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Swelling Behavior of Electric Arc Furnace Aggregates for Unbound Granular Mixtures in Road Construction

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Abstract: Artificial aggregates, which result from the treatment of electric arc furnace slags (EAF aggregates), represent a very interesting technological solution to replace natural aggregates in different road construction applications. In spite of excellent mechanical properties, the swelling nature of some expansive compounds present in their mineralogy could be detrimental to volumetric stability of civil works. In light of these considerations, the main objective of this research was to analyze the volume stability of different unbound granular mixtures composed by EAF aggregates (aged and fresh) through two accelerated swelling procedures: water-bath swelling test (ASTM D4792/D4792M-13) and steam test (EN 1744-1).

The results demonstrated how the expansive developmental process follows, in general, three different progressive phases. Both expansion development and final swelling extent were a function of preliminary exposition to aging treatment and different physical factors, such as particle size, grain size distribution, and degree of compaction. The expansive behavior was more evident for fresh slag aggregates, which did not undergo any type of stabilization procedure. Specifically, the residual voids content, which is in close correlation with the degree of compaction, can be considered the main factor affecting swelling ratio. All specimens analyzed, however, showed appropriate expansion values according to ASTM and EN standard requirements.

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***Key words**: EAF aggregates; Swelling; Unbound mixtures.*

Introduction

The demand for high quality aggregates for road construction has progressively increased in recent years. However, most of these aggregates are natural, which are usually supplied from alluvial deposits and quarries. Environmental concerns have led to research on the development of new materials and new technologies, deriving from the reuse of waste and by-products, to safeguard the available natural resources and reduce the environmental impact of building materials. In this context, the use of artificial aggregates, resulting from the treatment of electric arc furnace slags (EAF slags), represents a very interesting technological solution for civil engineering applications [1, 2].

EAF slags are a by-product of the steel-making process. They are obtained by a treatment process based on controlled solidification and subsequent crushing of slags from scrap melting in the electric arc furnace. After every crushing step, magnetic belts extracted the newly freed iron particles and the slags were screened in different grain sizes, becoming artificial aggregates.

Several researchers focused their attention on the possible use of steel slag aggregates as substitutes of natural aggregates in the concrete industry. In particular, the results of these studies showed that the addition of EAF aggregates did not negatively affect the physico-mechanical properties and the durability of the produced concrete [3-7], ensuring an improvement in the fire resistance of the concrete mixture [8, 9].

EAF aggregates were also successfully used in road construction due to their excellent mechanical characteristics. Some authors noted the excellent performances exhibited by steel aggregates in road bases and sub-bases both in bound and unbound layers [10-13]. Others also demonstrated satisfactory application of EAF slags in surface layers of road pavements using hot mix asphalt (HMA) mixture [14-19] and warm mix asphalt (WMA) mixture [20]. Specifically, the pavements incorporating steel slag aggregates showed excellent engineering properties, such as high skid and rutting resistance, high Marshall stability, and low abrasion susceptibility.

However, the chemical composition of steel slags, which depends significantly on the properties of the recycled steel, have limited their potential use as construction material in road applications. Typically, the main chemical constituents of EAF slags are FeO (22-60%), CaO (6-48%), SiO_2 (9-32%), Al_2O_3 (3-14%) and MgO (3-15%) [21].

On the one hand, the possible leaching of heavy-metals (Pb, Zn, Cu, As, Sb, Cd) can cause soil and groundwater pollution [22-26]. 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 [27, 28].

On the other hand, the presence of free expansive compound (CaO, MgO) in EAF slags mineralogy can have an adverse impact on pavement volume stability, producing upheaval, cracking, and accelerated deterioration [29, 30]. In the presence of water, free lime forms portlandite ($Ca(OH)_2$) and magnesium oxide forms periclase ($Mg(OH)_2$). The increases in solid volumes in this topochemical reaction are about 90-130% for $Ca(OH)_2$ and 120% for $Mg(OH)_2$ [31, 32]. The technical literature generally agrees that free lime

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hydrates rapidly (weeks), while magnesium oxide takes months or years to develop significant expansion [21, 33, 34]. Besides the chemical composition, there are several factors that determine the swelling characteristics of steel slags. Gradation, degree of compaction, confinement and other environmental conditions (access to water, temperature and pressure) also play an important role in their expansion potential [12, 21].

In order to assess the potential expansion of steel slags, several swelling test methods have been developed. These test methods can be grouped into long-term swelling tests (ASTM D1883) and accelerated swelling tests (ASTM D4792, ASTM C151-05 and EN 1744-1). The values obtained from laboratory testing are not directly indicative of those expected in the field [35, EN 1744-1].

In literature there are also examples of steel slag stabilization techniques for reducing their volumetric instability [36]. These techniques include using additives, water quenching or spaying, high temperature steam treatment and aging. Aging or weathering treatments refer to slowly cooling and open-air stock piling under atmospheric conditions of steel slag to provide adequate exposure to moisture, which allows the correct hydration of free calcium and magnesium oxides [21]. Authors suggested a minimum aging period of 4-6 months for EAF slag aggregates used in road construction, for both bound and unbound applications [12, 17, 18, 37].

Experimental

After a preliminary characterization of chemical and physico-mechanical properties of EAF slags was evaluated, the volume stability of different unbound granular mixtures composed by EAF aggregates, in different experimental conditions, was measured by means of two accelerated swelling procedures: water-bath swelling test (ASTM D4792/D4792M-13) and steam test (EN 1744-1).

Material Characterization

Two different aggregate types were selected for the experimental analysis: electric arc furnace aggregates and limestone aggregates. Steel aggregates were supplied by a steel mill operating in northern Italy; crushed limestone was supplied by a quarry near the steelmaking mill.

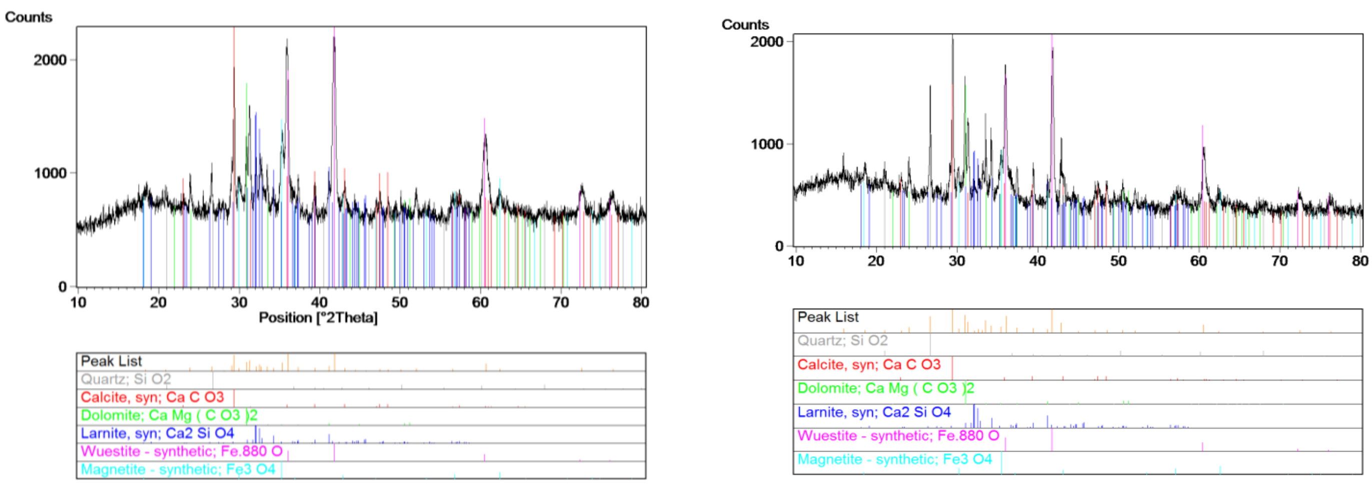
EAF aggregates were industrial by-products resulting from the manufacturing process for steel bars used for building construction. They were obtained by a separation process (scorification) of the cast steel from impurities present in the electric arc furnace. After the black steel slag was slowly cooled, the material was stockpiled for metal recovery and crushed in three suitable grain sizes for civil engineering applications (0/14 mm, 14/20 mm and 20/32 mm). A preliminary selection of vehicle scrap and wreck metal permitted generation of EAF aggregates characterized by similar mineralogy composition. In particular, two types of EAF aggregates were considered: fresh and aged. Only aged EAF aggregates underwent an oxidation phase, by exposure to weathering over 6 months, to allow the free lime (CaO) and free magnesium oxide (MgO) to be transformed into stable forms.

The oxide composition of aged EAF aggregates was determined using X-ray fluorescence (XRF). Table 1 shows that the major chemical components of EAF aggregates were CaO, SiO_2, Al_2O_3, MgO, FeO and MnO, which together represent more than the 90% of the total weight.

Table 1. Oxide Composition of Aged EAF Aggregates.

Parameter	Value	Literature Values
Calcium Oxide (CaO) (%)	21.79	6-48
Silicon Dioxide (SiO_2) (%)	8.77	9-32
Aluminium Oxide (Al_2O_3) (%)	7.37	3-14
Magnesium Oxide (MgO) (%)	2.15	3-15
Iron Oxide (FeO) (%)	42.99	21-48
Manganese(II) Oxide (MnO) (%)	3.80	1-16
Titanium Dioxide (TiO_2) (%)	0.25	0-1
Phosphorus Pentoxide (P_2O_5) (%)	0.33	0-2
Chromium(III) Oxide (Cr_2O_5)(%)	1.19	0-2
Sulfur (S) (%)	0.21	-
Chromium (Cr) (%)	0.84	-

The mineralogical properties of EAF aggregates were investigated using a X-ray diffraction analysis (XRD). Both fresh and aged EAF aggregate samples showed very similar and complex



(a) (b)

Fig. 1. X-ray Diffraction Patterns for (a) Fresh EAF Aggregate and (b) Aged EAF Aggregate.

Table 2. Concentrations of Pollutants in the Leachate (EN 12457-2:2004).

Parameter	Value	Ministerial Decree 06/186 Limit Value
Nitrates (NO_3) (mg L^{-1})	< 1	50
Fluorides (F) (mg L^{-1})	< 0.1	1.5
Sulphates (SO_4) (mg L^{-1})	2.9	250
Chlorides (Cl) (mg L^{-1})	1	100
Cyanide (CN) (μg L^{-1})	< 10	50
Barium (Ba) (mg L^{-1})	0.33	1
Copper (Cu) (mg L^{-1})	< 0.01	0.05
Zinc (Zn) (mg L^{-1})	< 0.01	3
Beryllium (Be) (μg L^{-1})	< 5	10
Cobalt (Co) (μg L^{-1})	< 10	250
Nickel (Ni) (μg L^{-1})	< 5	10
Vanadium (V) (μg L^{-1})	96	250
Arsenic (As) (μg L^{-1})	< 10	50
Cadmium (Cd) (μg L^{-1})	< 3	5
Chromium (Cr) (μg L^{-1})	< 10	50
Lead (Pb) (μg L^{-1})	< 10	50
Selenium (Se) (μg L^{-1})	< 5	10
Mercury (Hg) (μg L^{-1})	< 0.1	1
Asbestos (μg L^{-1})	n.r.	30
DOC (mg L^{-1})	4	30
pH	11.4	5.5 - 12.0

XRD patterns, with several overlapping peaks due to the presence of several crystalline phase in material (Fig. 1). The mineral phases were identified according to the intensity of the peaks, which gave an indication of the quantity of the mineral present in the sample. The major mineral phases were calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and wüstite ($Fe_{.880}O$), while minor phases included larnite (Ca_2SiO_4), magnetite (Fe_3O_4) and quartz (SiO_2).

Toxic characteristic leachability procedure (TCLP) analysis, according to EN 12457-2:2004, was performed on aged EAF aggregates to assess their leaching properties. In Italy, the recovery of non-hazardous wastes, such as steel slags, is regulated by the Legislative Decree 2006/152, amended and supplemented by Legislative Decree 2008/04. Table 2 provides the results of the TCLP analysis compared to the leachate concentration limit values defined by the Italian Ministerial Decree 186/2006.

The engineering properties (physico-mechanical properties) of aged EAF and limestone aggregates are reported in Table 3, whereas Table 4 reports the chemical properties of aged EAF aggregates. All the aggregates met physical, chemical, and durability requirements of EN 13242:2013 (Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction). Regarding the geometrical requirements, the EAF slag aggregates showed a polyhedral and angular shape. The excellent toughness, abrasion and polishing resistance, the limited ice sensitivity, and the small imbibition coefficient characterized this material. Due to the presence of high iron oxide contents, EAF aggregates have specific gravity values (38.11-39.22 kN m^{-3}) larger than those of natural aggregates, such as limestone (28.54 kN m^{-3}).

Samples Preparation

The laboratory tests were performed on samples which were manufactured using both single-sized aggregates (5 monogranular fractions: 5/8, 8/16, 16/19, 19/25.4 mm) and mixtures according to two different types of grain-size distribution curve. The mixtures were combined in accordance with Fuller parabola [38] or Italian government-owned road company corporation (ANAS) specifications for granular mixtures (Fig. 2).

The samples were prepared with limestone (L), fresh EAF aggregates (F), and aged EAF aggregates (A), and were compacted according to modified Proctor procedure (EN 13286-2: 2010) with 4.5 kg hammer B in the large Proctor mold B or through vibrating

Table 3. Physical and Durability Properties of Aged EAF and Limestone Aggregates.

Test	Standard EN	EAF 0/8 mm	EAF 8/16 mm	EAF 16/32 mm	Limestone 0/32 mm
Flakiness Index (%)	EN 933-3:2012	9.24 (FI_{20})	13.07 (FI_{20})	11.50 (FI_{20})	10.67 (FI_{20})
Shape Index (%)	EN 933-4:2008	7.62 (SI_{20})	7.67 (SI_{20})	7.63 (SI_{20})	7.02(SI_{20})
Los Angeles Coefficient (%)	EN 1097-2:2010	15.10 (LA_{20})	13.00 (LA_{20})	12.44 (LA_{20})	23.1(LA_{25})
Micro-Deval Coefficient (%)	EN 1097-1:2011	6.3 ($M_{DE}15$)	6.1 ($M_{DE}15$)	7.0 ($M_{DE}15$)	13.8 ($M_{DE}15$)
Polished Stone Value (%)	EN 1097-8:2009	-	52.9	61.1	48
Water Absorption (%)	EN 1097-6:2013	0.63 ($WA_{24}1$)	0.60 ($WA_{24}1$)	0.59 ($WA_{24}1$)	0.47($WA_{24}1$)
Freezing and Thawing Resistance (%)	EN: 1367-1:2007	3.30 (F_4)	2.30 (F_4)	2.14 (F_3)	1.16(F_1)
Sand Equivalent Test (%)	EN 933-8:2012	77	-	-	68
Specific Gravity (kN m^{-3})	EN 1097-6:2013	39.62	38.57	38.11	28.54

The initials in ( ) are the category for each parameter described in EN 13242:2013.

Table 4. Chemical Properties of EAF Steel Slag Aggregates.

Test	Standard EN	Value	EN 13242:2013 Category
Water-soluble Chloride Salts (Mohr method) (% by Mass)	EN 1744-1:2013	0.002	-
Acid Soluble Sulfates (% by Mass)	EN 1744-1:2013	0.586	$AS_{0,8}$
Total Sulfur Content (% by Mass)	EN 1744-1:2013	0.108	S_1
Water Soluble-sulfates	EN 1744-1:2013	0.543	$SS_{0,7}$

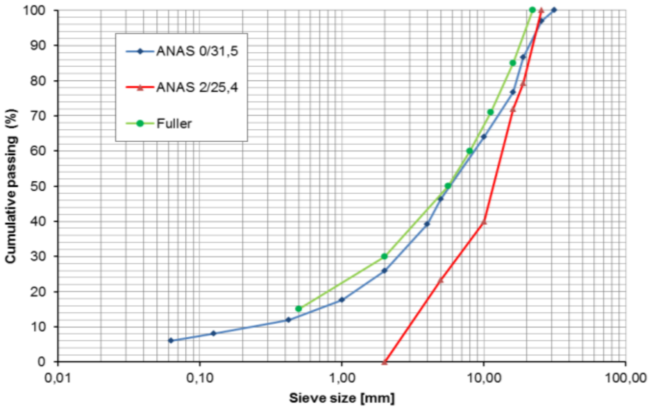


Fig. 2. Grain Size Distribution Curves of Steel Slag Samples: ANAS (0/31.5), ANAS (2/25.4) and Fuller.

table at frequency of 48 ± 3 Hz (EN 1744-1:2013). The optimum moisture content (w_{opt}) and maximum dry unit weight (γ_d) of EAF aggregate samples were in the ranges of 5.75-6.73% and 21.57.8-22.6 kN m^{-3}, respectively. A total of 18 series, each of which was composed of three independent samples, were considered (Table 5). The F_30*P samples was composed of 30% fresh EAF aggregates (16/31.5 mm) and 70% limestone (0/16 mm), while the F_60*P was composed of 60% fresh EAF aggregates (5/31.5 mm) and 40% of limestone (0/5 mm).

The necessity to study an assortment of aggregates with different mineralogical nature and specific gravity required a volumetric approach in the mix design of the mixture.

Test Methods

In order to verify the effective use of EAF slag in road applications, two accelerated swelling test methods were developed in this research program. In these procedures, compacted specimens in cylindrical molds are soaked into hot water (ASTM D4792/D4792M-13) or exposed to steam (UNI EN 1744-1:2013) to accelerate the hydration reaction. The swelling rate, monitored for a shorter period of time, is calculated from measurements of the vertical expansion of laterally constrained samples. Swelling tests were performed on both fresh and aged EAF slag samples with different gradations to evaluate the effects of aging and particle size on the accelerated expansion.

Water-bath Swelling Test

EAF samples were initially compacted according to EN 13286-2:2010 with 4.5 kg hammer B in large Proctor molds (type B) at their optimum moisture content. Each sample was then flipped onto the mold’s perforated base plate and loaded down with two weights producing a surcharge of 4.54 kg. The molds were completely immersed in a water bath maintained at 70 ± 3°C for 7 days. In order to assure that both surfaces of each sample had free access to water, spacer blocks were placed at the bottom of the plastic soaking container (Fig. 3).

After soaking the molds in hot water for 30 min, the time necessary for thermal expansion of the apparatus, the base reading values were measured by a dial gauge placed on the collar of each mold using a specific support (tripod). The rate of swelling was calculated from each day’s measurements, which were taken every 60 min, by dividing the difference between the daily dial gauge reading and the base reading by the initial specimen height and multiplying by 100. The final expansion value considered for each type of mixture was the mean of three independent specimens.

ASTM D2940 (Standard specification for graded aggregate

Table 5. Samples Experimental Configuration.

Test	Series	Composition	Grain-size Distribution (mm)	Compaction	Voids Content (%)
Water-bath	A1P*	Aged EAF	ANAS (0/31.5)	Proctor	22.97
	A1’P*	Aged EAF	ANAS (0/31.5)	Proctor	23.76
	F1P*	Fresh EAF	ANAS (0/31.5)	Proctor	19.97
Water-bath (No Surcharge)	F_30*P	30% Fresh EAF 70% Limestone	ANAS (0/31.5)	Proctor	20.52
	F_60*P	60% Fresh EAF 40% Limestone	ANAS (0/31.5)	Proctor	20.61
Steam	A1P	Aged EAF	ANAS (2/25.4)	Proctor	35.64
	A1V	Aged EAF	ANAS (2/25.4)	Vibrating Table	40.56
	A2P	Aged EAF	Fuller (0/22)	Proctor	27.51
	A2V	Aged EAF	Fuller (0/22)	Vibrating Table	37.40
	A5/8V	Aged EAF	5/8	Vibrating Table	45.43
	A8/16V	Aged EAF	8/16	Vibrating Table	40.12
	A8/16P	Aged EAF	8/16	Proctor	36.88
	A16/19V	Aged EAF	16/19	Vibrating Table	46.30
	A19/25.4V	Aged EAF	19/25.4	Vibrating Table	45.43
	F1P	Fresh EAF	ANAS (2/25.4)	Proctor	32.09
	F1V	Fresh EAF	ANAS (2/25.4)	Vibrating Table	43.78
	F2P	Fresh EAF	Fuller (0/22)	Proctor	27.61
	F2V	Fresh EAF	Fuller (0/22)	Vibrating table	36.79

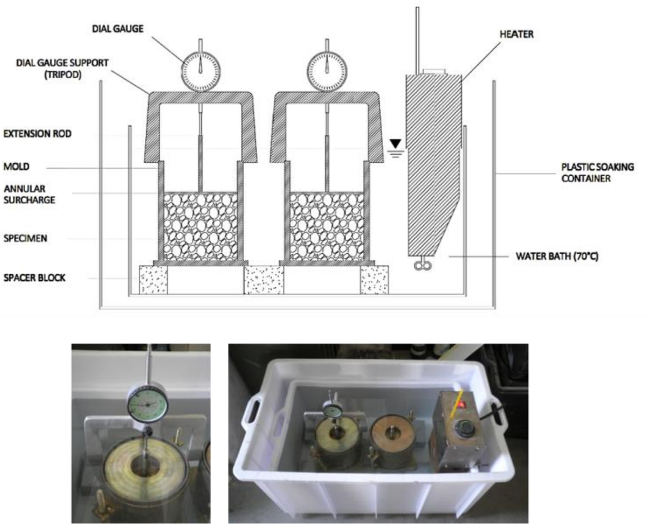


Fig. 3. Experimental Equipment for Water-bath Swelling Test (ASTM D4792/D4792M-13).

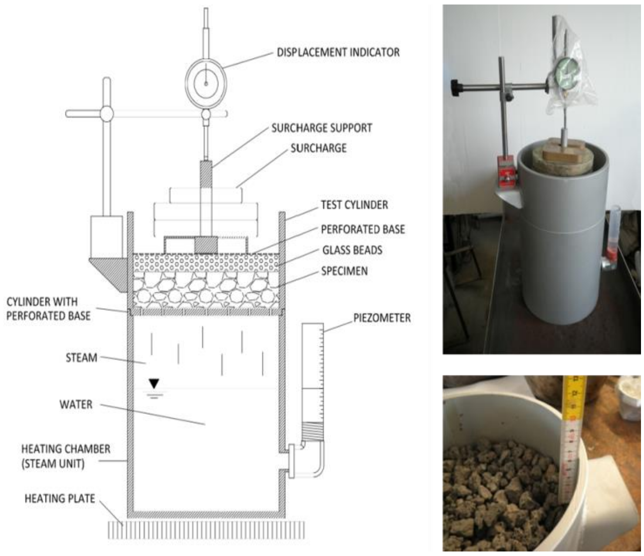


Fig. 4. Experimental Equipment for System test (EN 1744-1).

material for bases or subbases for highways or airport) considers suitable aggregates for pavement applications those which exhibit expansion values not greater than 0.50% at seven days when tested in accordance with test method D4792/D4792M-13.

European Steam Test

In the steam test, a bottom-up flow of steam at a temperature of about 100℃ is applied to a compacted sample in a steam chamber. In order to reproduce this experimental procedure, a suitable prototype was designed on the basis of the prescriptions provided by EN 1744-1 (Fig. 4).

The equipment consisted of a main body characterized by two parts. A cylindrical steam unit with a volume of 18 l, in which water is heated up to boiling point, was placed on a heating plate to maintain the correct temperature. An external piezometer was used to control the water level and to add hot water to compensate losses due to evaporation. Above the heating chamber was the test cylinder with a perforated base (h = 123 mm; Ø_{int} = 210 mm), necessary to steam transmission, in which the sample was placed. The displacement indicator (dial gauge), which registers the volume expansion, was placed, using a specific system of support, on the collar of the mold.

Each sample was dynamically compacted on the vibrating table for 6 min at frequency of 48 ± 3 Hz applying a static load of 8.67 kg. Alternatively, the sample was compacted by Proctor hammer, according to EN 13286-2:2010 (hammer (B) and mold (B)). The specimen was then covered with a layer of glass beads (Ø = 5 mm), which have been lubricated with silicone oil to reduce internal friction, to evenly distribute the loads. Annular surcharge weights (total mass of 6.51 kg) were placed on a perforated plate.

The procedure lasted 7 days (168 h), with daily switch on/off (10h/14h) steam cycles. After a start-up period of 30 min necessary for thermal expansion of the apparatus, dial gauge measurements began at intervals of 60 min (15 min in the first 4 h). The increase of volume was calculated in % volume in relation to the original volume of the compressed sample. The expansion of each type of mixture was evaluated considering the mean value of three independent specimens.

Table 6. Maximum Expansion Values for Steel Slag Aggregates (EN 13242:2013).

Maximum Expansion (% by Volume)	Category
< 5	V_5
< 7.5	$V_{7.5}$
< 10	V_{10}
>10	V_D

Steel slag aggregates can be categorized into four main groups (from V_5 to V_D) according to EN 13242:2013, based on the percent expansion obtained with the steam test (Table 6). Based on the German experience, steel slag aggregates are suitable for unbound layers and asphalt layers if they satisfy the requirements of group V_5 (maximum expansion < 5%) [1, 21].

Results and Discussions

The analysis of the different kind of EAF mixtures expansion curves in different experimental conditions provided a preliminary description of the swelling process. Volumetric expansion increased following an ideal succession of three different progression stages. Fig. 5 shows a first line (primary phase), which can be considered linear as a first approximation, and a second line (secondary phase), characterized by a gradual slope reduction. The secondary expansion ended in a third region in which the expansion phenomenon can be considered completed. The tertiary phase is described by a horizontal line. In this study, the increase in swelling ratio for EAF aggregates was observed only for few days (36-72 h).

It's credible to attribute these expansions (primary and secondary phases) to the expansive reactions of free CaO and MgO, with slightly different kinetics. In fact, hydration rate of CaO is relatively faster than the hydration rate of MgO. It takes only weeks for CaO minerals to complete their hydration process while it takes years for MgO minerals [21, 33, 34]. Moreover, it can be speculated that the low content of MgO minerals (2.15%) could be the main reason for

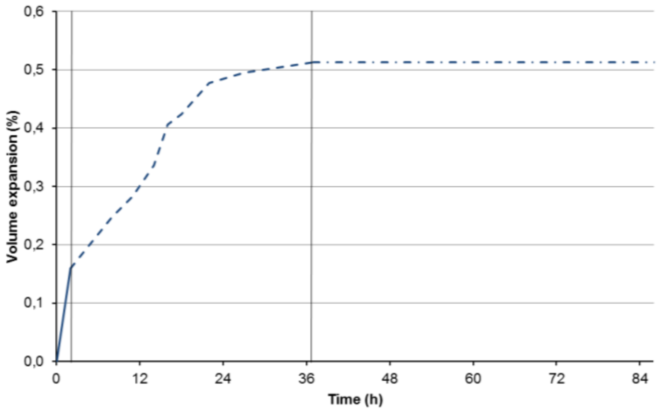


Fig. 5. F1P Series Progression of Volume Expansion Phases (European Steam Test).

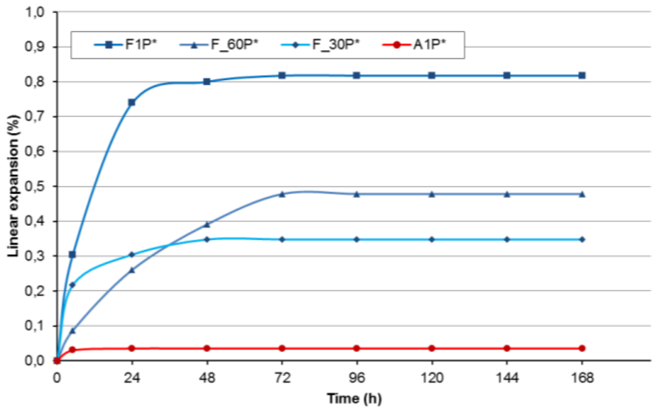


Fig. 6. Rate of Linear Expansion During Water-bath Test (ASTM D4792/D4792M-12).

achieving volumetric stabilization in few days.

Each type of expansion test provides a different maximum expansion value for the same steel slag. The limiting value of expansion for specific applications reported in standard specification depends on the type of swelling test performed. Hence, the analysis of swelling behavior was performed by distinguishing between water-bath test and steam test. Swelling measurements from the steam test are generally expected to be higher than those water-bath swelling test [21, EN 1744-1]. The steam test procedure eliminates the wash off effects (dissolving of expansive compounds in water) that may be present in water-bath test. Moreover it avoids some unrealistic conditions induced by high pressures in autoclave tests.

Water-bath Swelling Test

With regards to the water-bath swelling test, the results showed a high volumetric stability of aged EAF aggregates samples (A1P*). The average height increment was of the order of a few hundredths of a millimeter (0.02 mm), corresponding to insignificant linear expansion (0.02%). This value was clearly smaller compared with the limiting expansion (0.5%) specified in ASTM D2940.

To make the expansive phenomenon more clear and understand its developmental mechanism, it was decided to carry out a parallel test, modifying the Standard procedure. The specimens were soaked in the water without any type of vertical surcharge [32]. Therefore, by changing the test method, the limit expansion value defined by ASTM D2940 becomes invalid. This experimental approach revealed different swelling behaviors for each mixture (Fig. 6).

First of all, Fig. 6 shows differences between fresh EAF samples (F 1P*) and aged EAF ones (A1'P*). The F1P* series was characterized by a linear expansion of 0.82%. The expansion trend differed, also referring to the time evolution of the process. A1'P* required 18 h for the volumetric stabilization (tertiary phase), while for F1P*, this time interval extended for 72 h. Subsequently, the blended mixture F_30*P and F_60*P exhibited an intermediate tendency. Increasing the EAF aggregates/limestone ratio increased the average swell amount and delayed the end of the expansion process.

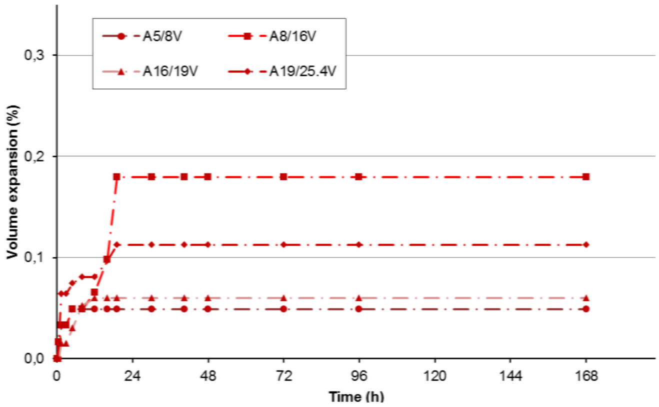


Fig. 7. Rate of Volume Expansion for Monogranular Samples During Steam Test (EN 1744-1).

European Steam Test

The mixture of monogranular aged EAF aggregates, compacted using vibrating table, showed limited volume expansion. However, the results indicate a specific trend. In general, increasing the particle size increased the swelling rate and time necessary to a volume stabilization (Fig. 7). The exception was represented by 8/16 fraction (A8/16V), which exhibited the maximum swelling values of 0.18%. This fraction, although it did not include the coarsest aggregates gradation, was characterized by the wide range of grain-size distribution and especially by the lowest voids content (36.88%).

This aspect underlines the importance of gradation and therefore of residual voids content after compaction on the expansion phenomenon development. The voids in the granular samples could indeed absorb partially the volume expansion of steel slag aggregates, limiting macroscopic effects on volume expansion. In particular, the analysis of 8/16 fraction samples after Proctor compaction (A8/16P) highlighted higher swelling values and a more delayed expansive process compared to samples compacted using vibrating table (A8/16V), confirming the crucial role played by degree of compaction and residual voids content (Fig. 8).

With regards to the ANAS particle size distribution, the swelling curves showed expansion values far higher than those registered by

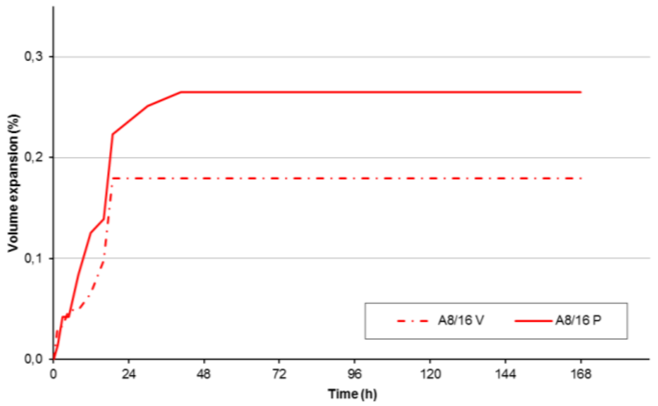


Fig. 8. Comparison between A8/16P and A8/16V Volume Expansion During Steam Test (EN 1744-1).

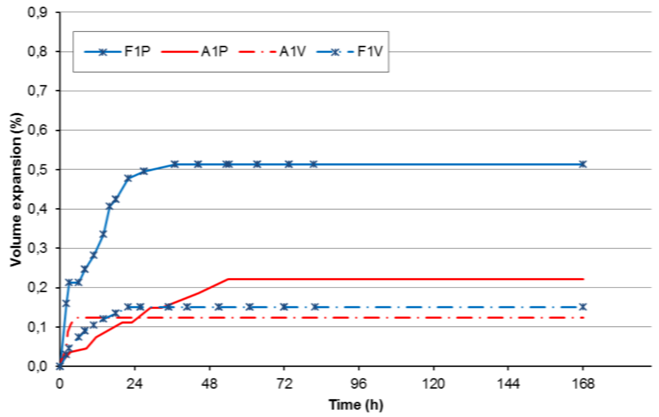


Fig. 9. Rate of Volume Expansion for ANAS Grain-size Distribution Samples During Steam Test (EN 1744-1).

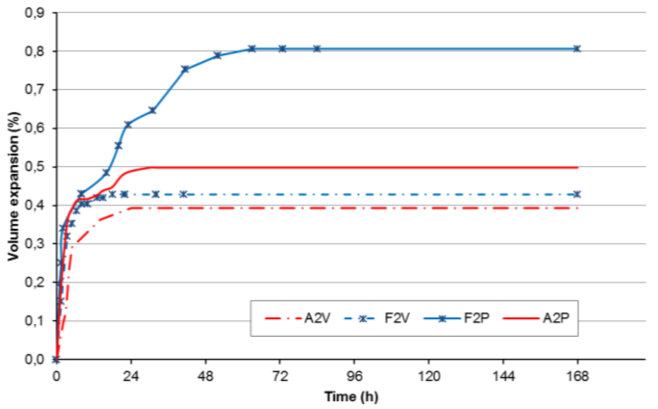


Fig. 10. Rate of Volume Expansion for FULLER Grain-size Distribution Samples During Steam Test (EN 1744-1).

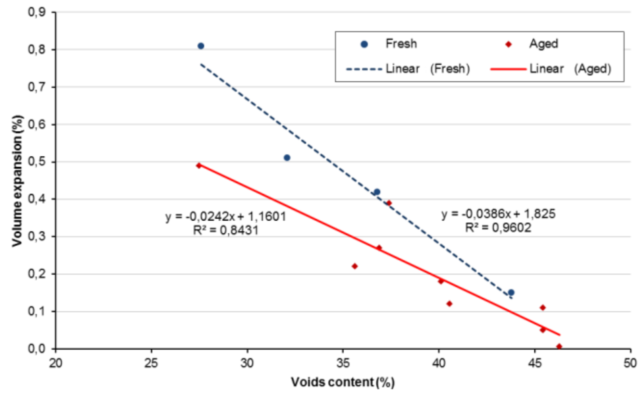


Fig. 11. Rate of Volume Expansion versus Voids Content for Aged and Fresh EAF Aggregates Samples (EN 1744-1).

monogranular fractions (Fig. 9). In this circumstance, the three different expansion phases were also more distinguishable. The F1P series showed the maximum final swelling value of 0.51%, which was clearly higher than those registered for vibrating table compaction samples (F1V). The same trendline was also verified for aged slag aggregates. In fact, average swell amounts of 0.22% and 0.12% were measured for A1P and A1V series, respectively.

Comparing specimens manufactured with the same compaction technique, characterized by similar voids content, it was noted that higher swelling rates were registered by fresh slag aggregates. It means that after steam exposition, fresh steel aggregates exhibited more significant and quicker expansive reaction than aged EAF aggregates. Moreover, increasing the degree of compaction increased the gap between aged and fresh slag aggregates. Using Proctor compaction, fresh aggregates (F1P) showed a swelling rate three times greater than aged ones (A1P). This phenomenon was less apparent for vibrating table compaction.

The samples of slag aggregates graded to the Fuller parabola in general displayed higher volume expansion than ANAS grain-size distribution specimens (Fig. 10). In particular, F2P series showed the maximum final swelling value (0.81%) of all among analyzed samples. These results could be explained by two characteristics of this series, which imply the same principle: the choice of Fuller grain size distribution and the presence of finer particles (0/2 mm). Both aspects involved a considerable reduction in the voids content.

The main considerations on swelling for F-series, regarding age treatment and compaction procedure, coincided with those mentioned above for ANAS mixes.

The same trend in the swelling nature can be observed for both types of mixture gradations. With equal compaction technique, higher swelling rates were shown by fresh slag aggregates; whereas with equal aged treatment, greater volume expansion was pointed out by samples with elevated density gradation.

All the specimens analyzed in the experimental program showed expansion values after 168 h, which did not exceed the requirements for category V_5 imposed by EN 13242:2013.

In order to verify the influence of samples void content on the expansion rate, a second type of analysis was conducted. As has been mentioned, increasing the degree of compaction increased the volume expansion. For this reason, the final expansion values of different samples were plotted as a function of their voids content, distinguishing between fresh and aged slag aggregates (Fig. 11). The chart clearly shows a trend that increasing the void content decreases the final volume expansion. Of course the fresh EAF aggregate trendline was described by higher expansion values and by a greater slope due to the greater swelling susceptibility of this material. The gap between the two lines gradually decreased with increased amount of voids content. This aspect, as stated above, highlights how the main factor affecting swelling ratio was the residual voids content.

Conclusions

The artificial aggregates, derived from electric arc furnace slags, showed excellent physical, chemical, and durability properties in the pre-qualification phase.

With regards to the swelling nature of these materials, different expansive processes in specific humidity condition were noted. All analyzed specimens, however, showed appropriate expansion values according to ASTM and EN standard requirements, probably due to the low content of MgO minerals. The expansive developmental process followed in general three different progressive phases. A primary phase, characterized by a high rate of expansion, was followed by a second phase described by a lower rapidity and a third phase in which the volumetric stability was achieved. In particular, the expansive behavior was more evident for fresh slag aggregates, which did not undergo any type of stabilization procedure. Both expansion development and final swelling extent were a function of preliminary exposition to aging treatment and different physical factors, such as particles size, grain size distribution and degree of compaction. Specifically, the residual voids content, which is in close correlation with the degree of compaction, can be considered the main factor affecting swelling ratio.

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