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# Experimental behavior of beam-column joints made with EAF concrete under cyclic loading

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A B S T R A C T

This paper presents the results of an experimental campaign carried on exterior beam-column joints made with recycled concrete, containing Electric Arc Furnace (EAF) slag as full replacement of coarse natural aggregates. Three real-scale joints, one made with a conventional mix and two with EAF slag concrete, were tested under horizontal reversed cyclic loading, applied in quasi-static conditions. The three joints exhibited the same failure mode, which involved shear failure of panel joint and yielding of beams steel bars. This failure mode is indeed mainly influenced by concrete strength and was chosen to better highlight the influence of EAF slag use. Similar hysteresis response, stiffness decay, dissipated energy and ductility were obtained both with the conventional and EAF concrete joints. Results demonstrate that the specimens made with EAF concrete are able to attain higher loads than the conventional specimen at the same imposed displacement, and that the panel joint is less damaged.



## 1. Introduction

Electric Arc Furnace (EAF) slag is a by-product of carbon steel production in Electric Arc Furnace facilities, where it is obtained after the separation of molten steel from impurities. According to Euroslag [1], 31% of the produced metallurgical slags in Europe are of EAF type, thus representing approximately 7 million t/y in Europe. Particularly, Italy is one of the first producers of steel in Europe, with about 14% of the total European steel industry, yielding a considerable quantity of EAF slag during the productive chain [2]. In the last decade, the great availability of this material pushed the research community to study possible alternative uses [3–9], also as building material for civil engineering applications [10–16]. Many research works were indeed performed aiming to analyze the re-use of waste and by-products, to promote a sustainable development of novel products, with low embodied energy and carbon footprint [17].

Several works demonstrated the feasibility of using Electric Arc Furnace slag as coarse aggregate to produce structural concrete, even if they studied limited mechanical [18–19] or durability problems on small specimens [20–21]. Typically, EAF slag appears as a crushed black-dark grey stone, very hard and dense. According to its high specific weight, it can be associated to heavy-weight aggregates, e.g. barite. Most of the studies in literature reported enhancement in concrete compressive and tensile strength, when slag is used as partial or total replacement of coarse natural aggregates. Abu-Eishah et al. [22] and Pellegrino et al. [23] attributed this strength gain to slag morphology and shape, which improve adherence with cementitious matrix. Arribas et al. [24] observed also that the quality of matrix – aggregate interfacial transition zone (ITZ) is better than in conventional mixtures, with a reduced number of pores and micro-cracks. Also elastic modulus is generally increased, as well as concrete specific weight. More concerns exist about the use of EAF slag fine particles, even if positive results were obtained up to 50% replacement ratio on natural sand [23]. However, expansion phenomena can hinder EAF slag safe use in cement-based materials: accordingly, it is well recognized that pre-treatment should be performed to prevent those reactions. Expansion is indeed due to hydration of potential free lime and magnesium presence in slag: when in contact with water, free CaO rapidly hydrates and volumetric expansion occurs, whereas free MgO reacts slower, with deleterious expansive effects over a long time. Typically an outdoor weathering of about 2–3 months and some daily cycles under drying-wetting conditions are suitable for preventing any further expansive phenomena [5,20,23].

Only few works have already been performed on real scale reinforced concrete (RC) elements using EAF slag as coarse aggregates: Pellegrino and Faleschini [25] analyzed the structural behavior of RC beams under four point bending tests. Flexural behavior in bending and shear failure was critically analyzed, comparing the results obtained with EAF slag and conventional concrete members

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with the same reinforcement. Results evidenced that EAF concrete beams had higher ultimate capacity, and reduced deflection, both in bending and in shear; particularly, shear resistance without stirrups was significantly enhanced, due to the increased strength of the conglomerate and a better aggregate interlock. Kim et al. [26] studied instead the behavior of spirally confined columns made with EAF concrete: experimental results revealed similar and in some cases enhanced ductility, compared to conventional specimens.

In this work, the results of the first experimental campaign about the use of concrete made with EAF slag as coarse recycled aggregate to produce real-scale beam-column joints is reported. The novelty element is represented by the fact that no other tests on RC beam-column joints made with EAF concrete have been conducted in literature yet. Tests about structural behavior of RC joints made with recycled concrete under horizontal actions have been performed in literature [27–29], but none of them used EAF concrete. In this work, three real scale beam-column joints were casted, two made with EAF concrete and one with a conventional mixture; the same reinforcement was used in all the specimens. The joints were tested under horizontal reversed cyclic loading, applied in quasi-static conditions. The objective of this study is to assess indeed the effect of using EAF slag on the overall structural behavior of the joints, i.e. evidencing how concrete resisting mechanisms are influenced on this type of structure. Accordingly, joints were designed to achieve a so-called beam-joint (*BJ*) failure, which is mainly governed by concrete properties, and particularly, by its compressive strength [30–31].

## 2. Materials characterization

### 2.1. Materials

EAF slag used in this work (Fig. 1) is constituted by hard and dense particles: its main chemical composition is made by a set of iron, calcium and silicon oxides (about 75%), plus minor amount of magnesium, aluminum and manganese oxides. Table 1 lists the main chemical compounds present in this slag, obtained through X-ray Fluorescence on a representative sample of pulverized slag. Leaching tests were preliminarily performed and the concentration of potential toxic compounds in the leachate complied with the limit values reported in the Italian standards, DM186 [32]. Slag were pre-treated according to the method described in [23], and their maximum expansion evaluated according to EN 1744-1 [33] was below 0.35%. Three slag sizes were used: 4–8 mm, 8–12 mm and 8–16 mm. Natural aggregates (NA) with siliceous origin were used: two sizes were employed, a 0–4 mm river sand, and a 4–16 mm gravel. Physical characteristics of both slag and natural aggregates are listed in Table 2.

**Table 1**
Chemical composition of EAF slag.

| | Oxide (%$_w$) |
|---|---|
| $Fe_xO_y$ (total) | 33.28 |
| $CaO$ | 30.30 |
| $SiO_2$ | 14.56 |
| $Al_2O_3$ | 10.20 |
| $MnO$ | 4.34 |
| $MgO$ | 2.97 |
| $Cr_2O_3$ | 2.67 |

Cement type CEM II-A/L 42.5R, with high content of clinker and limestone, was adopted for concrete production. Additionally a water-reducing admixture (WRA) was used to allow mixes to reach the required workability (S4 slump as defined in EN 206–1 [34]).

Concrete mixtures were designed using Bolomey aggregates proportioning method: two mixes included EAF slag as coarse aggregate, and one had only natural aggregates. Concrete strength target was to achieve at least a cubic compressive strength of 45 MPa after 28 days. Table 3 lists mixtures details: Mix C and Mix E1 were designed with almost the same materials proportions, having a w/c = 0.45, and a nominal cement dosage of 400 kg/m$^3$. Mix E2 was designed with a lower binder content (320 kg/m$^3$), lower WRA content and higher w/c ratio, in order to produce a more environmentally sustainable mixture, with less cement dosage. In E1 mixture a slight increase in WRA dosage with respect to the conventional conglomerate was necessary to achieve the S4 slump class. Additionally, also a slight increase in sand content was necessary for improving fresh concrete workability in slag mixtures, as done also in previous works [19,21].

### 2.2. Fresh and hardened concretes properties

All the concretes displayed a good workability, with a measured slump belonging to the S4 slump class, ranging between 19 and 20 cm, evaluated through the Abrams cone method. No significant differences between the control and the EAF slag mixtures were experienced during casting operations. Concerning mechanical properties, for each mixture, other than the joint, nine cubic specimens with 10 cm sides and six cylindrical specimens with $d$ = 100 mm and $h$ = 200 mm were casted. After mixing, all the


**Fig. 1.** Black/oxidizing EAF slag used in this work.