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Ladle furnace slag in asphalt mixes

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HIGHLIGHTS

- LFS works properly as filler, presenting good adhesion with the bitumen.
- The LFS had superior bitumen absorption than the conventional materials.
- Porous mixes with LFS provided results in line with those of the standard mixture.
- LFS mixes presented good cohesion and excellent mechanical behavior.

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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.

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

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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. First, 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 60 °C (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.

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 Fig. 1a and b.

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.