Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Web only Papers. http://www.claisse.info/Proceedings.htm

Electric Arc Furnace Granulated Slag as a Partial Replacement of Natural Aggregates for Concrete Production

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ABSTRACT

The present paper deals with the use of industrial by-products from Electric Arc Furnace (EAF) for the partial replacement of natural aggregates commonly used to manufacture concrete. Three different grading of EAF granulated slag were considered. The rheological and mechanical properties of concrete manufactured with a partial replacement of natural aggregates with slag were determined. Dry shrinkage of hardened concrete was also evaluated. Results indicated that the maximum percentage of natural aggregate replaced with EAF granulated slag is about 15% in order to limit the superplasticizer dosage to attain the same workability class (S4) of the reference mixture at the end of the mixing procedure. The higher the percentage of granulated slag, the higher the specific mass, the elastic modulus in compression and the compressive strength of the concrete. On the other hand, dry shrinkage of the concrete increases by adding a greater amount of EAF granulated slag. As a consequence of the experimental results use of EAF granulated slag in concrete production is limited for the higher specific mass (higher dead loads and seismic vulnerability of the structures) and the higher sensitivity to crack (higher elastic modulus and dry shrinkage) with respect concrete manufactured with natural aggregates only.

INTRODUCTION

During last years, sustainable development issues are becoming even more important. Research on sustainable progress is very widespread especially in the field of construction industry which involves 6% of world energetic resources and CO_2 emissions. One of the most important issue is the consumption of natural aggregates, that leads to inexorable hydro-geological modification of land. These problems should be obviously reduced, for example, by considering the replacement of natural aggregates for concrete production with industrial by-products [Del Fabbro, Stefanutti and Ceschia 2003].

Durability and mechanical properties of structures manufactured by using industrial wastes are both important and the chemical and physical properties of the by-products must be seriously taken into account in concrete production. Granulated blast furnace slag is the most important steel industry by-product. The production is almost 0.23 tons of slag each tons of cast iron and 0.1÷0.2 tons each ton of steel [Milella 2006]. In Italy, electric steel plants are widespread and wastes generated by electric arc furnace (EAF) runs to spoil for a percentage approximately equal to 60% in European Community. The huge amount of EAF slag means an increase of waste disposal costs. Consequently, recycling becomes economically interesting for the steel industry. Furnace slag must obviously be treated and stabilized to become suitable to replace natural aggregates in concrete manufacturing. Different aggregate gradings (10÷20, 8÷12, 4÷8, 0÷4 mm) are produced crushing solid slag blocks into mills and then subdivided by sieving [Sersale, Amicarelli, Frigione and Ubbriaco 1986]. Natural aggregates replacement leads also to economical advantages: the concrete producer reduces, in fact, raw materials utilization and the steel industry saves money by eliminating costs for waste disposal [Gimenez, Bouillon, Ferey and Sorrentino 2005].

In this paper use of EAF granulated slag from steel industry is investigated as a partial replacement of natural aggregates for concrete production [Coppola, Lorenzi, Marcassoli and Marchese 2007].

EXPERIMENTAL INVESTIGATION

Concrete Mixtures

Several concretes were produced by using EAF slag as partial replacement of natural aggregates. Fresh and hardened properties were evaluated and compared with those of a reference mixture manufactured with natural aggregates only.

Cement

A cement CE II/A-LL 42.5R (Limestone Portland Cement) according to EN 197-1 was used. The chemical composition of this cement is shown in Table 1.

Table 1. Chemical composition of cement CE II/A-LL 42.5R

Chemical component	CEM II/A-LL 42,5 R
SiO_2	19.03
Al_2O_3	4.31
Fe_2O_3	2.45
TiO_2	0.12
CaO	60.57
MgO	2.64
SO_3	3.02
Na_2O	0.35
K_2O	0.95
Cl	0.05

Superplasticizer

Dosage of a polycarboxylate-based superplasticizer was adjusted to attain the same workability at the end of the mixing (S4 class, according to EN 206-1) as that of the reference concrete. The main properties of this chemical admixture are summarized in Table 2.

Table 1: Main properties of polycarboxylate-based superplasticizer

Side chain length (g/mol)	Monomer type	Acid/Ester
1000	Ester of acrylic or methacrylic acid	3.5

Aggregates

Three natural aggregates and three waste products (EAF granulated slag) were considered to manufacture experimental concrete mixtures:

- S1: fine sand (0 ÷ 4 mm)
- G1: fine gravel (6 ÷ 14 mm)
- G2: coarse gravel (11 ÷ 22 mm)
- L1: waste fine sand (0 ÷ 4 mm)
- L2: waste fine gravel (8 ÷ 12 mm)
- L3: waste gravel (10 ÷ 20 mm)

Natural and waste aggregates grading was evaluated by sieve analysis according to UNI EN 933-1 (Figure 1): waste aggregate gradings are very similar to natural ones. In particular, EAF slags L2 and L3 can be considered equivalent, in terms of grading, to natural gravels G2 and G1, respectively. Natural sand S1 is very similar, in terms of size, to waste fine sand L1, however S1 is finer than L1.

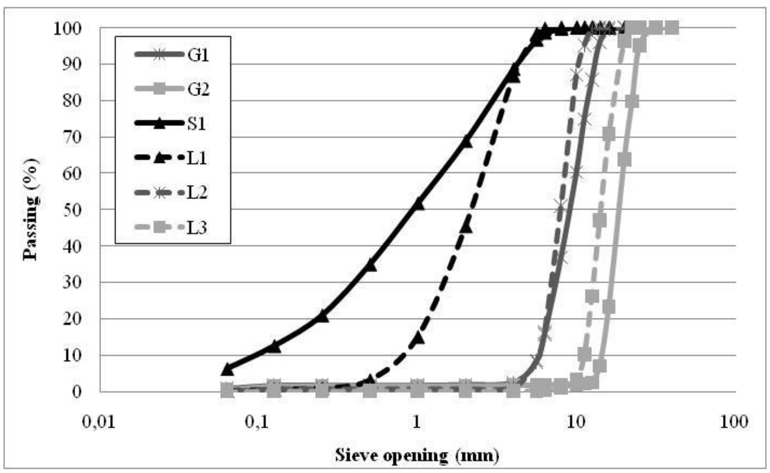

Fig. 1. Grading curve for each specific aggregate

Water absorption and specific mass of natural and slag aggregates were evaluated according to UNI EN 1097-6 (Table 3). EAF granulated slags showed higher specific mass than natural aggregates as a consequence of their high iron content (Table 4). Hence, the more the amount of slag in the mixture, the higher the specific mass of concrete. Wastes showed also higher water absorption with respect natural aggregates. Chemical analyses were also carried out according to UNI EN 1744-1: sulphates, sulphur and soluble chlorides content were lower than limits fixed by EN 12620. Petrographic analysis (UNI EN 932-3) evidenced no gypsum, amorphous silica or pyrite in waste aggregates. Blue-methylene test (UNI EN 933-9) excluded presence of mud and clay in EAF slag. Los Angeles test was performed on both waste and natural aggregates: the Los Angeles class of the two families of aggregates was LA20 and LA30 according to UNI EN 1097-2, respectively.

Table 3: Specific mass and water absorption of natural and waste aggregates

Aggregates	Specific mass (Kg/m^3)	Water absorption (%)
G1	2670	1.04
G2	2650	1.71
S1	2670	0.70
L1	3337	4.32
L2	3320	2.89
L3	3328	2.46

Table 4: Chemical composition of EAF granulated slag

Principal constituents (weight %)	
CaO	25 ÷ 30
CaO_{free}	0 ÷ 4
SiO_2	8 ÷ 18
Al_2O_3	3 ÷ 10
MgO	2 ÷ 9
Fe_{total}	20 ÷ 30
Mn_{total}	2 ÷ 8
CaO/SiO_2	1.7 ÷ 4.0

Tests on concrete

Concrete mixtures were manufactured in order to evaluate the possibility to replace natural aggregates with EAF slag. Both natural and waste aggregates were mixed to meet Bolomey curve. The total aggregate volume (natural and waste aggregates) was fixed at 0.708 m^3 for all the mixtures. Concrete were manufactured by increasing EAF aggregates content up to 25% with respect the natural aggregates mass. The w/c ratio was fixed at 0.54 and the superplasticizer dosage was adjusted to attain the same workability (S4 class according to EN 206-1) of the reference mixture without waste aggregates. Concrete flow table according to UNI EN 12350-2 was also measured at the end of the mixing and after 30 and 60 minutes. Air entrapped and specific mass were also evaluated on fresh concrete according to UNI EN 12350-6 and UNI EN 12350-7, respectively. Specific mass and compressive strength at 1,2,3,7 and 28 days, flexural strength, splitting tensile strength and elastic modulus at 28 days and dry shrinkage up to 90 days were determined on hardened concrete.

RESULTS AND DISCUSSIONS

Fresh concrete

Compositions and fresh properties of concretes are summarized in Table 5. Waste aggregate addition sensibly affects initial workability: the higher the amount of EAF slag the more the superplasticizer dosage (Figure 2). This effect can be ascribed to the crushed nature and rough texture of waste aggregates that sensibly increase water demand to attain the same initial workability of the reference mixture. Workability loss at 60 minutes becomes more pronounced by increasing waste aggregates addition. This effect can be explained by considering the higher water absorption of EAF granulated slag (Table 5) consuming partially mixing water during concrete transportation. As a consequence of the increase of water demand and workability loss, from a practical point of view the maximum percentage of EAF slag in concrete production is 25%. Experimental data seems to indicate that the optimal waste addition is 15% with respect the mass of natural aggregates. In fact this percentage requires a moderate increase of the superplasticizer dosage and, at the same time, doesn't promote a significant workability loss at 60 minutes. Since the specific mass of EAF slag is higher than that of natural aggregates the more the waste replacement, the higher the specific mass of fresh concrete (Table 3 and Table 5). The air entrapping tendency of the mixtures increases with the EAF slag content as a consequence of the side effect attributable to the higher dosage of the superplasticizer required to attain the same initial workability of the reference mixture (consistency class S4).

Table 5: Composition and fresh properties of concretes

COMPOSITION	Reference	MIX_10	MIX_15	MIX_20	MIX_25
CE II/A-LL 42.5R (Kg/m^3)	320	320	320	320	320
Water (Kg/m^3)	174	174	174	174	174
w/c ratio	0.54	0.54	0.54	0.54	0.54
Superplasticizer dosage (% vs cement mass)	0.95	0.95	1.10	1.15	1.20
S1 (Kg/m^3)	993	946	946	946	983
G1 (Kg/m^3)	441	369	331	303	208
G2 (Kg/m^3)	460	389	332	313	228
Total natural aggregate (Kg/m^3)	1894	1704	1609	1562	1419
L1 (Kg/m^3)	-	165	224	140	120
L2 (Kg/m^3)	0	35	82	140	235
L3 (Kg/m^3)	0	35	44	130	235
Total waste aggregate (Kg/m^3)	0	235	350	410	590
EAF slag percentage (%vs natural aggregates mass)	0	10	15	20	25
Initial workability class	S4	S4	S4	S4	S4
Specific mass (Kg/m^3)	2390	2435	2460	2470	2505
Entrapped air (%)	1.0	1.4	2.4	2.0	1.8

Hardened concrete

Cube compressive strength test were carried out to evaluate the effect of waste aggregate addition on this mechanical property. The cubic specimens were soaked into water at 20°C for 1, 2, 3,7, and 28 days. An increase in waste aggregates addition generally improves the compressive strength of concrete since at early ages (Figure 3). The higher compressive strength of concretes manufactured with EAF slag is mostly related to higher Los Angeles class of wastes with respect that of natural aggregates. Furthermore, the rough texture of slag aggregates is responsible for the improvement of the quality of the transition zone at the interface aggregate/cement matrix and consequently for the higher compressive strength of concrete containing EAF slag. Only 1-day compressive strength of concretes manufactured with slag was lower compared to that of the reference mixture. This result can be ascribed to the higher superplasticizer dosage (of the concretes containing EAF slag) and consequently to the retardation of the cement hydration.

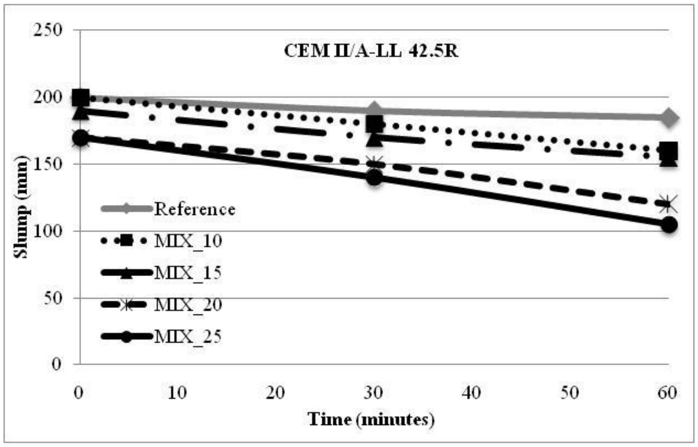

Fig. 2. Slump loss of different concretes mixtures

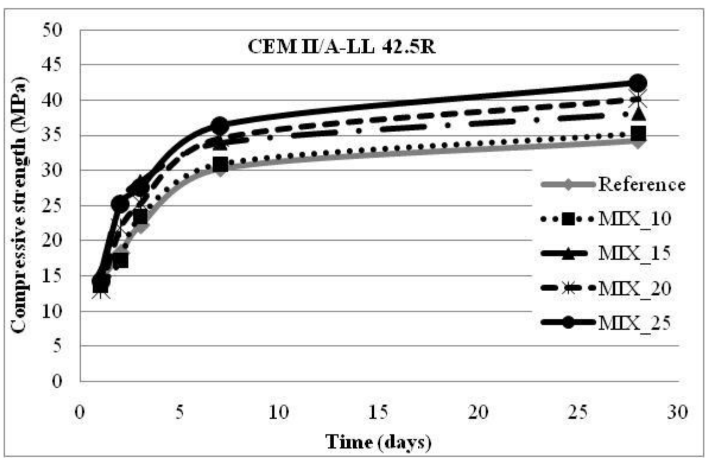

Fig. 3. Compressive strength development of concrete mixtures

Results of the four points bending tests - carried out according to UNI 12390-5 and splitting tensile test (UNI 6135) are shown in Figures 4 and 5, respectively. Replacement of natural aggregates with EAF slag generally improves both flexural and splitting tensile strength of the concrete. This effect can be ascribed to the rough texture of waste aggregates and consequently to the improvement of the transition zone at the interface aggregate/cement matrix.

A higher waste aggregates replacement dramatically enhances dry shrinkage (Figure 6). In the specific, a 25% natural aggregates substitution lead to about 30% worsening in dry shrinkage. Due to the considerable shrinkage enhancement, the waste aggregates replacement must be limited to avoid severe cracking in concrete structures.

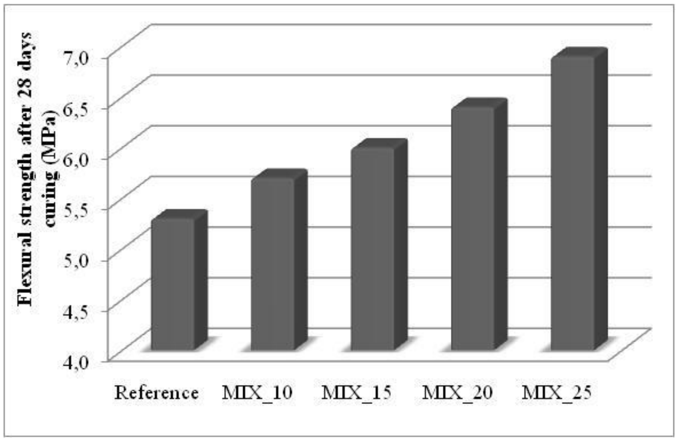

Fig. 4. Flexural strength of concrete mixtures

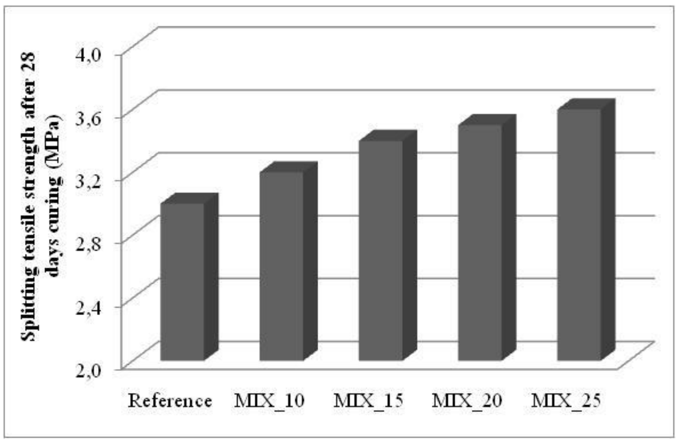

Fig. 5. Splitting tensile strength of concrete mixtures

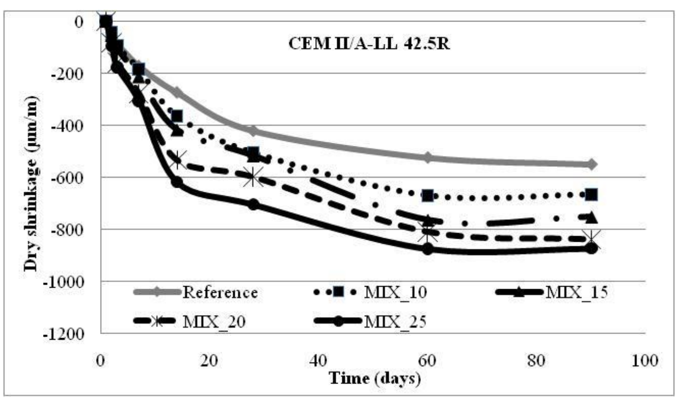

Fig. 6. Dry shrinkage of concrete mixtures

Young Modulus of hardened concrete was measured on cylindrical specimens at 28 days (UNI-EN 6556). The higher the EAF slag replacement the higher the Young Modulus (Figure 7). However, the increase of the Young modulus is lower than that expected as a consequence of the higher specific mass of mixtures manufactured by adding a higher amount of EAF slag. A high value of the Young modulus improves structure stiffness and reduces beam deflection. However, it enhances internal stress induced by restrained shrinkage.

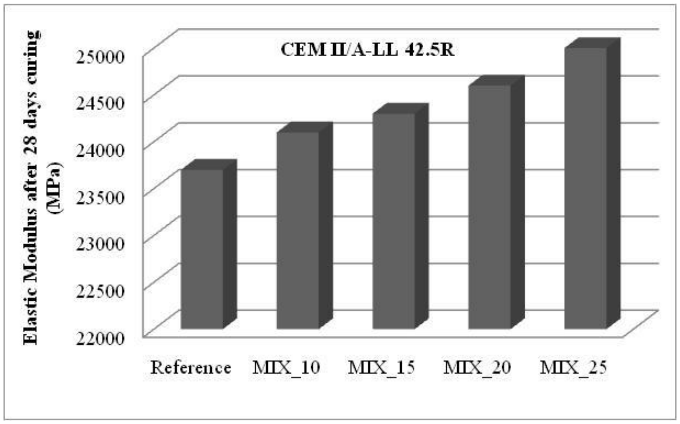

Fig. 7. Elastic Modulus of concrete mixtures after 28 days

In conclusion, EAF slag aggregates addition determines an increase in mixing water (or in the superplasticizer dosage) and in slump loss of fresh concrete. Replacement of natural aggregates with EAF slag improves compressive strength, flexural and splitting tensile strength of hardened concrete. Moreover, use of EAF slag determines an increase of the specific mass, the elastic modulus in compression and the dry shrinkage of cementitious mixtures. All these effects are summarized in Figure 8. It can be noticed that a percentage of slag higher than 15% (MIX_15) promotes a slump loss, after 60 minutes, 30% higher than that of the plain concrete and leads to a shrinkage worsening close to 50% if compared to the reference mixture. For these reasons, on the basis of the experimental results a maximum natural aggregates replacement equal to 15% is suggested to limit superplasticizer dosage, workability loss and shrinkage.

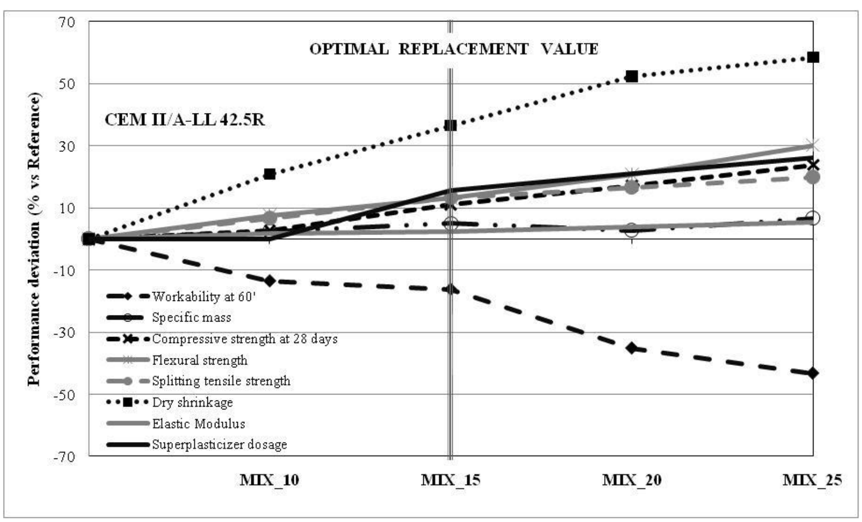

Fig. 8. Performance deviation (%) of concretes manufactured with waste aggregates compared to reference concrete (natural aggregates only)

CONCLUSIONS

Experimental results indicated that the maximum percentage of natural aggregate replaced with EAF granulated slag is about 15% in order to limit the superplasticizer dosage to attain the same workability class (S4) of the reference mixture at the end of the mixing procedure. The higher the percentage of granulated slag, the higher the specific mass, the elastic modulus in compression and the compressive strength of the concrete. On the other hand, dry shrinkage of the concrete increases by adding a greater amount of EAF granulated slag. As a consequence of the experimental results use of EAF granulated slag in concrete production is limited for the higher specific mass (higher dead loads and seismic vulnerability of the structures) and the higher sensitivity to crack (higher elastic modulus and dry shrinkage) with respect concrete manufactured with natural aggregates only.

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