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Cementing efficiency of electric arc furnace dust in mortars

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HIGHLIGHTS

- Electric arc furnace dust is used as *SCM* until 10% of replacement ratio.
- Cementing efficiency of EAFD is estimated for varying w/b ratios and dust content.
- Flexural and compressive strength were taken into account to asses EAFD *k*-value.
- EAFD efficiency depends also on curing time.

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ABSTRACT

The aim of this study is to evaluate the cementing efficiency (*k-value*) of an electric arc furnace dust (*EAFD*), used in as-received conditions, as a supplementary cementing material (*SCM*). The investigated variables are the amount of *EAFD* in the mix, water/binder ratio and curing age. Fifteen mixtures are manufactured to estimate the *k-values*, both considering compressive and flexural strength. In both cases, *k-values* depend on replacement percentage, and decrease raising the *EAFD* content in the mix. Water/binder ratio and hydration time significantly influence *EAFD* efficiency, too. Additionally, results show that flexural *k-values* are greater than compressive *k-values* in the analyzed mortars.

1. Introduction

Research about mineral additions, such as pozzolana, limestone, fly ash, silica fume and blast furnace slag as supplementary cementing materials (*SCMs*) has been transferred and implemented in several standards, which regulate the use of such materials in concrete [1,2]. The benefit of using blended cements, besides CO_2 emissions abatement and resources conservation, is that the additions improve certain properties, such as workability, strength development and durability [3]. Accordingly, time-variant structural reliability of aging reinforced concrete elements subject to environmental deterioration can also be improved [4].

In recent years, many studies attempted to develop new *SCMs*, aiming to solve environmental problems linked to the disposal of solid waste. The re-use in construction industry is seen as an attractive alternative to landfill, because it allows to encapsulate potential toxic elements in a stable matrix. This is the case of electric arc furnace dust (*EAFD*), a metal-rich waste formed during steel-making process in the electric arc furnaces. This solid waste has high density, and it is typically constituted by fine particles, with a heterogeneous distribution [5,6]. Apart from iron, *EAFD* contains high quantity of zinc [7,8], and in lower amount, also other heavy metals, e.g. cadmium, lead, and chromium [9–11]. Due to its chemical composition, many works studied already immobilization techniques of *EAFD* heavy metals [12], stabilization in cementitious matrixes [13,14] and leachability of harmful compounds [15,16].

EAFD has been treated and used in different ways, such as: source for the recovery of valuable metals [17–19], additive to ceramic industry [20,21], in asphalt cement [22], in geopolymers [23,24] and polymer composites [25], or addition to cement paste, mortar and concrete [26–30]. When *EAFD* is used in cement-based materials, two main effects on the blended paste are observed during the hydration. First, the dust reacts as a set retarder due to the

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presence of zinc oxide [26–32]; indeed, it is well-recognized that Zn^{2+} delays the early hydration of C_3S. Then, in a longer time, the hydration degree is promoted, due to several concurring causes, including the increase of pH and the presence of some metals, such as Cu^{2+}, Pb^{2+} and Cr^{3+}. The former allows calcium zincate dissolution, and the latter may ease C_3S hydration [33].

Some studies reported that replacing cement with *EAFD* until 5% does not worsen concrete or mortar mechanical strength [26,33,34]. However, when the substitution ratio raises up to 15%, a reduction of about 20% in compressive strength is noticed [34]. Furthermore, several works demonstrated how benefits could be obtained in terms of durability-related properties [9,11,28], and on slump retention [9], when *EAFD* is used in limited quantity.

The Abrams law, which was originally formulated for proportioning concretes with cement as the only binder, and valid also to design mortars [35], is not directly applicable to this new generation of concretes. This formula cannot directly capture the influence of chemical and mineral admixtures currently used to design concretes, which may influence mechanical strength, at the same level than water/cement (w/c) ratio does. If the total amount of binder, being cement plus the *SCM*, simply substitutes the amount of cement, the Abrams law provides an incorrect estimate of concrete compressive strength. This occurs because the cementing efficiency of alternative binders might be not the same as that of cement, and additionally it is influenced by different variables, e.g. curing conditions, hydration time, type of cement, strength grade and quantity of the admixture itself [36,37].

Many studies were carried out to quantify the so-called cementing efficiency, or k-value, for different types of mineral admixtures, to assess how they affect concrete compressive strength [38–44]. According to Papadakis and Tsimas [38], the k-value is defined as the part of *SCM* which can be considered as equivalent to Portland cement in a pozzolanic concrete, having the same properties under consideration. Hence, the efficiency factor corresponds to the number of parts of cement that may be replaced by one part of *SCM*, without changing the property under investigation (e.g. concrete compressive strength) [37]. The quantity of *SCM* can be multiplied by the k-value to estimate the equivalent cement content in the mixture, which should be added to the cement amount for calculating the w/c ratio. Obviously, if k is equal to 1, the *SCM* has the same efficiency as cement. It is worth to recall that the k-value can be applied to many properties, other than compressive strength. Indeed, many researchers have already derived k-values related to costs, durability, maturity, lime consumption and workability of *SCM*s [36,37,40–46]. Results demonstrated that, generally, the k-value resulting from compressive strength cannot be considered as a proxy-criterion for other properties, unless otherwise demonstrated. Mineral addition may have different effects on the above-mentioned properties, which should be separately analyzed.

Several research works investigated already cementing efficiency of fly ash, silica fume and blast furnace slag, used at varying dosages. However, no studies were carried out to assess *EAFD* k-value yet. Accordingly, in this research, the efficiency of an *EAFD,* used as *SCM,* on the strength of mortar mixtures is estimated. The analyzed variables are the amount of binder replacement ratio (5% and 10%), the water/binder (w/b) ratio (0.35, 0.4, 0.5, 0.6 and 0.7) and the curing age (7 and 28 days). In particular, k-values are evaluated considering both compressive and flexural strength, aiming to investigate whether compressive strength can be considered as a proxy criterion for flexural properties.

2. Background about cementing efficiency models for *SCMs*

The concept of the cementing efficiency factor, or k-value, was initially introduced by Smith in 1967 [47] for a fly ash concrete, defining that a mass of fly ash f can be considered as equivalent to a mass of cement $k{\cdot}f$, for its ability in influencing the strength development of the concrete. The rational model by Smith assumes that the strength and workability of two concretes with the same effective water/binder ratio, should be equal. In other words, if $w/(c + k{\cdot}f)$ in a fly ash concrete is equal to w/c of the reference mix, the two mixtures should have the same strength.

In general, the k-value approach is based on the assumption that a relationship exists between the tested property (typically, 28-days compressive strength) and a compositional parameter, which is the w/c ratio, if Abram's law [44] or Bolomey's equation [48] are considered for the reference Portland cement concrete. However, also other approaches could be applied, e.g. comparing the strength of two mixes with the same workability [49–51]. For instance, Schiessl and Hardtl [49] estimated the difference between the w/c ratio of a reference concrete, and the water/binder content $w/(c + k{\cdot}f)$ of a fly ash concrete, necessary to achieve the same strength, and named this as the Δw concept. Bijen and Van Selst [50] used the same mathematical approach of Smith, and they found that the k-value depends on w/c ratio, cement type, fly ash quality, and concrete age. They reported that the cementing efficiency value of fly ash tends to decrease, as the w/c ratio increases. This dependence was higher in rapid setting Portland cement than in Portland blast furnace slag cement. Lastly, Babu et al. [51] separated the efficiency factor into two parameters, the general efficiency factor k_e, and the percentage efficiency factor k_p. The k_e value is assumed constant for each *SCM*, whereas the k_p value depends on the amount of the *SCM* inside the mix. The *overall efficiency factor k* is calculated by multiplying these two factors. Babu used the Δw concept [49] to assess the efficiency of concretes with pozzolana [51], fly ash [39], silica fume [52] and ground granulated blast furnace slag [53]. Those studies revealed that the overall efficiency factor may change with type and amount of cement, age and concrete curing conditions. Hassaballah and Wenzel [54] proposed a method based on a comparison of the compressive strength between a fly ash concrete and a control, with the same workability. Fly ash contribution to compressive strength was calculated as the strength difference between the two mixtures, thus assessing the *pozzolanic efficiency factor*. According to this method, positive values of k indicate a strength increase, while negative values indicate a strength loss. Wong and Razak [41] used an alternative approach to determine the efficiency of calcined kaolin and silica fume, calculating k as $(R_s{\cdot}C - C'P)$. R_s is the relative compressive strength between the concrete with and without *SCM*; C is the cement quantity in the reference concrete; C' is the amount of cement in the *SCM* concrete; and lastly, P is the amount of the mineral addition.

3. Experimental program

3.1. Materials

The materials used to prepare the mortar mixes are: Portland cement; electric arc furnace dust (*EAFD*); sand; and tap water. The cement used is a rapid setting ordinary Portland cement type I 52.5R, as defined in BS-EN 197-1 [2], with a density of 3080 kg/m^3. *EAFD* is used in as-received condition from the dust collection system of a carbon steelmaking factory in Italy, and has a density of 3488 kg/m^3. The natural sand has a 2 mm maximum particles size, apparent density of 2.64 g/cm^3 and saturated surface-dried (s.s.d.) density of 2.76 g/cm^3.

Fig. 1 shows particles size distribution of cement, *EAFD* and sand, obtained using laser diffraction technique. *EAFD* has a wide range of particle sizes, with coarse particles having a diameter up to 478 μm. The characteristics of the distribution are: d_{10} equal to 2.57 μm; median particle size d_{50} of 10 μm and d_{90} is 67.58 μm. Cement is characterized instead by d_{10} = 1.35 μm, d_{50} = 10.68 μm and d_{90} = 32.75 μm, being finer than the *EAFD* used in this work. Fig. 2 shows instead a scanning electron microscope (SEM) image of *EAFD*, taken in the secondary electron mode; it is possible to observe the dust morphology, made by ultrafine, spherically shaped particles.

Table 1 shows the chemical composition of Portland cement and *EAFD*, obtained with X-ray Fluorescence (*XRF)* analyses. As it is possible to see, the composition of this dust is rich in *Zn*, *Fe* and *Ca* oxides, with few quantity of *Si*, *Mg*, *Mn*, *Pb* and *Cl*