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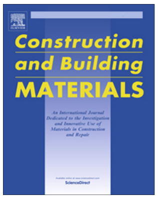

Use of ladle furnace slag as filler in hot asphalt mixtures

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HIGHLIGHTS

- Ladle furnace slag (LFS) mainly consists of quicklime (about 50%) and silica (20%).
- 0.25-mm sifted and hydrated LFS guarantees the best asphalt concrete (AC) performance.
- AC including sieved and hydrated LFS has improved stiffness and strength.
- AC including sieved and hydrated LFS has an excellent resistance to fatigue.

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ABSTRACT

Worldwide, recycling of ladle furnace slag (LFS), one of the waste produced by ironmaking and steelmaking industries, actually represents a big challenge which involves different field of material and construction industry.

This paper deals with the reuse of LFS as filler in hot asphalt mixtures. In particular, the physical and chemical properties of LFS were evaluated and a procedure to treat LFS and make it suitable for the application in asphalt concrete (AC) was defined. Finally, the volumetric and mechanical properties of the AC containing LFS were determined.

Experimental results showed that the hydrated LFS allows achieving an excellent performance of the AC (in terms of volumetric properties, stiffness, indirect tensile strength and resistance to repeated loads) with respect to the reference mixture with ordinary filler.

1. Introduction

Ironmaking and steelmaking industries currently generate many million tons of slags as a byproduct during the separation of the molten metal, iron and steel, from oxides. These slags can be identified in four types: the blast furnace (BF) iron slag, the basic oxygen furnace (BOF) steel slag, the electric arc furnace (EAF) steel slag, and the ladle furnace (LF) basic slag, also called the secondary refining slag or the white slag [1,2].

The ladle furnace slag (LFS) is produced in the secondary metallurgy process, during the final stages of steelmaking. In this phase, steel is heated in the ladle furnace and, through the addition of quicklime (CaO), subjected to desulfurization, degassing of oxygen, nitrogen, and hydrogen, removal of impurities and final decarburization (done for ultralow carbon steels) [3,4]. As highlighted by Serjun et al. [5], LFS has a low potential for recycling due to its fine grain size and adverse properties with regard to leaching. For this reason in the European Union about 80% of LFS is currently landfilled [6].

In the recent years, LFS has been object of many studies worldwide in order to characterize its properties and identify suitable solutions for its reuse [3,5,7–14].

As LFS is composed by 50% of CaO approximately, one of the applications is exactly in ladle furnace, in substitution of the quicklime additive [7–9]. However, the entire ladle furnace process is not sustainable in terms of ratio between LFS produced and recycled, as only part of LFS can be reused.

Other researches showed that, since the chemical composition of LFS is characterized by a CaO/SiO_2 ratio of around 2 and a high content of C_2S, it has interesting cementitious properties that can be exploited in civil and building engineering [3,5,10].

Radenovic et al. [11] proved that LFS is a nonhazardous industrial waste, as it does not contain constituents which might affect the environment harmfully, and demonstrated that LFS can be used as a low cost adsorbent for uptaking the dangerous substances from aqueous solutions.

Only few studies aimed at evaluating the possibility of recycling LFS in road pavements: Pasetto and Baldo [12] focused on reusing different industrial by-products (steel slag, ladle slag, foundry sand, coal ash and glass wastes) to produce cement bound

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mixtures for base and sub-base layers. The results showed that the cement-treated recycled mixture containing 8% of LFS presented toxicological, physical and mechanical characteristics that make it suitable to be reused. Yilmaz and Sutas [13] used a CaO-rich slag (so-called Ferrochromium filler) to produce a hot asphalt concrete (AC) and obtained promising results from Marshall and creep tests. Skaf et al. [15] used LFS in substitution of fine aggregate and filler in porous AC, which showed a good performance in terms of mechanical behavior, moisture susceptibility and mix durability.

However, two important issues must be considered when using LFS, and in general steel slags, in unbound mixtures, cement bound mixtures or AC.

The first regards the volume stability of the mix [16]. Indeed, the significant advantages (in terms of increase in mastic stiffness, reduction of moisture damage and bitumen aging, increase in mix durability) related to the use of lime-based filler in AC have been largely demonstrated [17–21]. Nevertheless, lime is typically employed in form of hydroxide $Ca(OH)_2$ (hydraulic lime), while the use of quicklime CaO, as that included in steel slags, is usually not recommended or limited to fixed amounts. In fact, as indicated by different authors [14,15,22], free CaO will react to hydroxide $Ca(OH)_2$ when in contact with water, causing a volume increase. For this reason, in many countries (for instance China and Germany) the immersion expansion ratio or the free CaO content are limited by national regulations [16,14]. Actually in Italy there is not a national specification for limiting LFS content in AC, but the European Norm EN 13043 (about aggregate for bituminous mixtures) states that for BOF and EAF slag the volume expansion shall be determined and declared, even if it does not fix any limit for slag content (in Annex A also "Ferrochromium slag" is provided, but no indications for its used are discussed in the document).

The second issue deals with LFS heterogeneity [5]. Since steel manufacturers do not share the same working practices, the composition of LFS is subjected to significant variations. Moreover, local conditions at the steelwork, batch syntheses, scrap-metal variations, exposure of slag stockpiles to the atmosphere and/or to water may lead to important differences in the LFS. For this reason, the determination of the chemical and physical characteristics of LFS in any specific case is fundamental, because the cementitious and mechanical characteristics, which play a key role in its possible reuse, are closely related to these properties [4].

2. Objective and experimental program

The present study deals with the use of LFS produced by Ferriere Nord in Osoppo plant (Italy) as filler for AC. The objectives of the research are:

- the evaluation of the physical and chemical properties of LFS, in order to verify the possibility to reuse it in hot bituminous mixtures;
- the definition of a suitable procedure to treat LFS and make it comparable, in terms of performance, to an industrial $Ca(OH)_2$-based filler;
- the laboratory validation, in terms of volumetric and mechanical properties, of the AC containing LFS.

At the light of the considerations made in the introduction, the preliminary phase of the experimental program (phase 1) aimed at the characterization of the LFS used. In particular, the steelwork provided two types of LFS: the first was exactly the white slag coming out from the ladle furnace and was indicated with the letter A; the second consisted in the finer part of LFS-A, passing at 0.25 mm-sieve, and was indicated with the letter B. Both LFSs were studied in terms of gradation, particle density, Rigden voids and chemical composition. The material conformity to European and Italian regulations was assessed.

In the second phase (phase 2), based on the results from LFS analysis, ACs were produced in the laboratory including LFS-A or LFS-B. Moreover, two further ACs were manufactured bu using hydrated LFS. In particular, LFS-B was hydrated following two procedures: the first consisted in immersing the white slag in a water bath for 24 h at 70 °C; in the second procedure LFS-B was damped with a fixed amount of water according to the stoichiometric ratio of the hydration reaction ($H_2O/CaO = 0.32$), put in a sealed bag and cured for 24 h at 70 °C. The LFS hydrated by immersion was indicated with the abbreviation LFS-B-HI and while the LFS hydrated with the "stoichiometric" water with LFS-B-HS. Two reference ACs were finally manufactured by using an ordinary limestone filler collected in a mix plant (abbreviation CF) and an industrial $Ca(OH)_2$-based filler (abbreviation IF).

The ACs, characterized by the same gradation and bitumen content (5.0% by mix weight), were compacted by means of a shear gyratory compactor (SGC) in order to analyze the volumetric properties in terms of air voids content (AVC), void in the mineral aggregate (VMA) and void filled with bitumen (VBF). The stiffness properties were investigated in terms of indirect tensile stiffness modulus ITSM at 20 °C, while the cracking resistance was evaluated by means of indirect tensile strength (ITS) tests at 25 °C. In addition, the broken specimens from ITS test were subjected to leaching test in order to check the release of any harmful substance.

The final part of the experimental program (phase 3) regarded the mix design and the mechanical characterization of the AC including LFS which allowed the higher performances to be reached during phase 2. The reference AC containing CF was analyzed as term of comparison. The mix design was carried out following the volumetric procedure, according to Italian Specifications [23]. Specifically, four ACs were manufactured using different bitumen contents (4.8, 5.1, 5.4 and 5.7% by mix weight) to identify the optimum that allowed an AVC equal to 5% to be obtained. The mechanical characterization of the mixtures was performed through ITSM tests at 20 °C and ITS tests at 25 °C. In addition, the water sensitivity of the ACs was determined in terms of Indirect Tensile Strength Ratio (ITSR). The behaviour at low temperatures was investigated by means of semi-circular bending SCB tests at 0 °C. Finally, the AC performance under repeated loads was studied through indirect tensile fatigue (ITF) tests at 20 °C at three horizontal stress amplitudes.

The summary of the experimental program is shown in Table 1.

3. Test methods

ITS was measured at the temperature of 25 °C by means of a electro-mechanical press, imposing a constant rate of deformation of 50 ± 2 mm/min until specimen failure occurred (EN 12697-23). During the test, load and vertical displacement were continuously measured and recorded. In addition, the total fracture energy (TFE), i.e. the area under the load-vertical deformation curve, was determined.

ITSR was determined to assess the water sensitivity of the mixtures. For each AC, 6 specimens were compacted with a SGC at 50 gyrations. The 3 water-conditioned specimens were kept in a water bath at 40 °C for 72 h, applying a vacuum, prior to testing. Then, ITS was measured at 25 °C and the ITSR was calculated as the ratio between the mean ITS from air-conditioned specimens and the mean ITS from water-conditioned specimens.

ITSM test was carried out at 20 °C through a servo-pneumatic machine by applying repeated load pulses with a rise time of 124 ms and a pulse repetition period of 3.0 s. For each specimen,