Pilot Scale Zero Waste PB Smelting for Iron and SCM Production

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Abstract

A novel zero waste process has been demonstrated in an industrial pilot scale for Processed Bauxite (PB) (formerly referred as Bauxite Residue) utilization. Under the EC funded ReActiv project PB was carbothermicaly smelted in METLEN's 1 MVA Pilot Electric Arc Furnace to produce pig iron and a slag phase. The slag was granulated using a high-speed air jet to produce amorphous granules. These granules were tested at Holcim Innovation Centre as a new SCM material used successfully to replace part of the cement clinker used in cement formulations. Thus, the new process demonstrated has the potential to completely valorise Processed Bauxite producing two high added value products.

Keywords: Processed Bauxite, Bauxite Residue, SCM, Granulated Slag, Cement.

1. Introduction

The EC funded ReActiv collaborative project aims at producing Supplementary Cementitious Materials (SCMs) from Processed Bauxite (PB), the by-product of alumina production (formerly referred also as Bauxite Residue). SCMs are materials that exhibit pozzolanic and/or hydraulic properties and can therefore be used in cement composition as a partial substitute to Portland cement clinker and/or in concrete as an active addition [1]. They can be natural materials (limestone, pozzolans, etc.) or by-products from other industrial processes (blast-furnace slag, fly ash, silica fume, calcined clay etc.). As clinker production is a CO_2 intensive process (due to the calcination of limestone), partial substitution of clinker with SCMs has been known for decades as a way to abate the CO_2 emissions per tonne of cement [2] and is widely used. The decarbonization strategies of the cement industry published in 2024 emphasize the use of the SCM as the first lever available today to be used to tackle climate change with an average target of 65 % of substitution by 2050 [3] to reach a clinker binder factor of 0.52 [4]. However, all industries are pulled towards more sustainable processes and less side-products production, which made it evident that today's available SCM will become more and more scarcer, and/or less reactive [5]. Some investigations are consequently needed to identify the new sources of the next generation SCM, as well as their impact once included in the building materials.

In the current work, the first industrial pilot scale test of this technology is presented, along with pilot-scale evaluation of the produced SCM in concrete formulation. Smelting of more than 5 tonnes of PB took place in the alumina refinery of METLEN in Greece and following slag air granulation the produced SCM termed Smelted Bauxite (SB), was evaluated at the Holcim Innovation Centre in France.

2. PB Smelting Pilot Trials

2.1 Materials

The materials used in the smelting pilot trials were Processed Bauxite (filter pressed bauxite residue from METLEN's alumina refinery) along with lime, silica sand as slag fluxes and metallurgical coke as the reducing agent. The chemical composition of all materials is presented in Table 1 (XRF analysis).

Table 1. XRF analysis of Bauxite residue and kaolin samples.

Material %wt	Al_2O_3	Fe_2O_3	CaO	SiO_2	TiO_2	Na_2O	LOI	Fixed C
PB	20.27	40.71	9.17	8.29	5.00	4.00	9.29	
Lime			74.89				24.09	
Silica Sand				99.5				
Coke								97.20

2.2 Pilot Unit and Process

METLEN's pyrometallurgical pilot unit comprises of a 1 MVA AC electric arc furnace (AMRT-EAF) which can treat dusty material without agglomeration. The furnace processing capacity per heating batch is between 500 to 750 kg of material. The refractory lining of the EAF consists of alumina-silicon carbide brick (ALUCARBON H 8810 SiC) with an external refractory zone consisting of Refratherm 150 insulation bricks. Material is fed into the EAF through a chute while slag pouring and metal casting at the end of each trial is made by tilting the furnace to first pour slag into ladles and then pour pig iron into smaller 35 kg ingots.

In addition, the pilot also features an indirect fired rotary kiln (CEMTEC). The kiln tube is 6 m long, made of stainless steel and is heated by 5 natural gas burners, positioned on its exterior. Material is fed in the tube through a feeding screw, which in turn is fed from a double helix mixer. Material exiting the kiln, can be fed directly into the EAF through a closed steel conveyor belt.

All tests conducted started with weighing and mixing raw materials in a mixer for homogenous feed, followed by drying and calcination of the mix at 700 °C in the rotary kiln furnace, the output of which, was fed directly to the EAF for reductive smelting at 1600 °C to produce pig iron and a slag phase. The slag was subsequently poured into a transfer ladle and then pig iron casting took place. Metal and slag samples were taken during pouring for chemical analysis.

Dry slag granulation was achieved by pouring the hot slag into an air granulation pilot unit designed by HATCH. The unit consisted of an inclined trough at the lower end of which the slag was met with a high-speed air jet, generated from air blower fitted with an appropriate nozzle. The granulated slag particles were shot into a container, where they were eventually collected after cooling. Figure 1 shows the Slag pouring from the EAF and the subsequent slag air granulation process.

2.3 Results

In total 5 tonnes of PB were processed over a series of tests in order to optimize slag chemistry and air granulation unit operational conditions (air velocity, ratio of air flow to slag flow) to achieve good granulation results, meaning amorphous material with little to no slag fibre formation.

Figure 1. Slag pouring from the EAF and the subsequent slag air granulation at METLEN's pyrometallurgical pilot.

The smelting recipe used was based on a previous lab scale investigation at the National Technical University of Athens and was further optimized at METLEN to produce a low viscous and low melting slag to achieve optimum slag granulation. The optimum recipe based on granulation results was found to be 15 % CaO, 20 % SiO_2, 13 % Coke weight addition per weight of dry PB. The resulting slag and pig iron chemical analysis from this recipe are shown in table 2 and 3 respectively. In table 4 the average mass and energy balance of the process is presented. The produced slag granules are shown in Figure 2 and their respective XRD pattern in Figure 3. It is evident that the granules are amorphous with the presence of unreacted carbon and small iron droplets inclusions (identified either as oxidized iron, i.e. wustite or as Fe-Si, the formation of which was favoured by the high SiO_2 in the charge of the EAF)

Table 2. XRF analysis of slag granules sample.

Material wt%	Al_2O3	Fe_2O_3	CaO	SiO_2	TiO_2	Na_2O	LOI
PB	32.17	4.38	25.31	28.75	4.15	0.82	-

Table 3. Mass spectrometry analysis of pig-iron sample.

Material wt%	Fe	C	Si	Mn	S	P	Cr
Pig Iron	<Balance>	4.58	6.78	0.04	0.06	0.11	0.37

Table 4. Average mass and energy balance per tonne of PB treated.

Inputs	
PB(t)	1.0
Coke (t)	0.13
Lime (t)	0.15
Sand (t)	0.15
EAF and utilities Energy (kWh)	1230
Rotary Kiln Natural Gas (m^3)	49
Air for granulation (m^3)	803
Outputs	
Pig Iron	0.30
Granulated Slag	0.68
Dust (filter)	0.07

3. SCM Testing in Reconstituted Cement

3.1 Grindability

The granulated Smelted Processed Bauxite was firstly compared to a reference Ground Granulated Blast Furnace Slag upon its grindability, meaning here the required energy needed to reach a given fineness. Figure 4 shows that SB needs at around 16 % more energy than GGBFS (Ground granulated blast-furnace slag) to be ground for both targets of D50 = 20 µm or D50 = 15 µm, and 37 to 52 % more when compared to Ordinary Portland Cement Clinker.

Figure 2. Slag pouring from the EAF and the subsequent slag air granulation at METLEN's pyrometallurgical pilot.

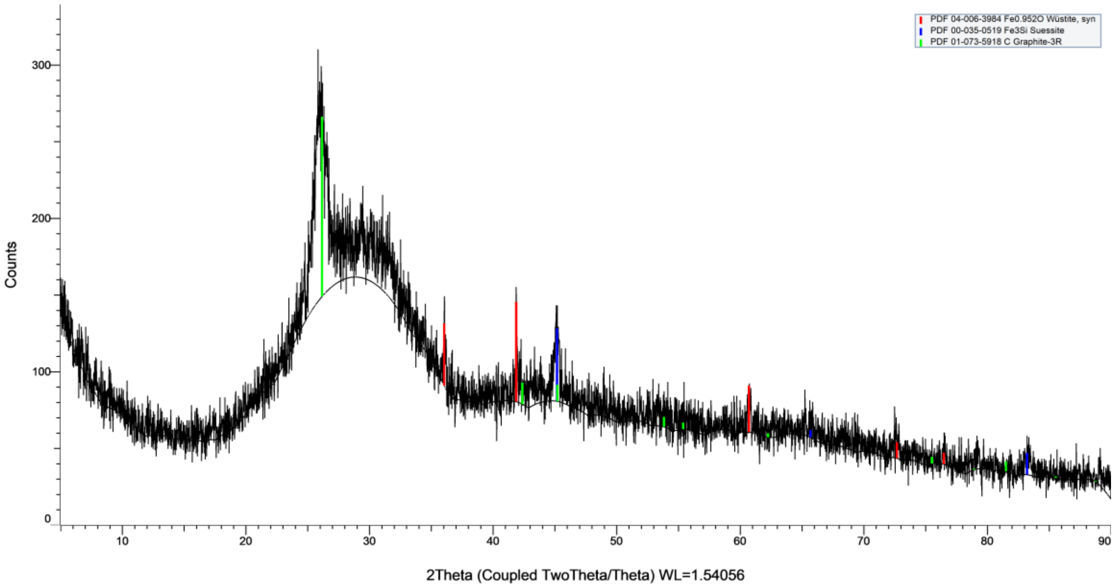

Figure 3. XRD pattern of the granulated slag.

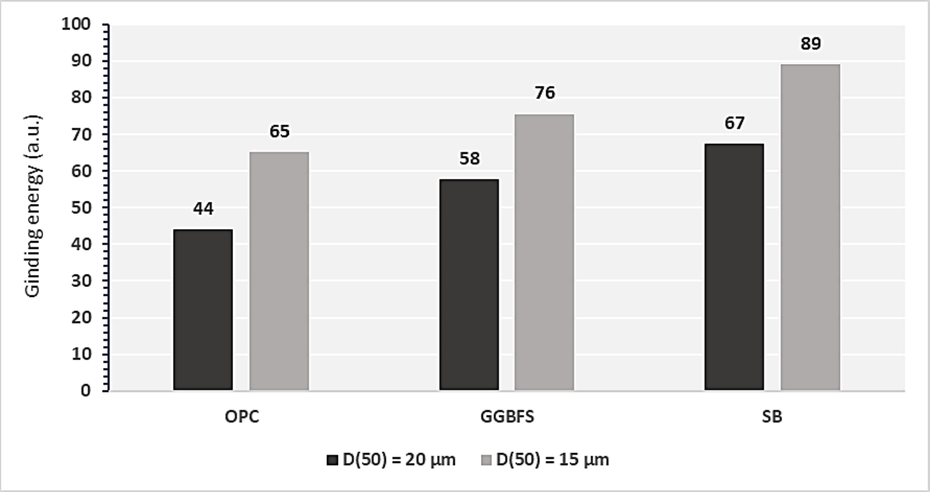

Figure 4. Grindability of SB to reach a given fineness compared to OPC and GGBFS references.

3.2 Cement Characteristics

A blended cement was then reconstituted as follows to be characterized according to the cement standards: 70 w% of a reference Ordinary Portland cement CEM I 52.5N was mixed with 30 w% of SB previously ground to a fineness of 4000 cm²/g without any calcium sulfate adjustment. Chemistry and physics-chemistry were characterised according to their respective standards (EN 196-2, EN 196-6, EN 196-9 and EN 196-10) as detailed in Tables 5 and 6.

Table 5. Chemical characteristics of the blended cement (in wt%).

Al_2O_3	Fe_2O_3	CaO	SiO_2	MgO	SO_3	TiO_2	LOI	f CaO	Na_2Oeq.	Na_2Oeq.sol.
13.5	3.6	53	22.8	1.0	2.1	1.3	1.4	1.5	0.81	0.39

Table 6. Physic-chemical characteristics of the blended cement.

D(10)	D(50)	D(90)	Density	Blaine fineness
3.2 µm	14.5 µm	43.2 µm	3.04	3990 cm²/g
Initial soluble Cr(VI)		**Heat of hydration (at 120h)**		**Unburnt C**
1.11 ppm		370 J/g		< 0.4 w%

3.3 Mortar Tests

The compressive strength evolution of mortars made from reconstituted cement containing the Smelted Processed Bauxite cementitious materials was measured according to the EN 196-1 standard. Note that the workability of the mortar was good from the start, thus being useless to add any admixture. The initial setting time was measured at 187 min.

A commercial CEM II/B-M (LL-S) 42.5N was used for comparison of compressive strengths. Figure 5 shows very good results for the SB used with 30 % replacement of the cement with compressive strengths above the ones of the commercial cement at all tested ages.

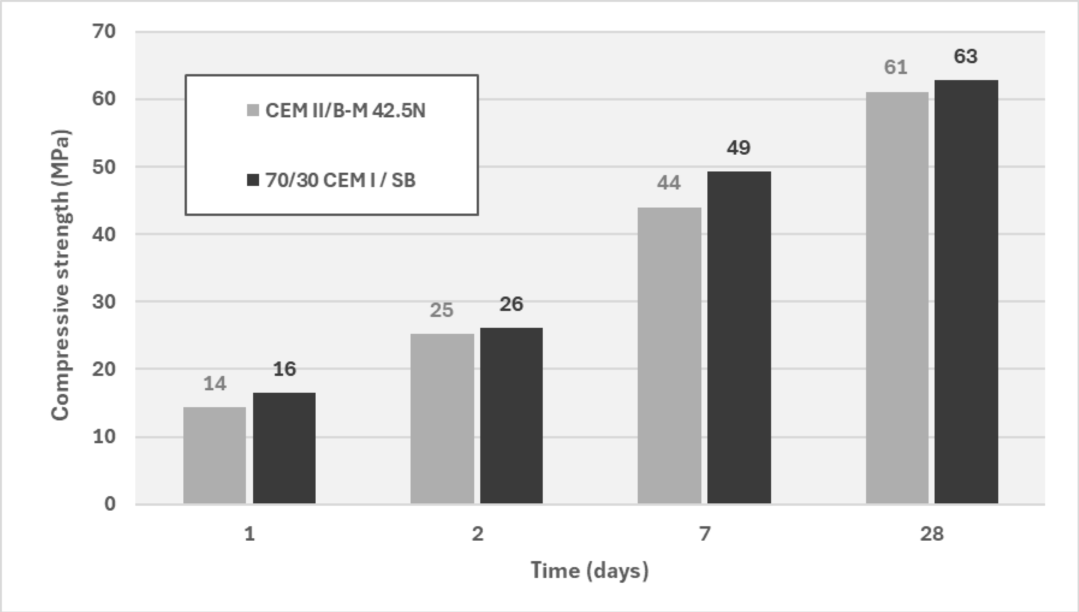

Figure 5. Compressive strengths of the reconstituted cement compared to a commercial reference.

3.4 Concrete Tests

A concrete mix design was chosen as described in Table 6 to be able to pour a slab and an A0 size (84.1 × 118.9 cm) wall as demonstrators for the ReActiv project. The concrete properties are listed in Table 7, reaching again good mechanical strengths such as 33 MPa from 7 days, and 45 MPa after 28 days. The demonstrator is illustrated in Figure 7.

The workability of the concrete was stable for 1 hour and neither the edge of the slab nor the wall showed any air bubbles entrapped. Dedicated samples were casted for durability tests like accelerated carbonation, or dynamic leaching of dangerous substances that require up to 16 weeks of exposure and will be released later on.

Table 7. Mix design of the concrete.

CONCRETE COMPOSITION	$\text{SB}|_{\text{CONCRETE}}$
Cement 70 % CEM I + 30 % Smelted PB	280 kg/m^3
Fine aggregates 0/4 mm	992 kg/m^3
Coarse aggregates 4/11.2 mm	704 kg/m^3
Coarse aggregates 10/16 mm	202 kg/m^3
Water/total binder	0.625

Table 8. Concrete properties.

Density	Entrapped air (%)	Initial slump (cm)	Compressive strengths (MPa)		
			1 day	7 days	28 days
2.34	1.6	130	2.2	33.1	45.2

4. Conclusions

The smelting of PB for pig iron production and subsequent slag granulation in an industrial pilot plant was successfully demonstrated at METLEN's Agios Nicolaos plant. Through a series of tests, the best slag granulation conditions to produce highly amorphous material were identified. The granulated slag was sent for SCM evaluation in Holcim Innovation Centre near Lyon. The cement properties were very satisfactory both in mortar, showing mechanical strength similar to a commercial CEM II/B-M (LL-S) 42.5N, and in concrete applications.

LCA (Life Cycle Assessment) performed under the Reactiv project shows that the climate change impact for CEM II/B with 30 % SB was 0.71 kg CO_2 eq. per kg of cement, which is comparable with conventional CEM II/B, calculated at 0.68 kg CO_2 eq. per kg of cement.

The breakeven price for the SB is approximately 292 EUR/t, as calculated in the ReActiv project economic analysis using a reverse-engineered model with NPV = 0 over 10 years. This is indeed higher than market prices for conventional SCMs, such as fly ash (35–110 EUR/t) and GGBFS (1–110 EUR/t). However, several strategic and economic factors support SB's industrial feasibility:

- Pig iron, produced as a co-product, adds a valuable revenue stream that can partially offset SB production cost.
- The model is highly sensitive to electricity prices and pig iron market value and their optimization could reduce breakeven cost dramatically.
- FCI (Fixed Capital Investment) and SG&A (Selling, General and Administrative expenses) costs are also major contributors, but economies of scale and integrated operations (e.g. symbiosis with alumina refineries or cement plants) can reduce them substantially.
- SB offers strong decarbonization potential by replacing clinker and therefore aligning well with EU Green Deal goals and circular economy incentives.
- As availability of fly ash and slag continues to decline, high-performing alternative SCMs like SB, even at a higher price point, become strategically important for securing future cement supply chains and meeting CO_2 reduction targets.

Figure 6. Picture of the Smelted PB demonstrator.

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