INFLUENCE OF ELECTRIC ARC FURNACE SLAGS ON THE MECHANICAL PROPERTIES OF CONCRETE

Alan Piemonti, Antonio Conforti, Luca Cominoli, Antonella Luciano, Sabrina Sorlini and Giovanni Plizzari

Speaker: Alan Piemonti

a.piemonti001@unibs.it

UNIVERSITÀ DEGLI STUDI DI BRESCIA

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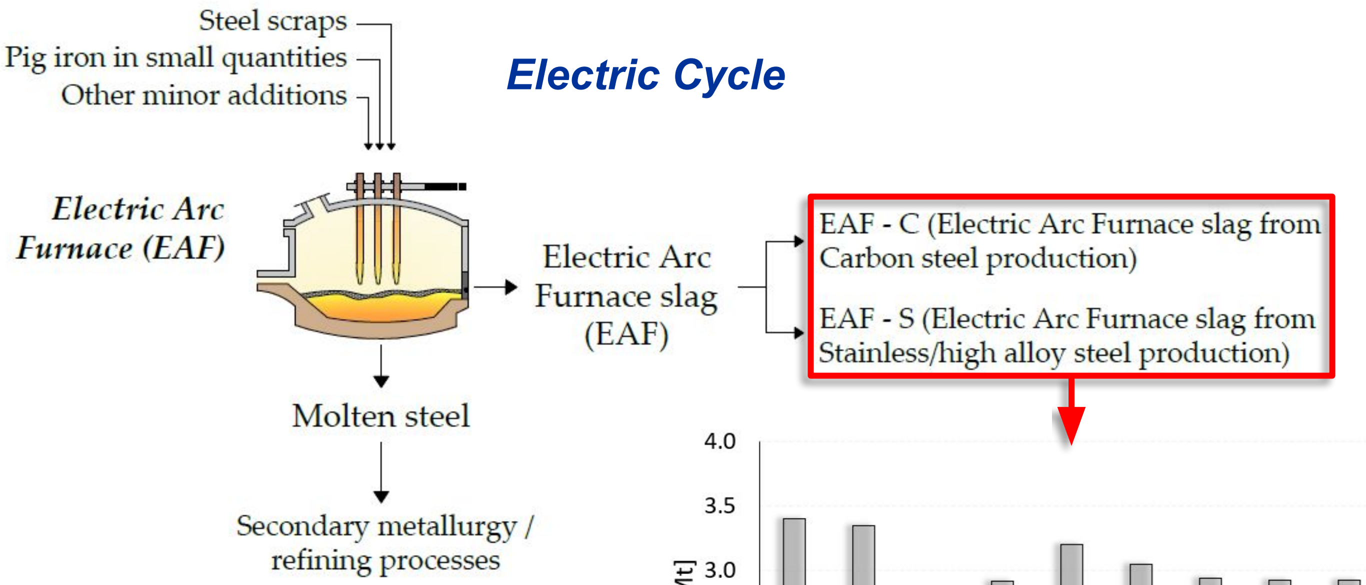
a.piemonti001@unibs.it

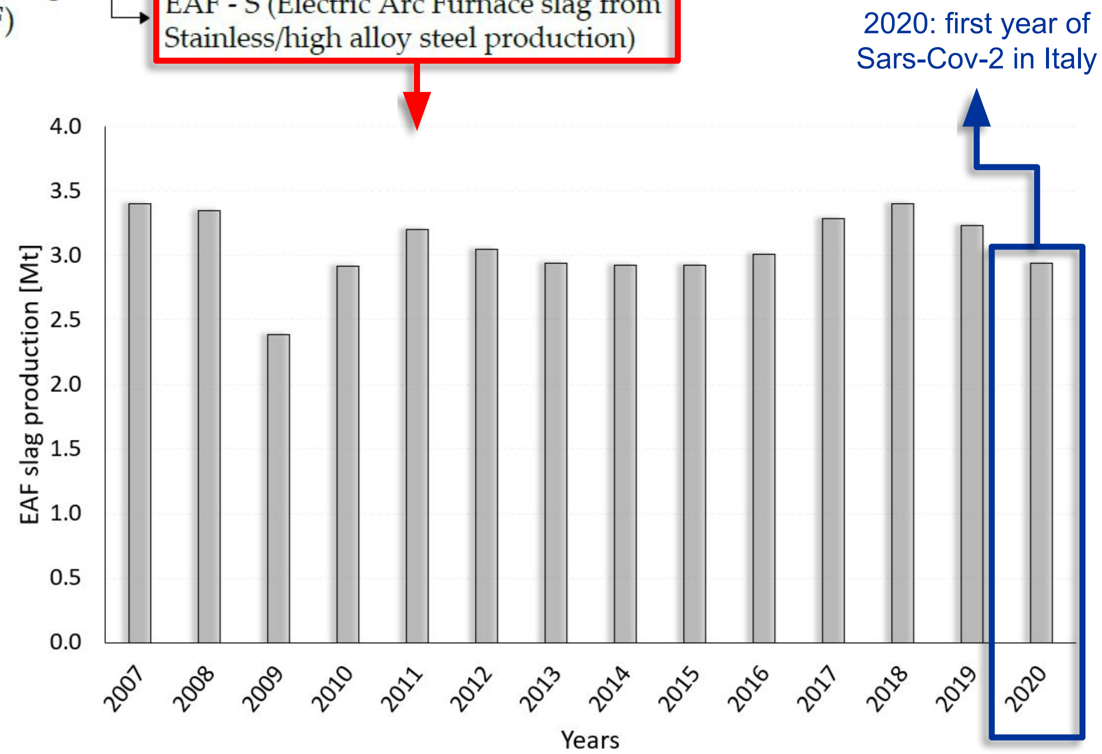
Electric Cycle and Italian EAF slag production

- **EAF slag production trend roughly constant** after the 2009 crisis and before the Sars-CoV-2 pandemic;
- Average Italian EAF slag production: **~ 3.25 million tonnes**;
- EAF slag quantities estimated considering about **150–180 kg of slag per ton of steel produced**;
- Of the total produced, **35–45% is still destined to landfill** □ Need to increase the reuse.

Electric Cycle



Estimated Italian EAF slag production



* Figure from Piemonti, A., Conforti, A., Cominoli, L., Luciano, A., Sorlini, S., Plizzari, G. Use of Iron and Steel Slags in Concrete: State of the Art and Future Perspectives. *Sustainability* ***2021***, *13*, *556*.

a.piemonti001@unibs.it

Electric Arc Furnace (EAF) slag applications

Slag	Nomenclature	Manufacturing Process	Applications (examples)
Electric Arc Furnace Steel Slag – EAF C	Slag, steelmaking, elec. furnace (carbon steel production)	Crushing and screening of the slag that has been air cooled and watered.	**As aggregate for:** - bituminous and hydraulically bound mixtures (asphalt, concrete, road binder etc.) - top layers for high skid resistance - unbound mixtures (unbound surface layers and wearing courses etc.) - dams (road construction and noise protection) - waste water treatment - embankments and fill - railway ballast - sealing in surface layers to protect deposits roofing - armour stone - gabions and noise absorbing walls - ground stabilisation **For the manufacture of:** - cement and other hydraulic binders - stone wool glass (blended with other components)
Electric Arc Furnace Steel Slag –EAF S	Slag, steelmaking, elec. furnace (stainless/high alloy steel production)	Crushing and screening of the slag that has been air or water cooled and watered.	**As aggregate for:** - bituminous and hydraulically bound mixtures (asphalt, concrete, road binder etc.) - unbound mixtures (unbound surface layers and wearing courses etc.) - dams (road construction and noise protection) - embankments and fill - sealings in surface layers to protect deposits - top layers for high skid resistance - roofing - armour stone - gabions and noise absorbing walls - industrial neutralisation product - ground stabilisation **For the manufacture of:** - cement and other hydraulic binders - stone wool - glass (blended with other components)

Present work:

Reuse of EAF–C slag in concrete production, as partial replacement (in 3 different percentages) of natural aggregates

Typical EAF slag applications in Europe (according to Table 4 of the "*Position Paper on the Status of Ferrous Slag, complying with the Waste Framework Directive (Articles 5 / 6) and REACH Regulation*", April 2012, EUROSLAG and EUROFER).

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Materials and mix design

Aggregates

Aggregates	Dimension [mm]	Density [kg/m³]	Water absorption [%]
Fine aggregate	0–2	2650	~ 1.00
Medium aggregate	0–5	2740	~ 1.00
Coarse aggregate	6–20	2720	~ 1.00
EAF–C slag	0–16	3600	~ 2.00

- Density ~ 30% higher than that of natural aggregates Higher concrete density means higher self-weight of the element;
- Chemical composition: CaO (26%), SiO_2 (14%), FeO_X (40%), MgO (7%) and other components in smaller percentages;
- Mineralogical composition: mainly wustite, larnite and mayenite.

Mix design

Components	NAT mix	Slag / natural aggregate replacement		
		10%	25%	50%
Portland Cement 42.5 R II/A-LL [kg/m³]	320	320	320	320
Water [l/m³]	160	160	160	160
Fine aggregate (0–2mm) [kg/m³]	283	264	226	188
Medium aggregate (0–5 mm) [kg/m³]	565	526	487	292
Coarse aggregate (6–20 mm) [kg/m³]	1084	948	735	483
EAF slag (0–16 mm) [kg/m³]	0	256	640	1279
Superplastcizier [l/m³]	0.25	0.50	0.50	1.00
Water/cement ratio (w/c) [-]	0.5	0.5	0.5	0.5

Reference mix (0% natural aggregate / EAF slag substitution percentage)

10% natural aggregates / EAF slag substitution percentage

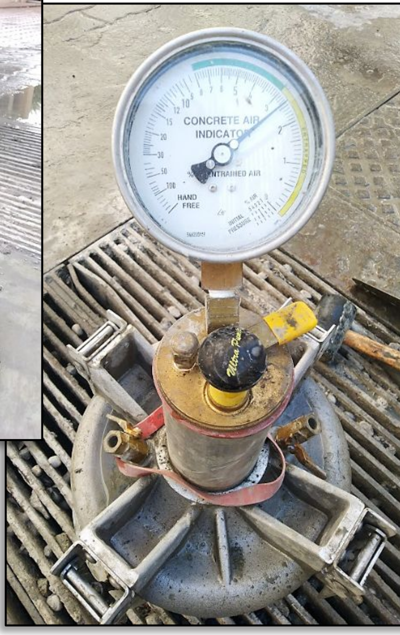
25% natural aggregates / EAF slag substitution percentage

50% natural aggregates / EAF slag substitution percentage

a.piemonti001@unibs.it

Results: fresh concrete

Property	Ref. standard	Mixes			
		NAT	10%	25%	50%
Workability [mm]	EN 12350-2	190	180	170	195
Air content [%]	EN 12350-7	2.40	2.50	2.50	2.30
Density in the fresh state [kg/m^3]	EN 12350-6	2440	2510	2610	2830



Comments

- As designed, **all mixes have consistency class S4** (workability within the limits set by the standard: 160 – 210 mm). Controlling workability by adding small doses of superplasticizer;
- **Very similar air content values** among the different mixes;
- **Higher natural aggregate / EAF slag substitution percentage means higher concrete density**, due to the higher specific weight of the slag compared to the natural aggregates (16% increase from reference mix to mix with 50% substitution percentage).

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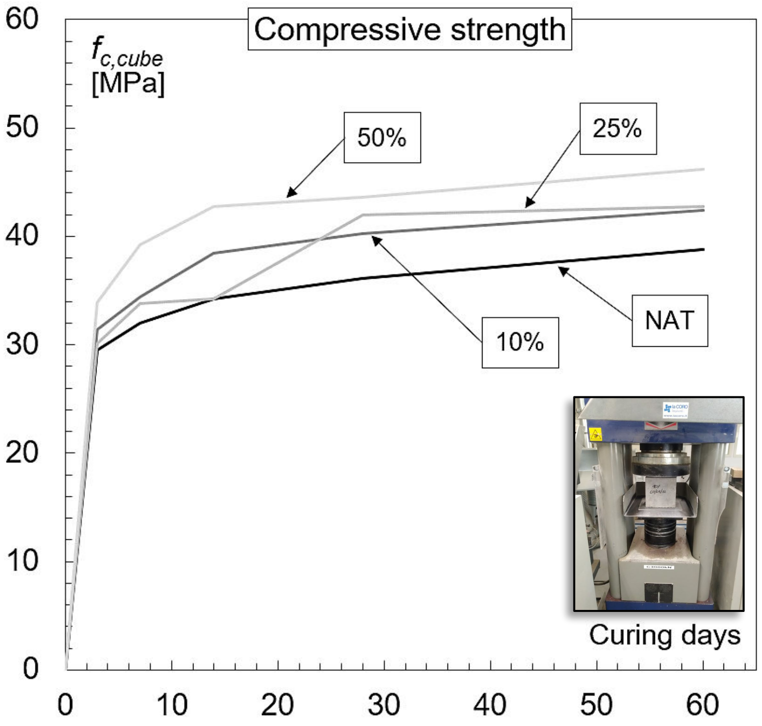
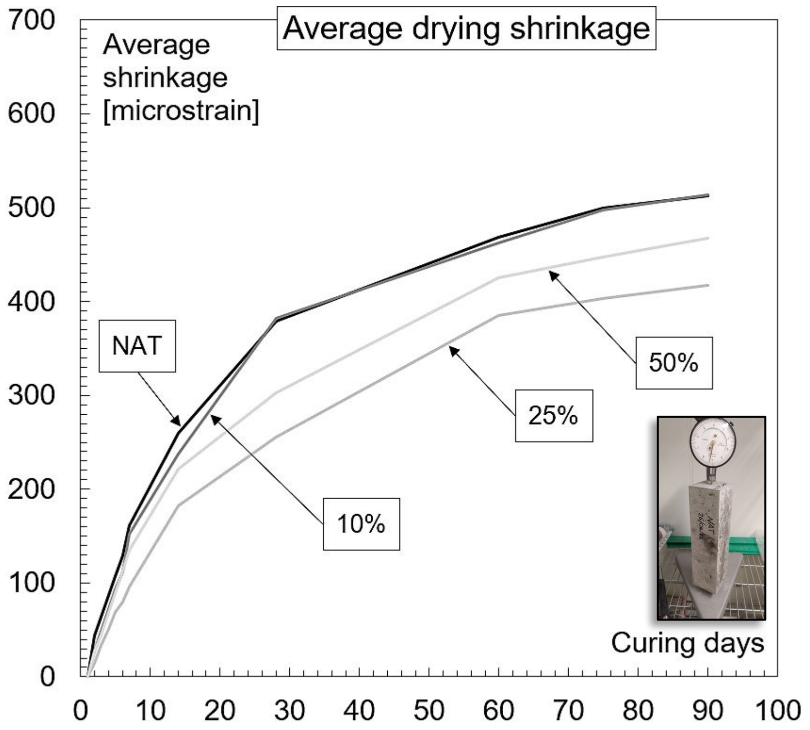
Results: hardened concrete

Compressive strength (EN 12390-3)



The **compressive strength increased as the percentage of natural aggregate / EAF slag replacement increased**

Drying shrinkage (ASTM C490)



The **EAF slag seem to slightly reduce the overall shrinkage of concrete**

Elastic modulus (EN 12390-13)

Mix	E [GPa]	Difference [%]
NAT	33.0	-
10%	34.0	+ 3%
25%	36.4	+ 10%
50%	41.1	+25%

The elastic modulus E was evaluated at 28 days of curing. **As the percentage of natural aggregate / EAF slag substitution increased, the elastic modulus also increased**

a.piemonti001@unibs.it

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Conclusions

- The knowledge of the **physical, chemical, mineralogical and performance characteristics of the raw materials** used, **well-designed mixes** and the awareness of the **behavior of Electric Arc Furnace slag (EAF) once introduced into the mix**, are fundamental for the proper reuse of the material for concrete production;
- All mixes showed **very similar workability** (consistency class S4), partly due to the addition of small amounts of superplasticizer to keep it under control;
- **Higher natural aggregate / EAF slag substitution percentage means higher concrete density**, due to the higher specific weight of the slag compared to the natural aggregates. This results in greater self-weight of a structural element and also affects transportation costs;
- **The air content** showed **very similar values** between the mixes, thanks to the careful pre-saturation of the slags before casting;
- **Increase in compressive strength and elastic modulus** in the EAF slag mixes (higher as the percentage of EAF slag–natural aggregate replacement increased);
- **Slight improvements in the shrinkage behavior** of the EAF slag mixes;
- The results previously presented (in agreement with those found in the literature) are the results of a **preliminary tests of a broader experimental campaign**, aimed at investigating aspects related to the **durability** of concrete with the addition of EAF slag, finally studying the behavior of some **full-scale elements** manufactured with this material.

a.piemonti001@unibs.it

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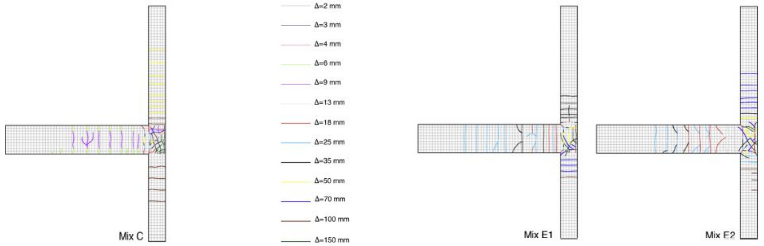
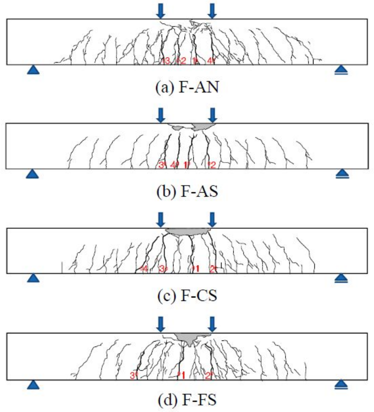
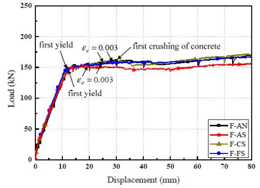
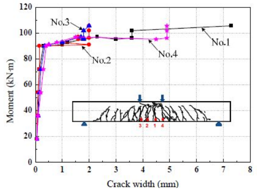
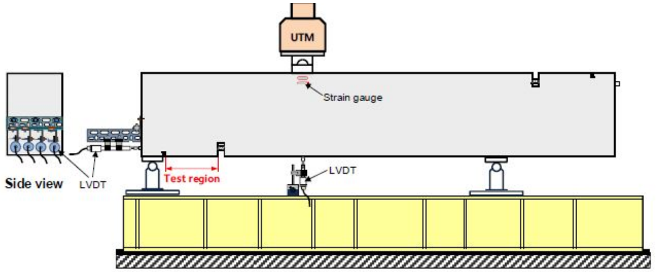
Example of full-scale elements in the literature

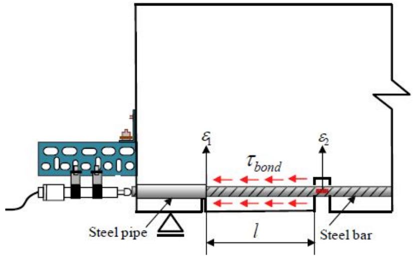


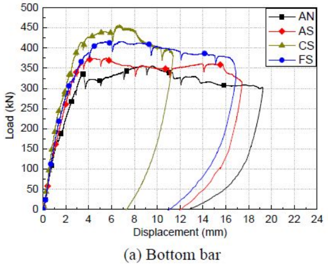












Faleschini, F.; Hofer, L.; Zanini, M.A.; Benetta, M.D.; Pellegrino, C. "*Experimental behavior of beam-column joints made with EAF concrete under cyclic loading*". Eng. Struct. 2017, 139, 81–95.

Objective: assess the effect of using EAF slag on the overall structural behavior of the beam-column joints, evidencing how concrete resisting mechanisms are influenced on this type of structure. EAF slag fully replaced coarse aggregates in concrete.

Kim, S.W.; Lee, Y.J.; Kim, K.H. "*Flexural behavior of reinforced concrete beams with electric arc furnace slag aggregates*". J. Asian Arch. Build. Eng. 2012, 11, 133–138.

Objective: flexural tests on simply supported RC beams to estimate the flexural behavior of RC beams with EAF oxidizing slag aggregates. The experimental results were compared with the flexural performance of RC beams with natural aggregates.

Kim, S.W.; Lee, Y.J.; Kim, K.H. "*Bond behavior of RC beams with electric arc furnace oxidizing slag aggregates*". J. Asian Arch. Build. Eng. 2012, 11, 359–366.

Objective: performing bond tests to evaluate the bond performance of RC beams with EAF oxidizing slag aggregate






Thank you for your kind attention!

University of Brescia, Italy