European Transport \ Trasporti Europei (2020) Issue 75, Paper n° 5, ISSN 1825-3997

The volume expansion of artificial road aggregates derived from steelmaking slags

Massimo Pisciotta

Politecnico di Bari - Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica

Abstract

The sustainability path that the steelworks has undertaken in recent years aims to enhance the value of slags derived from the production processes, transforming them into certified inert materials that can be used as artificial aggregates in various works of civil engineering. In the road construction sector, the use of artificial aggregates derived from electric arc furnace (EAF) slags is becoming a widespread practice both for unbound and bound mixtures, while the ladle furnace (LF) ones still play a marginal role and are more often used in the stabilization of clayey soils and as a substitute for lime. But, steel slags usually contain volumetrically unstable phases that makes them unsuitable for such purposes. Thus, the article analyzed the expansive behavior of EAF and LF artificial aggregates, both in the form of unbound granular mixes and cement-treated materials. The results showed that these materials represent with appropriate differences a new opportunity and alternative solution that have a potential use in the road sector, but must be properly pre-treated, especially when their application is expected in environments characterized by high moisture content and significant temperature changes.

Keywords: electric arc furnace, ladle furnace, road construction, swelling

1. Introduction

In the international context increasingly oriented towards the recycling and the reduction of natural resources consumption (Pisciotta 2018; Sherwood, 2001), the steelmaking industry represent one of the symbolic sectors in which the slags generated by the production processes are no longer considered as waste, but as by-products that can be reused in different civil engineering applications (Motz and Geiseler, 2001; Wang, 2016). These materials, depending on the production process, the type of raw material and the post-production treatments have quite different characteristics and compositions (Jiang et al., 2018). Specifically, two by-products of electric steelmaking can be included: electric arc furnace (EAF) slags to be distinguished and carefully separated, also from the point of view of management in the steelworks, from ladle furnace (LF) slags, which are instead produced in the ladle furnace during the secondary refining of steel. EAF slags can be assimilated to natural effusive rocks of volcanic origin and mainly consists of a ternary mixture of calcium oxide (CaO), silicon dioxide (SiO2) and iron oxides (FeO), to which are added, in smaller percentages, other components. LF slags contain instead higher concentrations of calcium oxide and lower content of iron oxides (Yildirim and Prezzi, 2011; Setién, 2009). In the road construction sector, the use of artificial aggregates derived from EAF slags is becoming a widespread practice both for unbound and bound mixtures (concrete, cement-treated materials and asphalts) (Autelitano and Giuliani, 2016; Kavussi et al., 2014; Pasetto et al., 2017), while the LF ones still play a marginal role and are more often used in the stabilization of clayey soils and as a substitute for lime (Manso et al., 2005; Skaf et al., 2016). But, the reuse of these slags as artificial products is primary subjected to the fulfilment of chemical requirements. In recent decades, thanks to the technological development, steelmakers have optimized the production processes to enhance the value of their slags, which today are very often compatible from the environmental point of view showing very limited leaching of heavy-metals to groundwater and soil, below the values set by law (Neuhold et al., 219). At the same time, the presence free calcium oxide and magnesium oxide, which are configured as expansive compounds, above specific limits can cause problems of volumetric instability and accelerated deterioration of the mixtures (Autelitano and Giuliani, 2015; Santamaria et al., 2018). The steel slag stabilization techniques (additives, water or steam spraying) or weathering treatments (slow cooling and exposition to atmospheric conditions) often allow to promote a natural process of hydration and carbonation, i.e. a stabilization of these oxides, but in some cases the swelling phenomenon remains, producing detrimental deferred effects to the road works (Juckes, 2003).

Thus, the article aims to analyze the expansive behavior of two types of artificial aggregates derived from the electric steelworks, i.e. EAF and LF slags, both in the form of unbound granular mixes and cement-treated materials

2. Material

Three different aggregates were selected for the experimental analysis. EAF and LF artificial materials and limestone aggregates, which served as reference. EAF slags derived from the metallurgical process of electric furnace smelting of ferrous and cast iron scrap with the contribution of heat in a basic environment; whereas LF slags were produced in the same steel mill during the secondary refining phase through the addition of lime (CaO) and dolomitic limestone (CaO·MgO). Both slags were "converted" in artificial aggregates after a multi-phase process of scorification, slow cooling, crushing, screening and aging, which consisted of open-air stockpiling for 4 months. The chemical composition of the artificial (EAF and LF) aggregates determined on the 0/32 fraction are reported in table1.

Table 1 - Physical properties of the selected artificial aggregates

Oxide	**EAF**	**LF**
Calcium oxide (CaO) (%)	25.51	49.10
Silicon dioxide (SiO_2) (%)	13.24	28.4
Magnesium oxide (MgO) (%)	1.13	9.70
Aluminum oxide (Al_2O_3) (%)	3.60	3.30
Chromium(III) oxide Cr2O_3 (%)	1.15	1.50
Iron(III) oxide Fe_2O_3 (%)	51.58	1.20
Manganese (II) oxide (MnO) (%)	2.55	0.63
Titanium dioxide (TiO_2) (%)	0.24	0.23
Phosphorus pentoxide (P_2O_5) (%)	0.35	-
Sulfur trioxide SO3	-	0.57
Density (kg/m^3)	3765	2851

3. Methods

The artificial aggregates volume expansion was determined on granular samples (16/32 mm), which were compacted through a vibrating table and exposed to a steam flow according to the EN 17744-1 standard. Moreover, the volumetric stability was assessed on cylindrical samples of cement-treated material prepared using the grain size distribution reported in table 2 following the modified Proctor procedure (EN 13286 2).

Table 2. Volumetric grain size distribution of the cement treated materials

	Sieve									
	32.0	25.4	19.0	16.0	8.0	5.0	2.0	0.425	0.125	0.063
Cumulative Passing (%)	100.00	100.00	84.00	69.00	49.40	39.00	23.50	13.60	7.90	4.75

Specifically, for the reference and EAF aggregates 3% cement (CEM II/A-LL 42.5R) and 6% water, expressed in volume, were used, whereas for the LF aggregate the samples were prepared without the addition of cement and with 10% water, which represented the optimal moisture content obtained downstream of Proctor compaction tests. Initially, volumetric changes were evaluated at the end of a canonical 28-day curing period (T=22 °C; RH=55%). Indirect tensile strength (EN 13286-42) was also evaluated on these specimens to estimate the cementitious property the ladle slag. The cured samples were then subjected to two accelerated aging cycling tests: wet&dry and freeze&thaw. The former involved 21 daily cycles of water immersion (16 h@22 °C) and oven drying (8 h@10 °C), while the latter implicated 21 daily cycles of freezing (16 h@-18 °C) and thawing (8 h@4 °C). The volume of samples was re-evaluated at the end of these procedures. All the volumetric variations were calculated as the average values measured on three independent samples for each mixture.

4. Results

The analysis of the steam test results provided several foods for thought. Although the weathering period of about 6 months, both EAF and LF aggregates showed a non-negligible volume expansion. However, the artificial aggregates exhibited very different swelling trends. EAFS showed a sharp volume increase in the first hours, reaching after about 24 h a peak (0.12%) which remained constant over time. The volume increase occurred in LFS at slower rate, but tended to grow almost linearly with the exposition time: the volumetric stability was not even reached after 336 h (14 days), period after which the volumetric expansion was no longer monitored. It should be noted that these expansion values are lower than those required by EN 13242, even if evaluated on a coarse fraction which is characterized by a high voids content and consequently is less prone to this phenomenon.

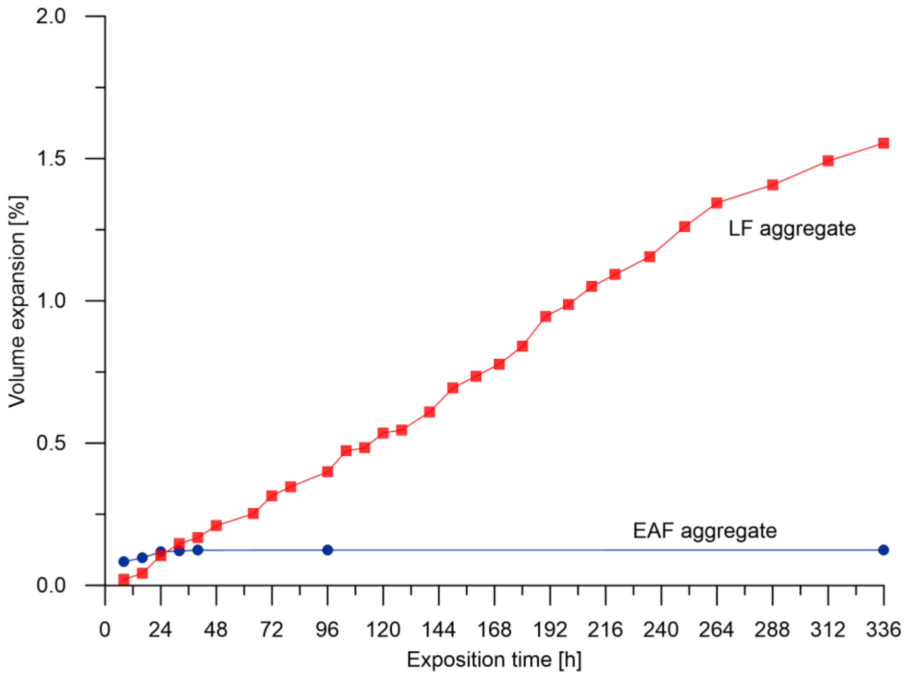

Figure 1. Volume expansion of artificial aggregates vs exposition time (steam test)

The volumetric stability evaluation carried out on the cement-treated materials and LF mixtures have confirmed the same behavior (Tab. 3). The volumetric expansion shown by the samples containing LF aggregates was always very marked and almost double that those recorded by EAF cement-treated materials, already after the curing time. The freeze&thaw test made the expansive phenomenon very evident for both the artificial aggregates.

Table 3. Volume variation of cement-treated materials and LF mixtures after curing and accelerated aging tests

Mixture	Volume variation (%)		
	Curing	Wet&dry	freeze&thaw
Limestone	-0.08	0.29	1.04
EAF	0.43	0.78	3.58
LF	0.63	1.37	6.32

As far as the mechanical resistance values are concerned, the ITS values are rather high (0.58 MPa) as far as the black slag is concerned, at the upper limit compared to what is required for mixtures cemented for road use, while those relating to white slag (without cement) have reached decidedly low values of about 0.12 MPa, even if compared to those of the reference mixture (0.31 MPa). This last value testifies a little cementitious property of ladle slag, which cannot be use as Portland cement replacement but only in a blended mixture.

5. Conclusions

The sustainability path that the steelworks has undertaken in recent years aims to enhance the value of slags derived from the production processes, transforming them into certified inert materials that can be used as artificial aggregates in various works of civil engineering, especially in the road sector. However, steel slags usually contain volumetrically unstable phases that makes them unsuitable for such purposes. The results of the experimental investigation showed that the post-processing treatments and the atmospheric weathering carried out on the slags have proved to be adequate pretreatments to inert the aggregates, especially with regard to the EAF products. The

LF artificial aggregates showed instead a rather marked expansive behavior, even if with values below those required by law. The same swelling trend was also found in bound mixtures, in which the expansion rates recorded by mixtures containing LF aggregates were significantly higher than those of EAF ones, especially following the accelerated ageing tests. In conclusion, these materials represent with appropriate differences a new opportunity and alternative solution that have a potential use in the road sector, but must be properly pre-treated, especially when their application is expected in environments characterized by high moisture content and significant temperature changes.

References

Autelitano, F., Giuliani, F. (2015) “Swelling behavior of electric arc furnace aggregates for unbound granular mixtures in road construction” *International Journal of Pavement Research and Technology*, 8(2), pp. 103-111.

Autelitano, F, Giuliani, F. (2016) “Electric arc furnace slags in cement-treated materials for road construction: Mechanical and durability properties” *Construction and Building Materials*, 113, pp. 280-289.

Jiang, Y., Ling, T.-C., Shi, C., Pan, S.-Y. (2018). “Characteristics of steel slags and their use in cement and concrete-A review” Resources, Conservation and Recycling, 136, pp. 187-197.

Juckes, L. M. (2013) “The volume stability of modern steelmaking slags” *Mineral Processing and Extractive Metallurgy. Transactions of the Institutions of Mining and Metallurgy: Section C*, 112(3), pp. 177-197.

Kavussi, A., Qazizadeh, M.J. (2014). “Fatigue characterization of asphalt mixes containing electric arc furnace (EAF) steel slag subjected to long term aging” *Construction and Building Materials*, 72, pp.158-166.

Manso, J.M.' Losañez, M., Polanco, J.A., Gonzalez, J.J. (2005). “Ladle furnace slag in construction” Journal of Materials in Civil Engineering, 17(5), pp. 513-518.

Motz, H., Geiseler, J. (2001) “Products of steel slags an opportunity to save natural resources” *Waste Management*,21(3), pp. 285-293.

Neuhold, S., van Zomeren, A., Dijkstra, J.J., van der Sloot, H.A., Drissen, P., Algermissen, D., Mudersbach, D., Schüler, S., Griessacher, T., Raith, J.G., Pomberger, R., Vollprecht, D. (2019) “Investigation of possible leaching control mechanisms for chromium and vanadium in electric arc furnace (EAF) slags using combined experimental and modeling approaches” *Minerals*, 9(9), Article number 525.

Pasetto, M., Baliello, A., Giacomello, G., Pasquini, E. (2017) “Sustainable solutions for road pavements: A multi-scale characterization of warm mix asphalts containing steel slags” *Journal of Cleaner Production*, 166, pp. 835-843.

Pisciotta, M. (2018) “The use of non-conventional fillers in asphalt mixtures for wearing course” *European Transport - Trasporti Europei*, 70, Paper n° 5.

Santamaria, A. Faleschini, F., Giacomello, G., Brunelli, San José, J.-T., Pellegrino, C., Pasetto, M. (2018) “Dimensional stability of electric arc furnace slag in civil engineering applications” *Journal of Cleaner Production*, 205, pp. 599-609.

Setién, J., Hernández, D., González, J.J. (2009) "Characterization of ladle furnace basic slag for use as a construction material” *Construction and Building Materials*, 23, pp. 1788-1794.

Sherwood, P.T. (2001) Alternative materials in road construction: A guide to the use of recycled and secondary aggregates, Thomas Telford, London.

Skaf, M., Ortega-López, V., Fuente-Alonso, J.A., Santamaría, A., Manso, J.M. (2016) “Ladle furnace slag in asphalt mixes” *Construction and Building Materials*, 122, pp. 488-495.

Wang, G.C. (2016). The utilization of slag in civil Infrastructure construction. Woodhead Publishing, Duxford.

Yildirim, I.Z., Prezzi, M. (2011) “Chemical, mineralogical, and morphological properties of steel slag” *Advances in Civil Engineering*, 2011, pp. 1-13.