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Influence of recycled slag aggregates on the conductivity and strain sensing capacity of carbon fiber reinforced cement mortars

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HIGHLIGHTS

- Cement mortars with Electric Arc Furnace slag aggregates show higher strengths.
- Recycled EAF slag aggregates enhance the conductivity of CF reinforced mortars.
- Percolation was achieved with lower CF dosage for EAF slag aggregate mortars.
- CF reinforced mortars with EAF slag aggregates presented strain sensing capacity.
- The highest sensitivity was measured for EAF slag mortars with 1.9 vol% CF.

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ABSTRACT

The electrical resistivity of carbon fiber reinforced cement composites (CFRCC) has been widely studied for the functional applications of these composites. CFRCC with enhanced electrical properties can be used as strain or damage sensor, heating or deicing material, or anode in different electrochemical techniques, like chloride extraction or cathodic protection. In this work, carbon fiber reinforced cement mortars have been prepared using a conductive aggregate produced from the valorization of Electric Arc Furnace slag (EAF slag). Cement based mortars containing EAF slag aggregates revealed lower resistivity; hence, the carbon fiber percolation threshold decreased. Additionally, the strain sensing capacity of those composites with conductive aggregates was also enhanced, indicating similar sensitivity and lower dispersion than equivalent mortars containing limestone aggregates. The best linear regressions between the electrical and mechanical measures were achieved for EAF slag cement mortar containing 1.29 vol % of oxidized carbon fibers.

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1. Introduction

The construction industry is constantly developing novel solutions for the valorization of waste materials and industrial by-products [1–5]. Some of these applications emerge as an upgraded option to turn waste materials into composites with enhanced performance. The use of supplementary cementitious materials in concrete manufacturing transformed conventional concrete into a material with higher mechanical properties and durability: e.g., silica fume [6,7], blast furnace slag [8,9], or spent cracking catalyst residue [10,11]. Currently other waste reuses are being tested as an alternative to Portland cement use in concrete, e.g. alkali activated blast furnace slags [12–14].

Electric Arc Furnace slag (EAF slag) is a by-product from the steelmaking industry, produced from the melting and the preliminary acid refining of the liquid steel. EAF slag can be easily crushed to produce granular materials for use in both civil and building applications: EAF slag powder has been used as supplementary cementitious material [15], EAF slag aggregates have been used in concrete fabrication [16] or in road construction [17]. Concrete manufactured with partial or total replacement of conventional limestone or siliceous aggregates by EAF slag aggregates exhibited higher compressive, bending strength, durability [5,18–20], and rebar-concrete bonding strength [21]. On the other hand, conductive concrete emerges as an interesting alternative giving response to new challenges in construction (smart infrastructures or monitoring of durability) [22–24]. Conductive aggregates like iron ore or slags, might contribute to enhancing conductivity for that purpose [25]. Some metallic oxides contained in steel slags reveal conductivities in the range of pitch-based carbon fiber (CF) [26].

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Concrete and, in general, those materials evidencing a brittle tension or flexural behavior have been historically combined with other elements showing superior tensile properties [27–29]. The addition of short fibers (e.g. steel, carbon, polypropylene) to the mixture can improve the mechanical performance of the fiber-reinforced concrete (FRC), i.e. higher compressive strength [30], enhanced bending behavior [31], better residual properties after high temperature exposure [32]. Furthermore, all kind of fibers (even those without structural purpose) have been traditionally added to cement composites to control creep and shrinkage [8,13]. In general, fibers have been eventually used in the construction industry because of their effect on the mechanical performance. Nonetheless, over the last decades, fibers have been used for new functional purposes; especially, conductive fibers such as steel or CF [33]. Concrete is a dielectric material. However, the addition of a conductive admixture, such as carbon materials (CF [34], CNF [35], CNT [36]), transforms that composite into a conductive material. This yields the possibility of using the new cement based composite for other applications different to structural purposes. It can be therefore considered a multifunctional material. Among diverse potential applications, the most common functions are as follows: strain-sensing [37–39], damage-sensing [35,40], EMI-shielding [41,42], resistance heating [43–45] and electrical contact for chloride extraction [46–48] or cathodic protection [49–51].

This work is focused on the application of carbon fiber reinforced cement composites (CFRCC) as strain sensors. This sensing function is defined by the ability of a structural material to detect its own deformation when subjected to some external load. If a longitudinal compressive stress is applied, the electrical resistance in that direction is reduced, and vice versa when the material is under tension. Both effects are reversible in the material's elastic range when conductive admixture is sufficiently added [52]; therefore, the baseline electrical resistance (when load is equal to zero) returns to its initial value if compressive loads are below 30% of the material's strength [26].

The strain sensing capacity is quantified by the gage factor (GF), as the change of the electrical resistance (or resistivity) per unit strain, Eq. (1), in which: ΔR refers to the variation in resistance; R_0 refers to the initial resistivity; Δl refers to the longitudinal deformation; l_0 refers to the initial length and ε refers to the longitudinal strain.

$$GF = \frac{\Delta R/R_0}{\Delta l/l_0} = \frac{\Delta R/R_0}{\varepsilon} \tag{1}$$

In order to know the limits of the CF addition, it is important to know the value of the property called percolation threshold, i.e. the minimum CF amount that guarantees a continuous path for the electrical current [34]. For a given CF geometry, the increase in CF content leads to a decrease in resistivity [37]. The typical resistivity vs CF addition function is an S-shaped curve, meaning that for values above and below the percolation phenomena it does not exhibit significant change, but it shows several orders of magnitude of decrease for CF% close to the percolation threshold [33]. Therefore, once the percolation threshold is reached, from a conductivity point of view, the increase in CF dosage does not make any sense because resistivity does not vary significantly.

Each particular application requires a different level of conductivity. Hence, there is a huge number of possible combinations of type and dosages of admixtures. As a general rule, as the fibers aspect ratio increases, percolation is achieved with lower CF content [33,37,53]. Therefore, in order to achieve the highest conductivity, possible combinations of either CF or CNT would be desirable [44,54]. The use of conductive waste materials has been also tested, e.g. carbon black [55] or steel shavings [56]. In fact, a combination of conductive admixtures has been demonstrated to be the best solution for reach balance between material costs, waste recycling and functional properties [56]. The contribution of EAF steel slag aggregates to conductive properties of cement based materials has not been extensively addressed, in previous research works thereby constituting a pioneering approach aiming to achieve novel upcycling valorization solutions for such industrial by-products. EAF slag aggregates have been used in combination with carbon fibers to improve the electrical properties of CFRCC.

In this paper, the use of EAF slag fine aggregate in CF reinforced cement mortars is addressed. EAF slag aggregates exhibit higher conductivity when comparing to conventional siliceous or limestone aggregates. The new derived cement based composites are therefore expected to present enhanced conductivity, while optimizing the CF content. Hence, the main objective of this paper is to study the effect of this EAF slag fine aggregate on the electrical properties of the material: resistivity and strain-sensing capacity. As a result, the multifunctional properties of CFRCC (enhanced by conductive aggregates) will be combined with an improvement in sustainability due to the incorporation of recycled industrial by-products.

2. Materials and Methods

2.1. Materials and preparation of specimens

Portland cement mortars with carbon fiber (CF) additions were fabricated. Portland cement, type CEM II B/L 32.5R, according to UNE-EN 197-1:2011 ("Cement. Part 1: Composition, specifications and conformity criteria for common cement"), was used. Unsized PAN-based CF, type PANEX 35, supplied by Zoltek (see properties in Table 1). A control sample (without CF) and four CF dosages were prepared, i.e. CF% by cement mass were 0%, 1%, 2%, 3% and 4%. According to previous research works, high contents of CF could lead to a reduction in the workability of the fresh mix, thereby producing cement based composites with higher porosity [37]. Therefore, in order to achieve good workability conditions, the water/cement ratio in this work was 0.5 for CF dosages below 3%, and was increased to 0.6 for 3% and 4% CF additions.

Two different types of fine aggregates (with particles sizes ranging between 0 and 4 mm) were used. Type 1 was a regular limestone aggregate from the Basque Country (North Spain). The limestone aggregates were mainly composed of calcite (95%) and dolomite (5%) used in conventional concrete fabrication, as control dosages. Type 2 was a granular valorized by-product from the steel industry (EAF steel aggregate), whose physical characteristics are detailed in Table 2, while chemical characteristics are shown in Table 3. In both cases, a 3:1 sand/cement ratio was used.

EAF slag aggregates met all the requirements to be used as aggregates in mortars, as specified in the UNE-EN 13139-1 standard ("Aggregates for mortar"). It is worth highlighting that water absorption of the EAF slag aggregates exhibited higher values than those revealed by the natural aggregates, as observed by other researchers [18].

Table 1
Characterization of Carbon fibers.

Type	PANEX 35
Diameter	7.2 μm
Carbon content	95%
Tensile strength	3800 MPa
Elastic modulus	242 GPa
Resistivity	1.52×10^{-3} Ω·cm
Density	1.81 g/cm^3

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