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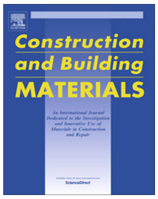

Structural behavior of RC beams containing EAF slag as recycled aggregate: Numerical versus experimental results

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HIGHLIGHTS

- The structural behavior of real scale beams with recycled concrete is investigated.
- EAF slag is considered as full replacement of natural aggregates.
- Twelve RC beams are analyzed, made of EAF concrete and conventional concrete.
- Both experimental findings and numerical models are discussed.
- Steel slags lead to higher flexural and shear capacity than conventional concrete.

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ABSTRACT

In the context of recycled concrete, the use of electric arc furnace (EAF) slag as partial or full replacement of coarse natural aggregates is particularly appealing because of the resulting economic and sustainability implications. Experimental investigation has been carried out on a set of reinforced concrete (RC) beams containing EAF slag as recycled aggregates under four-point bending tests. It has been found that the presence of steel slags leads to a higher flexural and shear capacity than the corresponding traditional RC beams, crack widths are reduced and the overall ductility is increased. Following these experimental findings, a numerical investigation is carried out. In particular, two different three-dimensional finite element procedures are adopted for comparative purposes against the experimental findings. The first procedure is a step-by-step incremental method based on a plasticity model for steel and a nonlinear stress-strain law for concrete in compression, while the post-failure behavior in tension is governed by a smeared-crack model. The second procedure is based on the limit analysis theory and permits one to simulate the limit state solution by carrying out simple elastic analyses in an iterative fashion. Comparison between numerical and experimental results is discussed and the main advantages and drawbacks of the two proposed numerical procedures are outlined.

1. Introduction

The use of recycled materials to develop sustainable construction materials represents a viable alternative to their landfilling, allowing considerable environmental impacts savings, especially in terms of natural bulk resources consumption. In this regard, promising results have been obtained recently using electric arc furnace (EAF) slag, as partial or total substitution of natural aggregates (NAs), to cast structural concretes [1–5]. This material is a by-product of steel production in electric arc furnace plants, where about 30% of the European carbon steel and low alloy steel production takes place. Such percentage increases until 70% in countries such as Italy and Spain, which alone contribute for about 30% of the overall European production. For each ton of EAF steel produced (20Mt/y in Europe), about 150–180 kg of EAF steel slag derive, thus representing a considerable quantity of material requiring an alternative valorization [6].

Existing research has mainly focused on the assessment of mechanical properties of cement-based materials including EAF slag, thus leading to an extensive available literature about EAF slag concretes. Particularly, previous studies demonstrated that the use of such slag as coarse aggregate improves concrete compressive and tensile strength, as well as the elastic properties [7–10]. Durability is also generally enhanced, even in aggressive environmental condition, i.e. under freezing/thawing cycles or

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chlorides exposure [11–14]. However, such performances depend to a large extent on slag characteristics, which are affected by the scrap composition inside the steel plant, by the steelmaking and slag cooling processes. Indeed, it is worth noting that mainly cooling rate and slag foaming phase influence not only the porosity of the slag, but also their grading, expansion potential, and mineralogical composition. Tests carried out on slag particles from various steelmaking plants highlighted how a controlled process is suitable for ensuring a good reproducibility of physical, chemical and mechanical characteristics of such material.

Even though mechanical properties of EAF slag concrete have been already sufficiently explored in literature, the knowledge about how this material performs in real scale structural elements is scarce. Kim et al. (2012) [15] studied the behavior of spirally-confined columns casted with EAF slag, to assess its influence on ductility and load capacity. They demonstrated that at least the same performance of similar specimens made with a reference concrete can be achieved if slag partially (or completely) substitutes coarse NAs. Instead, only one work (of some of the authors of this paper) dealt with the structural behavior of RC beams casted with EAF concrete, to study the ultimate capacity both due to bending and shear failure [16]. The structural behavior of EAF RC beams was analyzed in experimental terms only, and results demonstrate that the response of such elements was at least comparable to the reference one, realized with the same mix design, just substituting the aggregate type. More recently, also the response of exterior beam-column joints subject to cyclic lateral loading, and failing due to shear in the panel joint, was assessed in [17]. Hysteresis behavior, ultimate capacity, ductility, dissipated energy and local joint panel deformation of two real scale specimens, made with EAF concrete, were compared with a reference joint. A numerical study was also carried out to study the influencing parameters on the structural response of the joints [18], evidencing how the use of the slag allows improvement in the ultimate capacity of the tested elements.

1.1. Scope of the investigation and research significance

Along this research line, this paper aims to analyze, both from an experimental and numerical point of view, the ultimate capacity of eight real scale RC beams made with EAF concrete, failing due both to bending and shear, compared to four reference ones. Numerical models are useful to investigate the influence of EAF slag in full-scale RC elements, as well as to perform parametric analyses avoiding expensive and time-consuming laboratory tests. The experimental tests of the RC beams with EAF concrete, described also in [16], are recalled here for a proper comprehension of the numerical study, and they are integrated with further experimental results about materials mechanical properties, necessary for developing the numerical models. Indeed, since this study aims to numerically analyze the behavior of RC beams with EAF concrete for the first time in the literature, a detailed characterization of the materials employed to cast the structural elements is necessary. In particular, two concrete mixtures were used to cast twelve RC beams, four of them made with a conventional concrete, including only NAs, and the remaining realized with a mix with EAF slag as whole replacement of the coarse NAs.

Two different methods of analysis are proposed to numerically simulate the tested EAF RC beams. The first numerical procedure is a finite element (FE) step-by-step incremental method based on a plasticity model for steel and a nonlinear stress-strain law for concrete in compression, while the post-failure behavior in tension is governed by a smeared-crack model so as to capture the fracture onset and development with increasing load. A set of material parameters are needed to describe the actual post-elastic behavior in compression and the post-failure response for cracking in tension, such as the fracture energy, the shear retention factor, the amount of tension stiffening, etc. The definition of these parameters requires extensive experimental tests, which obviously results in high costs. For this reason, a second numerical procedure, based on the *limit analysis theory*, is also adopted in this paper to obtain an estimate of the collapse load in a direct manner [19–21]. The peculiarity of this limit analysis procedure is that the limit-state solution is obtained by solving a sequence of simple linear elastic FE analyses. Therefore, in contrast to the above incremental method, the set of material parameters needed is limited to the elastic properties and basic strength values of concrete and steel, with obvious benefits for the design engineer who does not have to perform extensive laboratory tests to characterize the constitutive parameters related to the post-elastic behavior. This procedure, already applied to other materials [22–24], is here for the first time rephrased to deal with EAF reinforced concrete.

While steel reinforcement bars (re-bars) are governed by the von Mises yield criterion to control yielding occurrence, the triaxial Menétrey–Willam failure surface, formulated in terms of the Haigh-Westergaard invariants in the principal stress space, is used for EAF concrete in both the numerical procedures. Therefore, despite the different underlying theoretical basis of the two procedures, the same failure surface is used for comparative purposes. Advantages and drawbacks, as well as potentialities and limitations of the two numerical procedures are outlined along with a detailed comparison against the experimental findings.

2. Experimental campaign

The experimental campaign belongs to an extensive research program aiming to find a viable solution for exploiting in a sustainable way metallurgical slag coming from EAF plant, where carbon steel is produced, and huge amount of slag are derived as by-products. The slag used here is produced from a steel facility sited close to Padova (North-East Italy), where liquid slag is discharged into a large pit, and the cooling method is realized through the deposit of successive slag layers, after their solidification. Several water jets are sprayed on the upper surface, thus allowing a slow cooling rate and, consequently, gases retained in the slag are able to escape, ensuring a low porosity material [4], as it will be shown in the next section. Then, the solid slag is stock-piled for a period ranging between two and three months, under outdoor weather conditions, in the slag management facility, just closed to the steel plant. After this period, slag is processed via screening, magnetic separation and crushing operations (both primary and secondary), and when the required aggregates grading is obtained, a last pre-treatment is carried out, to ensure particles dimensional stability. Such phase, realized immediately before EAF slag use, consists in outdoor weathering for about one week, in which drying and wetting conditions are alternated, allowing that free CaO hydroxylation reactions occur, limiting further expansive potential. Additionally, this last phase allows also the leaching of potential harmful compounds from the aggregates. The current employment of such slag is in bituminous mixes; however, further valorization routes are needed to be explored, because still huge amount of slag are landfilled.

2.1. Materials

EAF slag used in this work is subdivided in three grading fractions (cf. Fig. 1): class 1E, with particles size between 4 and 8 mm; class 2E, with size between 8 and 16 mm; and lastly, class 3E, with size between 16 and 22 mm. Concerning NAs, two coarse and one fine fractions are used: class 1 N has particles size between 4 and 16 mm; class 2 N with size between 16 and 31.5 mm; and lastly, class S (which stands for “sand”), with size between 0 and 4 mm. Their physical properties are listed together in Table 1: it is worth noting that EAF slag has a significantly higher apparent specific weight (evaluated macroscopically with the pycnometer test method), which represents almost the upper limit among the slag analyzed in the literature [25]. This is due principally to the high content of metallic iron, iron and manganese oxides (which have a density higher than 5000 kg/m^3), which compose the slag. Indeed, the composition of the slag, expressed in oxides weight percentage, can be summarized as follows: iron oxides (Fe_xO_y) 34%; CaO 28%; SiO_2 17%; Al_2O_3 11%; others (MgO, MnO, Cr_2O_3) 10%. Additionally, also the internal porosity of such aggregates is low, as a consequence of the slow cooling rate applied to the fresh slag. The results of a Mercury Intrusion Porosimetry (MIP) test on three representative slag samples, carried out with a Thermo Scientific Pascal Mercury porosimeter, demonstrate that the porosity ranges between 0.49% and 2.69%. The bulk density evaluated with this test method ranges between 3770 kg/m^3 and 4280 kg/m^3, being slightly higher than the one estimated with the pycnometer method. Concerning water absorption, the experimental results evidence that slag