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Durability studies on fiber-reinforced EAF slag concrete for pavements

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HIGHLIGHTS

- Steel reinforcement fibers imply lower porosity, permeability and drying shrinkage.
- Fiber-reinforced EAFS concrete performed well in freeze-thaw and wet-dry tests.
- Fiber-reinforced EAFS concrete resisted sulfates and industrial environments.
- EAFS concrete slabs performed well after weathering for five-years outdoors.

GRAPHICAL ABSTRACT

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ABSTRACT

The long-term behavior of fiber-reinforced hydraulic concretes for pavement applications is studied in this paper. These concretes are manufactured with Electric Arc Furnace Slag as aggregate and exposed to aggressive environments. Mechanical properties, porosity, capillary structure, and long-term variations in length are measured in compressive, tensile, Mercury Intrusion Porosimetry, Fagerlund, and shrinkage tests. The concrete samples are subjected to conventional durability – freeze/thaw and moist-dry – tests and exposed to aggressive agents as sulfates, carbon dioxide, and sulfidic atmospheres with good results. Finally, a set of concrete slabs prepared outdoors are successfully left to weather under detrimental conditions.

1. Introduction

The vast amount of natural aggregates consumed in both construction and civil engineering prompts us to search for alternative materials that can replace natural resources. Furthermore, the use of recycled aggregates in construction and building applications contributes to savings on waste disposal. This philosophy of a circular economy and industrial symbiosis is in line with European Union policies that promote sustainability and environmental assessment in the construction sector [1,2]. A wide range of recycled aggregates has recently been introduced in replacement of natural aggregate for various construction applications [3,4], among which hydraulic [5–8] and bituminous mixtures [9–13], highlighting the use of several types of slags from metallurgical processes in industrial production [14–18].

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Over recent decades, the steelmaking industry in Europe has been transformed, in such a way that Electric Arc Furnace (EAF) steelmaking technology has partially replaced outdated blast furnace – LD converters. EAF technology is used for around 30% of European carbon and low alloy steel production. In Spain alone, approximately 70% of all steel is produced in electric arc furnaces (10 MT per year of EAF steel), representing around 15% of total European EAF steel (67 MT per year) [19,20]. The practical use of electric furnaces in steelmaking is divided into two stages: the primary melting-oxidizing processes and the secondary-reducing processes. In the first, an Electric Arc Furnace will generate slag (EAFS) in proportions of 150–180 kg per ton of steel and, in the second, a Ladle Furnace will produce slag (LFS) in proportions of 60–80 kg per ton of steel.

In relation to the above, several studies were carried out to characterize both EAFS [21–25] and LFS [26–34], in addition to the manufacture of hydraulic mixes with EAF slag: mortar [35], plain concrete [36–42], structural and reinforced concrete [43–50] and self-compacting concrete [51,52].

The use of artificial (metallic or synthetic) fibers in the reinforcement of concrete [53–62] poured in situ, carrying the weight of indoor-outdoor wheeled-rolled traffic, has been presented as a good solution for industrial pavements in factories and storehouses. Among other advantages such as stiffness, long-term dimensional stability, cleanliness, liquid absorption, abrasion resistance, toughness and surface fatigue resistance, the easy use of fibers in construction and easy substitution-recycling have greatly enhanced their popularity; several research groups around the world have contributed to advancements in this field. Hence, the use of fibers in this application is a solid engineering solution in substitution of reinforcing steel bars (rebars) in elements submitted to moderate tensile stress, as happens with these ballast-supported paving elements [63,64].

Some of the authors of this paper have recently published a previous study [65], which may be considered directly related to the present paper, on fiber-reinforced concrete made with electric arc furnace slag (CEAFS) used in industrial pavement slabs. They studied its mixtures and performance, prioritizing the engineering aspects of the problem, to go on to conclude that CEAFS reinforced with about 0.5% by volume of metallic or synthetic fibers achieved good mechanical behavior, in terms of strength, toughness and post-cracking behavior; as well as satisfactory abrasion resistance for its use in pavements and concrete ground slabs withstanding rolling traffic. However, issues in that work relating to both the physical and the chemical durability of these concretes were not resolved and these questions now form the subject of the present study, in which the presence of fibers and steelmaking slags and their effects are analyzed.

Studies in the literature (including those of the present authors) generally define the durability of CEAFS (without fibers) as acceptable, though slightly lower than the durability of conventional concrete, especially in terms of carbonation and sulfate attack [40,66] and in freezing/thawing tests [67,68]; results that are attributed to the high porosity of EAFS and, in consequence, the higher permeability of the CEAFS. Researchers in Italy [69] evaluated the durability of concretes manufactured with EAFS in terms of freezing/thawing, wetting/drying, and accelerated aging in hot water. They concluded that it was similar to conventional concretes; however, resistance to chloride-ion permeation of the EAFS concrete was enhanced, observing improvements in the durability of the concretes exposed to chloride environments and lower diffusion coefficients. Probably the main variable inducing differences between the results of the various research teams in the world is the quality of the slag.

The experience of the present team in this field has contributed to satisfactory results in the aforementioned tests and in others (sulfate attack, aggregate-alkali reaction); results that are attributed to good adhesion between the slag aggregate and the surrounding concrete matrix; however, the results obtained for the CEAFS in cases of exposure to marine environments, seawater and chloride penetration tests were not as good as those of the conventional concrete.

In this study, CEAFS with and without fiber reinforcement were manufactured for comparative purposes, to understand the way in which CEAFS containing slag and fibers behave over time, even in the presence of aggressive industrial indoor-outdoor environments. Several in-fresh and in-hardened state properties of CEAFS such as consistency, density, compression, flexion and splitting tension strengths and their elastic moduli are included in this study (showing slightly different values than those detailed in the aforementioned article [65] of the authors), to contribute an overall understanding of the context. Mercury Intrusion Porosimetry (MIP), permeability and porosity tests were performed together with long-term shrinkage evaluation of the mixes. The aggressive environmental conditions under consideration in this work due to their relevance were as follows: freezing/thawing cycles, wetting/drying cycles, sulfate-containing water attack, and exposure to atmospheres rich in gaseous carbon dioxide and sulfur dioxide. Evaluation tests of compressive strength, dimensions, weight, and variations in the external appearance of the mixes performed under those environmental conditions are reported with explanations of the behavior that was observed.

Finally, a number of full-scale slabs were manufactured with these types of concrete and exposed to regional weather conditions (rain, freezing, insolation...) in a five-year weathering process, after which their characteristics and final state were also evaluated.

2. Materials

- *Cement, water, admixtures and natural aggregates*: Ordinary Portland cement (OPC) CEM I/42.5R (EN 197-1:2001 [70]) with a density of 3.1 Mg/m^3, and mix water from the urban mains supply of the city of Burgos (Spain) were employed. The plasticizer admixture was a modified poly-carboxylate polymer and the natural rounded siliceous aggregate was provided as a fine fraction 0/4 mm, fineness modulus (f.m.) 2.5, water absorption 1.4% and oven dry density 2.65 Mg/m^3, the main component of which was SiO_2 (96%).
- *Fibers*: Metallic steel fibers of 50 mm in length, with a density of 7.9 Mg/m^3, a length/diameter aspect ratio of 45, and synthetic fibers of 50 mm in length composed of polyolefin (polypropylene), with a density of 0.92 Mg/m^3, and a length/diameter aspect ratio of 50 were used. The tensile strengths and the moduli of the steel fibers and the synthetic fibers were, respectively, 1000 MPa with a modulus of 210 GPa and 400 MPa with a modulus of 5 GPa.
- *Electric Arc Furnace Slag (EAFS)*: The crushed and weathered EAFS used in this research was supplied by a slag recycling plant in three size fractions (EN 933-1 [70]), 0/4 mm (f.m. 3.3), 4/10 mm (f.m. 5.5), and 10/20 mm (f.m. 7.1). A summary of the main properties are shown here, as the information on grading curves, and both the physical and the chemical properties of the EAFS, together with the characteristics of the natural aggregates, have previously been described in detail in a previous paper [62]. The EAFS used in this work had a density value of about 3.5 Mg/m^3, a water absorption rate of 3.5%, Los Angeles wear loss of under 24% and a flakiness index of under 3%. Almost 75% by weight of the slag aggregate was formed of Fe, Ca and Si oxides, in addition to 20% of Al, Mg, Mn oxides and 5% of other oxides (K_2O, Na_2O, P_2O_5, and TiO_2). Compounds associated with expansive processes, such as free lime and free