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Electric arc furnace slags in cement-treated materials for road construction: Mechanical and durability properties

Federico Autelitano, Felice Giuliani *

Dipartimento di Ingegneria Civile, dell'Ambiente, del Territorio e Architettura-DICATeA, University of Parma, Parco Area delle Scienze, 181/A, 43124 Parma, Italy

HIGHLIGHTS

- The aged EAF slags represented suitable aggregates for CTMs.
- Increasing the EAF aggregates content, CTMs developed lower degree of compaction but higher ITS.
- CTMs containing only EAF aggregates showed poor durability performance.
- EAF aggregates partial replacement (30–60%) of natural aggregates produced suitable and durable CTMs.

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ABSTRACT

Electric arc furnace (EAF) slags are by-products of a widespread steelmaking process. The recycling of these materials as artificial aggregates in different road applications is a well established practice, which has allowed to reduce the consumption of natural resources and to minimize waste production and costs of landfilling. However, these aggregates are still underutilized in cement-treated materials (CTMs), which consist of mixtures of aggregates blended with small amounts of cement and water that harden after compaction to form a strong paving material. In the light of these considerations, different cement-treated materials, each containing different percentages of natural and artificial aggregates were analyzed. After a preliminary characterization of chemical, physical and durability properties of EAF slag aggregates, a mix design procedure based on both moisture-density approach (gyratory compactor) and mechanical testing (unconfined compression test and indirect tensile test) was performed to identify the optimum cement and water content of CTMs. The design mixtures were then subjected to 5 different accelerated aging procedures in order to study the influence of some factors (temperature, pressure and humidity) on the durability of the cement-treated materials. The results highlighted how the EAF slags represent suitable aggregates for cement-treated materials. The use of these aggregates produced a greater compaction difficulty, but guaranteed excellent mechanical performances, above all in terms of indirect tensile strength. The durability analysis demonstrated that the recycled mixtures showed a worse behavior than the reference one, composed only by limestone aggregates. However, if correctly designed, balancing the percentage of natural aggregate replacement, these mixtures could represent suitable and durable solution for base and sub-base pavement layers.

1. Introduction

Italy is the second country in Europe, after Germany, for the production of steel, with 23.7 million tons in 2014. With regard to the process, the production of electric arc furnace (EAF), which recycles mainly steel scraps, accounts for about 72.5% of the total (17.2 million tons). In this steel-making process about 150 kg of EAF slag per ton of steel are produced, leading to a total amount of more than 2.5 million tons every year [1]. The recycling of steel slags, as artificial aggregates, in concrete and cement industry or in road and geotechnical applications has progressively increased in recent years both in Italy and in all industrially-developed countries. This practice promotes a model of sustainable development, based on reducing the consumption of natural resources and on minimizing waste production and costs of landfilling [2–4].

In comparison to other recyclable materials, such as fly ash, bottom-ash, tire shreds, cement kiln dust or foundry sand, steel slags are underutilized [5]. In fact, many countries have limits and allowances on the use of EAF aggregates, due to their chemical

* Corresponding author.
E-mail address: felice.giuliani@unipr.it (F. Giuliani).

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composition. The presence of free expansive compound (CaO, MgO) in EAF slags mineralogy can have a deleterious impact on pavement volume stability, producing upheaval, swelling and accelerated deterioration [2,6,7]. In presence of water, free lime forms portlandite ($Ca(OH)_2$) and free magnesium oxide forms periclase ($Mg(OH)_2$), with an increase in solid volumes of about 90–130% for $Ca(OH)_2$ and 120% for $Mg(OH)_2$ [8,9]. In literature there are examples of steel slags stabilization techniques (exposure to weathering, use of additives, water quenching or spaying, high temperature steam treatment) for reducing their volumetric instability. Authors suggested a minimum aging period of 4–6 months to transform these expansive components into stable forms [6,7,10]. Moreover, the possible leaching of heavy-metals (Pb, Zn, Cu, As, Sb, Cd) can cause soil and groundwater pollution [11]. Studies were recently conducted to solve this environmental problem. Different laboratory treatments were developed to transform EAF slags into environmental friendly materials, characterized by very low hazardous polluting elements content [12].

With reference to road construction, EAF aggregates were successfully used due to their excellent mechanical characteristics. Some authors demonstrated satisfactory applications of EAF slags in non-structural pavement surface treatments using hot mix asphalt (HMA) mixtures [13–15] and warm mix asphalt (WMA) mixtures [16]. Others underlined also the outstanding performances exhibited by steel aggregates in road bases and subbases both in bound and unbound layers [17–19]. Nevertheless, EAF aggregates have seen relatively few road applications in cement bound mixtures, above all in cement-treated layers [20].

Generally, cement-treated material (CTM) consists of an intimate mixture of graded natural or crushed aggregates blended with measured amounts of cement (2%–4%) and water (4%–7%) that hardens after compaction to form a strong paving material [21,22]. The CTM needs proper mix design, adequate thickness, and diligent construction in order to obtain suitable fatigue strength and stiffness, which do not lead to shrinkage and thus cracking in the surface paving. A suitable stiffness of CTM can improve the fatigue resistance and reduce deflection, rutting and other asphalt strains, but can also avoid the sharp step of rigidity between the concrete slab and the subgrade [23]. Moreover, it represents a durable solution, because it is resistant to freeze-thaw and wetting-drying deterioration. Depending on project needs, CTM increases the construction speed, enhances the structural capacity of the pavement, or in some cases reduces the overall time project [24]. The physical and mechanical performances of CTM and the thickness of the layer are strongly affected by several factors, such as cement content, compaction characteristics, aggregate gradation and the quality of aggregates [25]. Too little cement can cause problems of homogenization of the mixture and provides insufficient structural capacity, allowing excessive pavement deflections under heavy traffic loading. Over-rich cement layers, besides being too expensive, are instead too stiff and prone to shrinkage cracking, causing accelerated pavement failure [24,26,27].

The requirements for CTM in different countries are generally expressed in terms of unconfined compressive strength (UCS) at 7-days curing time (Table 1) [25,27–29]. The required values strongly depend on the road class and material type relies heavily on the required UCS. The international requirements for CTMs suggest that the unconfined compressive strength test is performed on specimens compacted with Modified Proctor procedure (EN 13286-2: 2010), whereas Italian specification considers also the gyratory compaction (EN 12697-31:2007). The compressive strength, which depends on several factors (degree of compaction, shape of the specimen, curing time and condition), is a representative parameter of stability and stiffness of the cement-treated layer. However, especially for the cement-treated base beneath a bituminous pavement, the assessment of the mixture's fatigue behavior is more important and significant. Therefore, some countries, besides the UCS performance, recommend limits on the indirect tensile strength (ITS), in order to evaluate the fatigue strength of CTMs.

Table 1
Requirements (technical specifications) for CTMs in different countries.

Country	Cement content (%)	Requirement	
		UCS at 7-days curing time (MPa)	
Australia	3–8	>3	
Brazil	∼4	>3.5	
China	>4% (Road-mix method) >5% (Central-plant mixing)	>2 (Base) >4 (Subbase)	
Spain	3.5–6%	4.5–6	
UK	2–5%	2.5–4.5 (CM1) 4.5–7.5 (CM2)	
USA	3–10%	3.5–6.9 (under PCC) 5.2–6.9 (under HMA)	
		UCS at 7-days (MPa)	ITS at 7-days (MPa)
Italy	2–4%	2.5–5.5 (Gyratory compactor) 2.5–4.5 (Proctor hammer)	0.32–0.60 (Gyratory compactor) >0.25 (Proctor hammer)
South Africa	1.5–3% 3–5%	1.5–3.0 0.75–1.5	>0.25 >0.20
		UCS at 90-days (MPa)	TS* at 90-days (MPa)
France	2.5–4%	5–10	1

* TS = Tensile strength.

Cement-treated materials containing EAF aggregates, as complete or partial replacement of natural aggregates, exhibits elastic compressive and tensile strength values comparable or better than those of the natural CTMs. Moreover, these recycled mixtures represents economical base pavements, besides being a sustainable paving option, allowing a decreasing in layer thickness [20,30–31]. With regards to the durability of these mixtures, there are no references in literature. Few studies provided the evaluation of both mechanical properties and durability only on concrete containing EAF slag. Some of these studies have shown acceptable durability of concrete with EAF, thought slightly lower than the conventional concrete, despite rather aggressive test conditions and accelerated aging procedures (freezing and thawing cycles, wetting and drying cycles, swelling procedures, climatic chamber and high pressure aging) [32–36].

This experimental study planned to investigate the chemical and mineralogical composition, the concentration of pollutants and the physico-mechanical properties of EAF aggregates. Additionally, several cement-treated materials containing different replacements of EAF aggregates were prepared to characterize their mechanical and durability performances.

2. Materials and methods

2.1. Testing program

The testing program was divided in three main phases. The first step consisted in a preliminary characterization of chemical, physical and durability properties of EAF slag aggregates, following the requirements of EN 13242:2008 and the toxic characteristic leachability according to EN 12457-2:2007. Secondly a mix design procedure based on both moisture-density approach (gyratory compactor) and mechanical testing (unconfined compression test and indirect tensile test) was performed to identify the optimum cement and water content of CTMs. Finally, the design mixtures, characterized by the optimum cement and water content, were subjected to a detailed study about the influence of some factors (temperature, pressure and humidity) on the durability of the CTMs.