-exposure tests from an abrasion-resistance approach were conducted on Marshall specimens compacted with 50 blows per face. The values obtained were compared with the abrasion resistance of unaged specimens. The results of the tests were generally in accordance with the applicable regulations, the full-scale porous asphalt mix with LFS exhibiting an adequate durability performance in terms of abrasion resistance.

Keywords
Ladle furnace slag; porous asphalt mixture; pilot road section; durability; abrasion loss.

INTRODUCTION

The environmental impact caused by bituminous mixtures is extremely high (Aslani *et al.*, 2023). On the one hand, there is the production of natural crushed aggregate in quarries. This practice damages the environment by modifying the habitat, landscape and water flows, among others, which in turn affects the development of flora and fauna (Ozcelik, 2022). On the other hand, there is the manufacture of bitumen, a product obtained during petroleum distillation. During this process, huge quantities of greenhouse gases are emitted, which contributes to phenomena such as global warming (Nimana *et al.*, 2017).

Increased environmental awareness in recent years has led to research into the production of construction materials with sustainable raw materials (Osial *et al.*, 2022, Segui *et al.*, 2023). They are often industrial wastes or by-products, the use of which not only increases the sustainability of the construction materials, but also revalues and gives a second life to products that have no practical use and that are destined to be landfilled (Chen *et al.*, 2022). In the field of asphalt mixes, research has widely addressed their manufacturing with waste aggregates to reduce the production and consumption of natural aggregate. Thus, the research on this subject is very varied and for instance, papers related to the use of recycled asphalt pavement (Antunes *et al.*, 2019), construction and demolition waste (Gedik, 2020), or glass powder (Mohajerani *et al.*, 2017) as aggregates in bituminous mixtures can be found.

Steelmaking is a very active sector in different parts of the world, producing iron and steel, which are nowadays fundamental products in the production system (Falsafi *et al.*, 2023). However, its activity also generates large quantities of a waste product known as slag. Several types of slag can be found, such as blast-furnace slag, converter slag or electric-arc-furnace slag (Brand and Fanijo, 2020). This situation has led research to evaluate the potential applicability of all these types of slag as aggregates in the production of bituminous mixtures, which has been shown to be successful in most of the cases (Loureiro *et al.*, 2022, Poulikakos *et al.*, 2017, Pasquini *et al.*, 2023).

The type of slag with possibly the most challenging reuse is the Ladle Furnace Slag (LFS). This type of slag is in the form of a grayish powder and comes from the refining in ladle furnaces of steel from both electric-arc furnaces and oxygen converters (Araos Henríquez *et al.*, 2021). It is estimated that 80 kg of LFS are approximately produced *per* ton of steel (Sheshukov *et al.*, 2021). The search for a valid application for this type of slag is complicated due to the high content of free lime (CaO) and magnesia (MgO) in its composition, which causes LFS to undergo expansive phenomena when carbonated or hydrated due to the formation of hydroxides (Rodríguez *et al.*, 2019). Adequate aging of the LFS prior to its use, by watering and exposure to outdoor environmental conditions, guarantees in principle that these expansive phenomena will occur prior to the addition of LFS as a raw material in construction materials, making this feature of LFS a non-problem for their performance (Santamaría *et al.*, 2020).

Despite all the above, the aforementioned expansive risk of LFS has to be borne in mind when defining its use. Thus, the use of LFS as the fine-aggregate and filler fractions in the production of bituminous mixtures is one of its recommended applications, mainly due to two aspects. First, LFS is completely covered by bitumen in an asphalt mixture. Bitumen is impermeable, which limits the contact of LFS with water or air, thus in turn reducing the probability of LFS expansion in the

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long term (Terrones-Saeta *et al.*, 2020). Second, a bituminous mixture is a flexible material, so in principle, it can adapt to potential small expansions of the LFS by deforming the bitumen without cracking or breaking (Nebreda-Rodrigo *et al.*, 2021). If, in addition, a porous asphalt mix is made, the voids within it would help to a greater extent to ensure that these possible expansive phenomena would not affect the performance of the bituminous mixture (Skaf *et al.*, 2016).

Researchers from the Universities of Burgos, Spain, and Padua, Italy, have demonstrated in the last years the suitability of steel slags and, more specifically, of LFS for the production of bituminous mixtures (Skaf *et al.*, 2016, Pasetto *et al.*, 2020). These studies have focused on laboratory-scale analyses, with specimens being prepared for study by testing the properties of the developed asphalt mixes. However, it is clear that if we really want to advance in the widespread use of sustainable construction materials, it is necessary to evaluate their behavior on a real scale, *i.e.*, when manufactured in a volume similar to that industrially produced in order to evaluate the consequences of increasing the amount of a certain construction material simultaneously produced (Lee *et al.*, 2023). In addition, it is necessary to conduct pilot building projects that address the full-scale applications intended for them (Skaf *et al.*, 2022).

This paper deals with the execution of a pilot road section with a porous asphalt mix incorporating LFS as an aggregate (Skaf *et al.*, 2022). More specifically, the construction process is described, and the durability of the mixture is analyzed from an abrasion-resistance approach. Wet abrasion loss, accelerated aging and frost exposure were all evaluated through laboratory tests on Marshall specimens prepared with the bituminous mixture used in the construction of the road section. Thus, the objective was to analyze whether a bituminous mix that had shown an adequate performance in terms of durability at the laboratory scale (Skaf *et al.*, 2016) is also suitable regarding its durability when produced at full scale for use on a real road section.

MATERIALS AND METHODS

Raw materials

The bituminous mixture evaluated in this research was composed of bitumen, siliceous aggregate, limestone filler and LFS. The LFS was supplied by a steelmaking-waste management company, after proper handling by the researchers in charge of this study. LFS constituted part of the amount of fine aggregate and filler defined in the mix design, the overall particle gradation being adjusted through the addition of the aforementioned siliceous aggregate and limestone filler (Terrones-Saeta *et al.*, 2020).

Bitumen, siliceous aggregate, and limestone filler were those commonly used in the asphalt plant where the mixture was manufactured. The bitumen was polymer modified with the labelling PMB 45/80-60 according to EN 14023 (2010).

Crushed siliceous aggregate from a quarry located in northern Spain was used. This made up the entire coarse fraction of the aggregate gradation of the asphalt mix and part of the fine fraction, which was combined with LFS. According to the quality control carried out by the aggregate supplier, all the physical characteristics of this aggregate were suitable for its use in the production of porous asphalt mixes (PG-3, 2014). These characteristics are detailed in Table 1.

The filler used was of limestone nature due to the good binder adhesion that it exhibits, which allows the production of quality mastics (Sheshukov *et al.*, 2021).

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Table 1 shows its physical characteristics, which correspond to usual values.

Table 1. Physical properties of the aggregate.

Property	Siliceous aggregate	Limestone filler	LFS
Sand equivalent (%)	77	68	50
Bulk density (g/cm^3)	2.6	2.7	2.8
Water absorption (% wt.)	0.5	1.8	1.9
Los Angeles wear loss (%)	18	-	-
Polished stone value (%)	52	-	-
Flakiness index (%)	16	-	-
Crushability index (%)	100	-	-

LFS had the appearance of grayish powder and a maximum size of 4 mm, with a fines content (particles smaller than 0.063 mm, filler-size particles) of around 20%, and a fineness modulus of 4.2 units. It was not subjected to any type of treatment prior to its use in the asphalt mix, although it was weathered to avoid potential expansion (Santamaría *et al.*, 2020) and air-dried before being added to the bituminous mix. Its physical characteristics are detailed in Table 1, highlighting mainly its slightly higher density than natural aggregates, which implied the need to design the mix by volume correction (Poulikakos *et al.*, 2017, Skaf *et al.*, 2018). Chemical analysis by X-ray fluorescence showed that LFS was basically composed of calcium, silicon and magnesium oxides, which represented 88% of its weight (51.7% wt. CaO, 29.6% wt. SiO and 6.7% wt. MgO).
Aggregates' gradation is shown in Figure 1. It can be noted the LFS can clearly act as both fine aggregate and filler in the bituminous mixture.

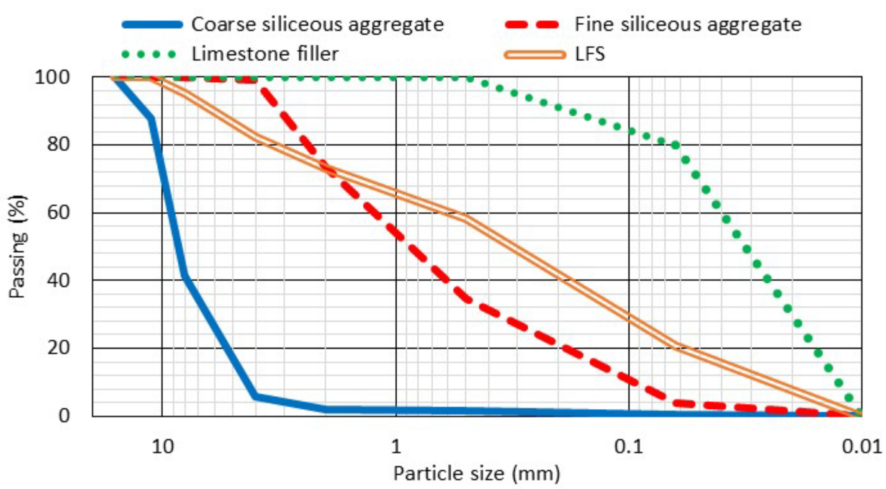

Figure 1. Gradation of the aggregates.

Mix design
The mix design of the porous asphalt mix was defined in accordance with the indications of the Spanish regulations for road materials (PG-3, 2014). A type of porous bituminous mixture known as PA-11 was chosen, which has a maximum aggregate size of 11 mm and a target void content of more than 20% thanks to a very coarse skeleton with a very low fines content. A PA-11 mixture has therefore a large number of interconnected pores which ensures adequate water penetration

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as well as sufficient friction and bearing capacity to support heavy traffic (Pérez-Acebo *et al.*, 2021). Thus, this mixture type is intended to act as a permeable thin wearing layer, on top of a dense asphalt mixture that serves as a waterproof barrier for the collection and channeling of the water (Skaf *et al.*, 2022).

The mix design was first conducted in the laboratory to define the optimum binder content (Skaf *et al.*, 2016). For that, four groups of mixtures were prepared with different bitumen contents, concluding that the best balance between all the asphalt-mix properties was achieved with a bitumen content of 5% and a filler-to-bitumen ratio of 1. In this way, the higher binder absorption of steel slags compared to natural aggregates was compensated (Pasetto *et al.*, 2020). These values were suitable for a PA-11 mixture (PG-3, 2014), and were maintained in this research to verify adequate mix compactability and the absence of binder bleeding in the full-scale mixture.

The proportions of the aggregates were determined using the PA-11 envelope (PG-3, 2014), which defines the overall particle size of this type of bituminous mixture, as shown in Figure 2. In this process, the LFS content was maximized, *i.e.*, the contents of the natural aggregates were adapted to the gradation of the LFS by adding the fractions that this waste did not provide in enough quantity (Skaf *et al.*, 2022). Thus, the bituminous mixture incorporated 81.1% wt. coarse siliceous aggregate, 5.6% wt. fine siliceous aggregate, 10.0% wt. LFS and 3.3% wt. limestone filler.

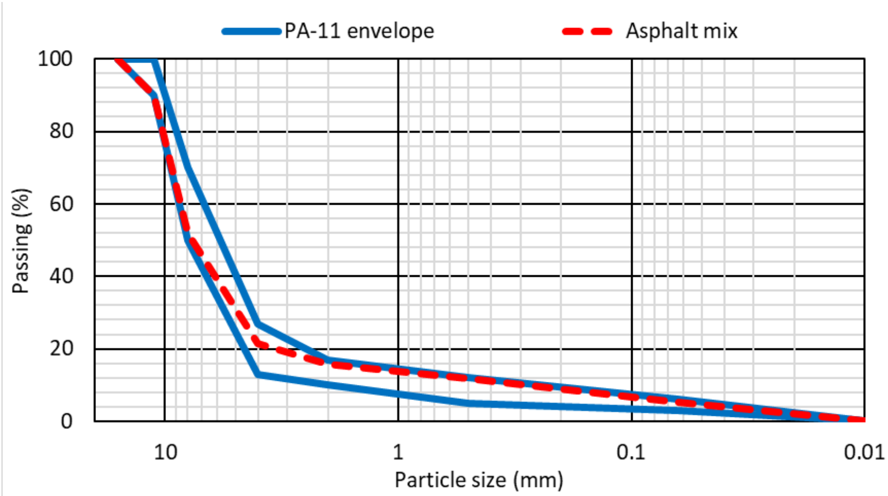

Figure 2. Target gradation of the asphalt mix.

Construction of the pilot road section

Once the mix design was defined, the porous bituminous mixture was produced in an asphalt plant in a quantity of 28 tons. The asphalt mix was used to pave a 4-cm-thick wearing course on an area of approximately 300 m^2 in the vicinity of the University of Burgos, Spain, where it was transported by a heated truck. Before paving, surface preparation operations were carried out, such as milling transverse joints, cleaning, sweeping, edge preparation and tack coating with 0.5 kg/m^2 of bituminous emulsion. Finally, the mix was placed and compacted in two different areas, consisting of a 4.5-meter-wide 30-meter-long parking lot and a 6-meter-wide 30-meter-long two-lane road. All stages of the construction of the two-lane-road section are shown in Figure 3. No compactability, binder bleeding, stripping, workability, or ridging issues occurred during construction.

Figure 3. Construction of the pilot road section.

Experimental plan

Once the road section was completed, a thorough laboratory-testing plan was conducted on specimens to analyze the performance of the asphalt mix. In addition, field tests were also carried out to evaluate the pilot section. The results of these tests are detailed elsewhere (Skaf *et al.*, 2022).

The durability of the asphalt mix was assessed during the year following its placement through water-sensitivity (wet abrasion loss), accelerated-aging and frost-exposure laboratory tests. Each test consisted of exposing three Marshall specimens of the mix to certain environmental conditions, after which they were

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subjected to the Cántabro test according to EN 12697-17 (2018). In this test, the specimens are individually introduced into the Los Angeles drum without any abrasive load (steel balls), applying 300 revolutions. The specimens are weighed before and after being introduced in the drum, the percentage difference in weight is the result of the test, also known as abrasion loss. The environmental conditions for specimen exposition in the three durability tests are:

- Water sensitivity (wet abrasion loss) according to NLT-362 (1992): introduction of the specimens into a water bath at a temperature of 60±1 °C for 24 h and subsequent exposure to 25±1 °C for another 24 h.
- Accelerated aging as per ASTM D-7064 (2021): introduction of the specimens in an oven at 60±1 °C for 7 days and exposure to the laboratory temperature for another 4 hours.
- Frost exposure in accordance with Alvarez *et al.* (2010): introduction of the specimens into a chamber at 1±1 °C for 24 h. Exposure to these low temperatures simulates frost exposure, which causes oxidation of the binder, increases its brittleness and makes the bituminous mixture more susceptible to particle stripping(Alvarez *et al.*, 2010).

The results of these tests were statistically analyzed by calculating 95%-confidence intervals. In addition, the results obtained were compared with the abrasion loss on unaged specimens obtained shortly after the execution of the pilot section.

Apart from this laboratory experimental plan, field durability tests are also being performed during the years following the execution of the pilot road section.

RESULTS AND DISCUSSION

Abrasion loss

Abrasion resistance is a key aspect of porous pavements since their high volume of voids means that they are very susceptible to spalling and cracking, which reduces their service life (Zhang *et al.*, 2020). The good performance of the filler is essential to avoid these phenomena, as it largely conditions mastic adhesion (Sheshukov *et al.*, 2021). LFS accounted for a very important part of the filler in the studied asphalt mix, so abrasion loss is a fundamental property.

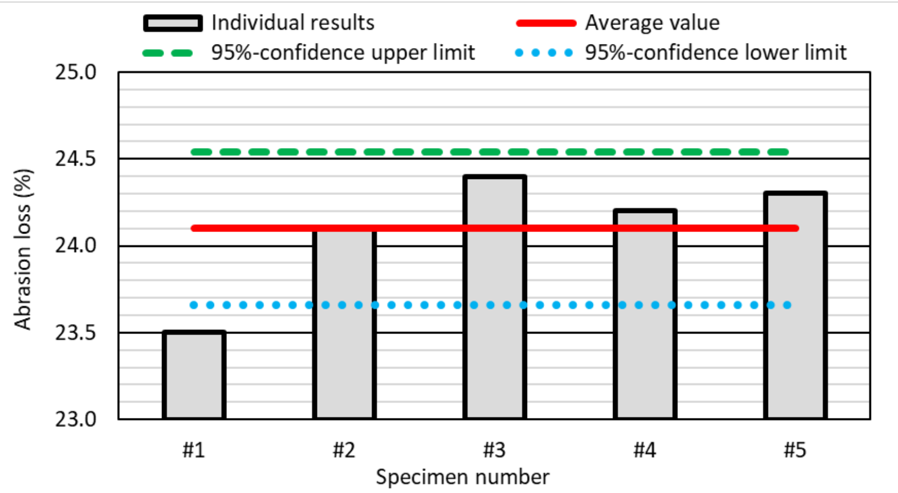

Figure 4. Abrasion loss on unaged specimens

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As shown in Figure 4, the abrasion loss had an average value of 24.1%, less than 25%, which is the upper limit for considering a pavement adequate for medium heavy-traffic intensities (PG-3, 2014). This situation was in line with the roadway executed. The dispersion of the results was low, as the confidence interval was lower than 1-unit wide, thus the mix exhibiting high homogeneity.

Water sensitivity (wet abrasion loss)

Adequate resistance to water damage is essential in porous asphalt mixes. They are in continuous contact with water, so the weakening effect it causes must be minimized to get an adequate performance throughout their whole useful life (Chen and Wong, 2018).

The studied porous mix exhibited exceptional wet-abrasion-loss results (Figure 5). The value obtained was around 34%, indicating that this mix would be valid for all heavy-traffic levels (PG-3, 2014). The use of LFS as fine aggregate and filler, thanks to its high CaO content, improves the cohesion of the mixes and, thus, their moisture resistance (Skaf *et al.*, 2016).

The dispersion of the results was greater than in the abrasion loss on dry specimens since the confidence interval presented a width of 8 units. However, considering the higher absolute value of the results of this test, this level of dispersion also corresponded to a mixture with a homogeneous behavior (Skaf *et al.*, 2022).

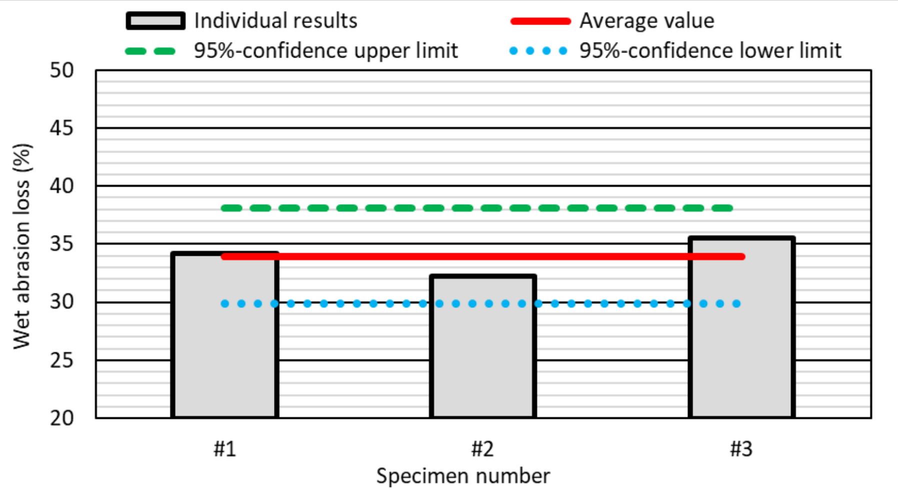

Figure 5. Wet abrasion loss.

Accelerated aging

Mix aging oxidizes and embrittles the binder, which reduces the adhesion of the binder to the aggregate particles, which in turn increases particle stripping in the pavement (Putman and Kline, 2012). This behavior can be analyzed by performing field tests over time. Nevertheless, this behavior can also be analyzed through the accelerated-aging laboratory test according to ASTM D-7064 (2021).

The results of the mixture in this test were correct (Figure 6), the average value obtained was 29.7%, which was slightly lower than the limit of 30% established in the standards (ASTM D-7064, 2021). In all cases, the individual results were lower than 50%, a limit also established in ASTM D-7064 (2021).

In dispersion terms, the confidence interval had a width of approximately 14 units. The mixture presented a more variable behavior when subjected to long-term aging, as simulated in this test (Pasetto *et al.*, 2020).

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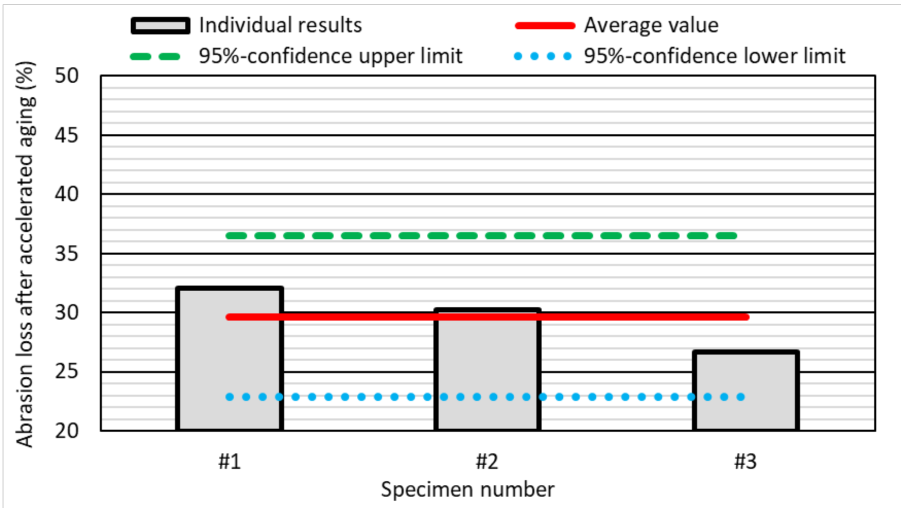

Figure 6. Abrasion loss after accelerated aging.

Frost exposure

Frost also adversely affects bituminous mixtures. They cause the binder to stiffen, making it more susceptible to brittle fracture and increasing particle stripping (Segui *et al.*, 2023). This phenomenon is exacerbated in porous mixtures because of their greater exposure to ice due to their high volume of voids (Alvarez *et al.*, 2010).

The abrasion loss of the mixture under these conditions was high (Figure 7), with an average value of 38.9%. However, if compared with the results of wet abrasion loss, the increase was quite small. This shows that the behavior of the mixture under these more demanding environmental conditions was adequate (Alvarez *et al.*, 2010).

The level of the dispersion according to the 95%-confidence interval was similar to that found in the accelerated-aging test, which demonstrates the high variability of the mixture's behavior under frost exposure.

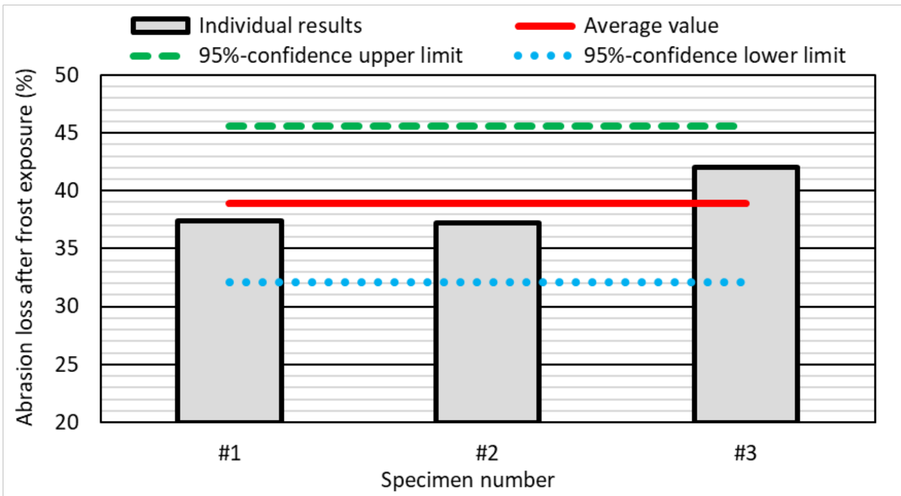

Figure 7. Abrasion loss after frost exposure.

Comparison of results and summary

The results of the durability tests were compared with the abrasion loss on unaged

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specimens. The comparative resistance indices were 1.41, 1.23 and 1.61 for the water-sensitivity, accelerated-aging and frost-resistance tests, respectively. As expected, all the durability tests increased the deterioration of the asphalt mix. However, its behavior was fairly uniform, and under the normative limits, with no environmental conditions causing excessive damage in the mixture. Frost exposure was the more demanding situation for the asphalt mix.

CONCLUSIONS

The following conclusions can be drawn from the durability tests conducted on a full-scale porous asphalt mixture made with Ladle Furnace Slag (LFS):

- The behavior of the mixture in all the environmental conditions evaluated (water sensitivity, accelerated aging, and frost exposure) was adequate, providing suitable results for its implementation in real road sections.
- The mixture showed a uniform behavior in terms of durability, with no test causing a much more pronounced deterioration in its performance. Frost exposure was the most unfavorable situation.
- The mixture showed greater variability of behavior in the accelerated-aging and frost-exposure tests than in the water-sensitivity one. This makes it advisable to further study this behavior.

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