FBA: FIRED BAUXITE AGGREGATE
A EUROPEAN INNOVATIVE SINTERED AGGREGATE ALTERNATIVE TO BFA FOR REFRACTORY APPLICATIONS

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ABSTRACT
FBA (Fired Bauxite Aggregate) is a new high – alumina refractory raw material (92% Al_2O_3, bulk density > 3.5 g/cm^3), developed by ARCIRESA as a European alternative, both technical and strategic, to Chinese imported BFA (Brown Fused Alumina) for refractory applications. The manufacturing of sintered FBA includes 2 firing stages (calcination + sintering) of BauxST^{AR} ore, the highest purity gibbsitic bauxite ore in the world (Fist Bauxite's deposits, Guyana). This paper reviews the properties of the new aggregate and results of FBA-based formulations performance in AMC bricks (lab-scale) and blast furnace runners castables (on site). An industrial trial of high-alumina bricks based on FBA is also successfully on-going in the lining of a cement rotary kiln. FBA introduction to the market is scheduled for the first quarter of 2023.

INTRODUCTION
Over the past 3 decades, the global and EU refractory industry has become extremely dependent upon Chinese imported brown fused alumina, partly on the basis of the traditional approach that 'higher Al_2O_3 content meant better performance' for most of the refractory high–alumina formulations/applications. Therefore, for many years, European refractory producers have coped with supply uncertainty and variations in quality and price of Chinese brown fused alumina (BFA) and refractory bauxite (RGB). Operation shutdowns by strict China's anti-pollution controls and regulations, decline in Chinese bauxite ore availability and Covid-19 pandemic related restrictions have recently impacted the supply chain in the form of shortage and delays, quality issues, increase of spot prices and surging logistics costs. It is also important to mention that bauxite is included in the EU Commission's List of Critical Raw Materials since 2020. With the supply of refractory BFA and RGB threatened, a key challenge facing EU refractory producers is the development of alternative high-alumina aggregates to ensure a continuous, reliable supply of stable quality products for the European refractory market. For this reason, ARCIRESA has focused its recent innovation strategy and investment (BAUXACEM project, 2019–2021) on the research and development of 2 new high-alumina refractory raw materials:

1. BauxST^{AR} 90, a premium refractory-grade fired bauxite with unique properties (92% Al_2O_3, < 0.8% Fe_2O_3, 3.2 – 3.3 g/cm^3 bulk density), that make this bauxite stand out in a class of its own. Since its introduction to the market, many customers have successfully included BauxST^{AR} 90 in their formulations.
2. FBA (Fired Bauxite Aggregate), high–alumina sinter aggregate (> 92% Al_2O_3, bulk density > 3.5 g/cm^3) with high potential for replacing Chinese BFA in different refractory applications and also for upgrading RGB-based refractory solutions.

This paper focuses on the properties of the new FBA aggregate and presents a brief overview of its production process. The results of the laboratory tests and industrial trials using FBA-based solutions in different refractory applications (AMC bricks and blast furnace runners castables) are also reported.

PROPERTIES OF FBA (FIRED BAUXITE AGGREGATE)
The test samples used in the evaluation of FBA properties were full –scale prototypes resulting from the first industrial production trial conducted by ARCIRESA, with a total output of 50 tonnes of the new refractory raw material.
The chemical composition of FBA samples was analysed by X-ray fluorescence (XRF) (table 1). The aggregate is a highly-refractory sintered material with Al_2O_3 content > 92% and minor quantities of SiO_2 (ca. 3.5%) and TiO_2 (ca. 3.2%). The major impurity is Fe_2O_3 (ca. 0.5%) with almost negligible amounts of CaO, MgO, Na_2O and K_2O.
The physical properties of FBA (bulk density, water absorption and apparent porosity) were determined according to ASTM C 357-94 (table 1). The bulk density values range from 3.62 g/cm^3 (lab-scale prototype) to 3.55 g/cm^3 (full-scale prototype). FBA grains exhibit highly reduced water absorption (ca. 0.8%) and apparent porosity (ca. 3%).

Tab. 1: Physical properties, chemical and phase analyses of FBA

Chemical analysis			**Physical properties**		
% Al_2O_3	92.5	Min. 92%	Bulk density, g/cm^3	3.55	Min.3.50
% SiO_2	3.5	Max. 4.5%	Water absorption, %	0.8	Max. 1.2
% TiO_2	3.2	Max. 4%	Apparent porosity, %	2.9	Max. 4
% Fe_2O_3	0.5	Max. 0.7%	**Phase analysis**		
% CaO	< 0.1		Major phase	α-alumina (corundum)	
% MgO	0.15		Minor phases	mullite	tialite
% Na_2O	< 0.1	**Available sizes**	DIN 70, 0 – 0.2 mm, 0 – 0.5 mm		
% K_2O	< 0.1		0 - 1 mm, 1 – 3 mm, 2 – 6 mm		

Regarding particle-size distribution (PSD), FBA aggregates will be commercially available in various sizes (2 – 6 mm, 1 – 3 mm, 0 – 1 mm, 0 – 0.5 mm, 0 – 0.2 mm, DIN 70) (figure 1).

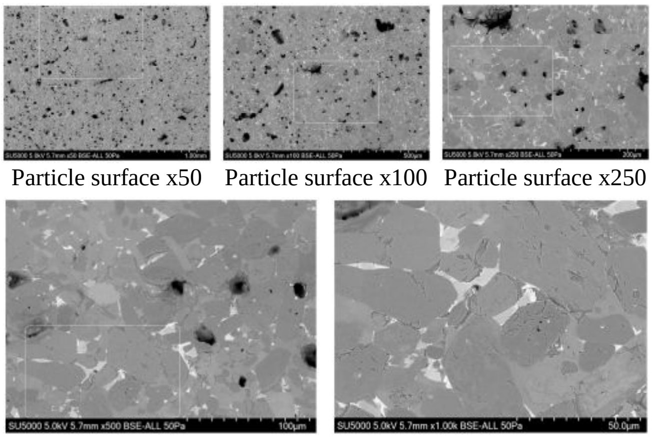
Fig. 1: ARCIRESA FBA (Fired Bauxite Aggregate)

The quantitative phase analysis of samples was performed by X-ray diffraction (XRD) (table 2). The major phase of FBA aggregate is corundum (ca. 84% α-Al_2O_3) with mullite (ca. 11% $Al_{2.4}Si_{0.6}O_{4.8}$) and aluminium titanate/tialite (ca. 5% $TiO_2 \cdot Al_2O_3$) as minor phases.

Tab. 2: X-ray diffraction quantitative phase analysis (XRD) of FBA

Major phase	**Minor phases**	
Corundum (α-Al_2O_3)	**Mullite ($Al_{2.4}Si_{0.6}O_{4.8}$)**	**Aluminium titanate (tialite, $TiO_2 \cdot Al_2O_3$)**
83.9 ± 0.2 (%)	10.8 ± 0.2 (%)	5.3 ± 0.2 (%)

The microstructural properties of FBA test samples were studied by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). Observation of microstructure by SEM (figure 2) reveals that FBA particles surface show inter-granular and intra-granular porosity, which is inherent of aggregates produced by the sintering process route.

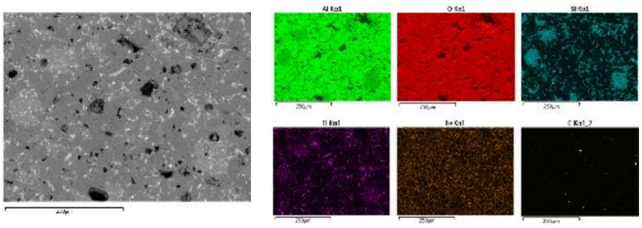


Particle surface x50 Particle surface x100 Particle surface x250

Particle surface x500 Particle surface x1000

Fig. 2: Scanning electron microscopy (SEM) of FBA

The elemental mapping of FBA particles by EDS (figure 3) shows the uniform distribution of minor elements and impurities through the matrix thus promoting a highly homogeneous aggregate.



Electron microscopy image Elemental mapping (microstructural level)

Fig. 3: Energy dispersive X-ray spectroscopy (EDS) of FBA

Mercury intrusion porosimetry (MIP) technique and He pycnometry test were utilized to evaluate the pore size distribution, the volume of accessible pores and other important index parameters of FBA pore structure (table 3). According to the results of MIP analysis, the open porosity associated to accessible pores > 1 µm, i.e. pores that can be easily infiltrated by molten metal and slag, is limited to ca. 2 % vol. thus ensuring high corrosion resistance of FBA.

Tab. 3: Mercury intrusion porosimetry (MIP) of FBA

Mercury intrusion porosimetry (MIP)			
Bulk density (MIP), g/cm^3....	3.50	Median pore diameter µm	5.13
Apparent density (MIP), g/cc	3.57	Pores > 10 microns, %......	43.79
Apparent density (He), g/cc*	3.64	Pores 1-10 microns, %......	23.53
* He pycnometry test		Pores < 1 microns, %........	32.68

For the purpose of comparison, the key parameters of FBA, BFA and premium refractory-grade fired bauxite BauxST^{AR} 90 are listed in (table 4). The different process routes of BFA (fusion) and FBA (calcining + sintering) have an impact on the aggregates properties. The differences on the characteristics between high-alumina fused and sintered aggregates and their influence on the final properties of the refractory formulations were discussed in detail by Schnabel et al. [1].

FBA bulk density (3.5–3.6 g/cm^3) is lower when compared to BFA (3.85 g/cm^3), which is mainly due to closed internal porosity in the sintered aggregates. However, it is important to remark that FBA properties with a significant influence on resistance corrosion, such as water absorption, open porosity and volume of accessible pores > 1 µm, are at comparable level to BFA. A distinguishing feature of FBA aggregate is its mullite content (ca. 11%), which is not present in BFA, thus upgrading thermal shock resistance, creep behaviour and mechanical strength of the refractory formulations.

Tab. 4: Comparison of BauxST^{AR} 90, FBA and BFA key properties

Chemical analysis	**BauxST^{AR} 90**	**FBA**	**BFA (95% China)**
% Al_2O_3............................	92.0	92.5	95.4
% SiO_2..............................	4.0	3.5	1.1
% TiO_2..............................	3.4	3.2	2.6
% Fe_2O_3............................	0.5	0.5	0.2
Physical properties	**BauxST^{AR} 90**	**FBA**	**BFA (95% China)**
Bulk density, g/cm^3...........	3.25	3.55	3.85
% Water absorption...........	3.00	0.80	0.50
% Apparent porosity..........	9.80	2.90	2.00
% Accesible pores > 1 µm	9.4	2.0 - 2.5	1.5 [1]
Phase analysis	**BauxST^{AR} 90**	**FBA**	**BFA (95% China)**
Major phase.......................	Corundum	Corundum	Corundum
Minor phases.....................	Mullite	Mullite	
	Tialite	Tialite	Tialite

PRODUCTION PROCESS OF FBA

FBA manufacturing process is based on 2 high–temperature firing stages (calcination + sintering) in rotary kiln of BauxST^{AR} ore, the highest purity gibbsitic refractory-grade bauxite ore in the world, mined at First Bauxite's Bonasika deposits in Guyana (figure 4).

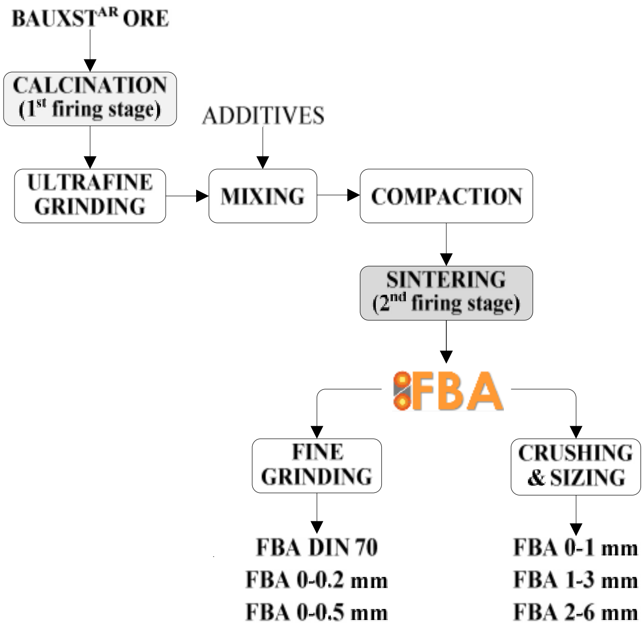


Fig. 4: Production process of ARCIRESA FBA sintered aggregate

The installation of the new FBA manufacturing line is successfully on-going at the Spanish ARCIRESA main production centre (Lugo de Llanera, Asturias). FBA introduction to the market is scheduled for the first quarter of 2023.

TESTING OF FBA IN REFRACTORY APPLICATIONS

Various refractory bricks and castables formulations based on FBA have been tested to evaluate its performance in comparison to BFA.

FBA as BFA replacement in Al_2O_3–MgO-C (AMC) bricks

The refractory products based on the Al_2O_3–MgO-C (AMC) system have been successfully applied to the steel ladle linings since the beginning of the 1990's. AMC bricks are mainly used in highly demanding areas such as the bottom impact zone and side wall of the ladle. Typical formulations of AMC bricks are based on high-alumina aggregates, commonly brown fused alumina (BFA) and fired bauxite (RGB), sintered/fused magnesia, carbon in the form of graphite and different matrix components (calcined alumina, resin binder, aluminium, etc.).

AMC bricks are characterized by a high corrosion resistance that is required to withstand the aggressive operational environment of the steel ladle. Therefore, the slag resistance of high-grade AMC bricks based on the new FBA aggregate and on a mixture 50% FBA + 50% BFA was evaluated in comparison to different commercially available grades (premium, high, medium and low) of AMC bricks based on BFA and RGB.

The AMC formulations were homogeneously mixed, dry pressed in the form of bricks (format 45/0) and tempered at 170 ºC for 18 h.

The chemical characterization tests performed on AMC bricks were X-ray fluorescence (XRF) and carbon quantification using a LECO elemental analyser (table 5).

Tab. 5: Chemical analysis of tested AMC bricks

Test specimen	**AMC1**	**AMC2**	**AMC3**	**AMC4**	**AMC5**	**AMC6**
AMC brick type	Premium	**High grade**	Medium	Low grade	**High grade**	**High grade**
BFA replacement	0%	**0%**	100% RGB	100% RGB	**50% FBA**	**100% FBA**
% Al_2O_3................	89.08	**74.59**	83.96	83.05	**72.09**	**70.93**
% SiO_2.................	0.87	0.93	2.67	2.52	2.83	2.57
% TiO_2.................	1.67	1.17	2.57	2.56	1.96	1.43
% Fe_2O_3...............	0.24	**0.24**	0.69	0.68	**0.58**	**0.39**
% CaO.................	0.25	0.46	0.27	0.28	0.43	0.49
% MgO................	7.65	**22.59**	9.70	10.77	**22.03**	**24.13**
% Na_2O...............	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
% K_2O.................	0.04	0.02	0.02	0.02	0.03	0.03
% P_2O_5.................	< 0.01	< 0.01	0.07	0.05	0.04	0.03
% C......................	7.80	**9.90**	6.18	5.38	**9.93**	**10.49**

The physical properties, bulk density and open porosity, of the test specimens were determined, in accordance with UNE-EN 993, on the pressed 'green' AMC bricks, after tempering at 170 ºC for 18 h and after firing at 1,000 ºC for 2 h in reducing conditions (table 6).

Tab. 6: Physical properties of tested AMC bricks

Test specimen	**AMC1**	**AMC2**	**AMC3**	**AMC4**	**AMC5**	**AMC6**
Type of AMC brick	Premium	**High grade**	Medium	Low grade	**High grade**	**High grade**
% BFA replacement	0%	**0%**	100% RGB	100% RGB	**50% FBA**	**100% FBA**
Bulk density, g/cm^3 Green	***	**3.17**	***	***	**3.03**	**2.98**
Bulk density, g/cm^3 Tempered 170ºC/18h	3.38	**3.20**	3.10	3.10	**3.01**	**3.00**
Bulk density, g/cm^3 Fired (red.) 1000ºC/2h	3.31	**3.15**	3.05	2.97	**2.96**	**3.00**
% Open porosity Tempered 170ºC/18h	1.03	2.96	7.76	8.24	6.66	6.67
% Open porosity Fired (red.) 1000ºC/2h	7.04	6.29	13.10	15.90	9.31	9.78

High-grade AMC brick based on 50% BFA + 50% FBA

High-grade AMC brick based on 100% FBA

Fig. 5: High-grade AMC bricks based on 100% FBA and 50% FBA

The bulk density difference between high-grade AMC bricks based on BFA and high-grade AMC bricks based on FBA is in the range 4.5% - 6.3%. The BFA-based bricks show the lowest open porosity after tempering and also after firing at 1,000 ºC.

The lower bulk density and higher open porosity of the tested FBA-based bricks, comparatively to BFA-based formulations, are partly due to the bulk density (3.55 g/cm^3) and apparent porosity (3-4 %) values of the FBA aggregate itself. It is important to highlight that multiple dislocations of FBA aggregates (mainly particles > 3 mm) occurred during handling and preparation of test specimens causing the effect of void areas on their surfaces which negatively impacted on the bulk density and open porosity values (figure 5).

The slag test for the behaviour comparison of AMC bricks based on FBA, BFA and RGB to the action of molten slag was conducted in a rotating test furnace at the Idonial Technological Centre (Spain), in accordance with the ASTM C847 standard. The 6 test specimens (AMC1/AMC2/AMC3/AMC4/AMC5/AMC6) constituted the test lining. The test furnace was preheated by the gas-oxygen torch in 2 h and, after reaching the test temperature (1,500 ºC), soaked for 1 h, during which time (0.9 kg) of slag pellets (table 7) were charged to coat the lining and provide a starting bath. Regular feeding of slag pellets at a rate of 1.25 kg of slag per hour was charged into the test furnace. The test was running for 4 h, at an average temperature of 1,530 ºC under oxidising atmosphere, after which it was aborted because of the high wear observed in the 2 test specimens of AMC bricks based on RGB.

Tab. 7: Testing slag properties (slag from transfer ladle)

Al_2O_3 (%)	SiO_2 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	F (%)	Na_2O (%)	SO_3 (%)	MnO (%)	TiO_2 (%)
12.52	21.59	9.32	41.88	7.34	1.30	0.34	0.36	1.39	0.29
Hemispherical temperature = 1,390 ºC						Flow temperature=1,391 ºC			

The test specimens were cut in longitudinal direction and the wear profile was measured at the slag level (figure 6). The depth of slag penetration and refractory wear index were also determined (figure 7) (table 8).

Test specimen AMC1 (ca. 230 mm long)
AMC brick-premium grade-100% BFA

Test specimen AMC2 (ca. 460 mm long)
AMC brick - high grade - 100% BFA

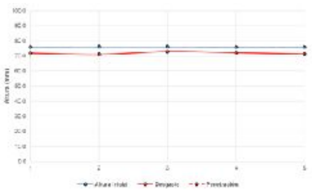
Test specimen AMC3 (ca. 460 mm long)
AMC brick-medium grade-100% RGB

Test specimen AMC4 (ca. 230 mm long)
AMC brick – low grade - 100% RGB

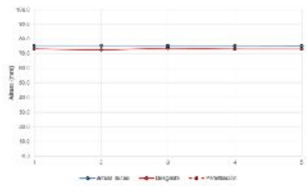
Test specimen AMC5 (ca. 460 mm long)
AMC brick – high grade - 50% FBA

Test specimen AMC6 (ca. 460 mm long)
AMC brick – high grade - 100% FBA

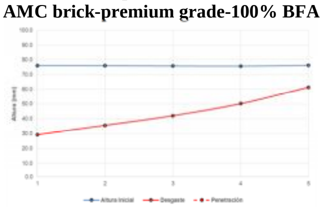
Fig. 6: Specimens after rotary slag-test 1,500 ºC (cut sections)



Test specimen AMC1
AMC brick-premium grade-100% BFA



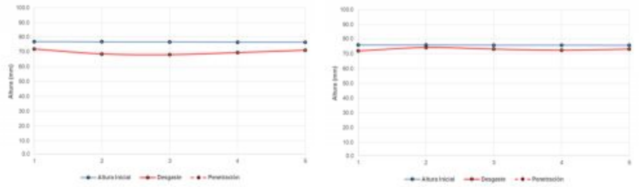
Test specimen AMC2
AMC brick - high grade - 100% BFA



Test specimen AMC3
AMC brick-medium grade-100% RGB

Test specimen AMC4
AMC brick – low grade - 100% RGB

Fig. 7: Slag penetration (mm) and wear at slag level of tested spec.



Test specimen AMC5 — **AMC brick – high grade - 50% FBA**

Test specimen AMC6 — **AMC brick – high grade - 100% FBA**

Fig. 7: Slag penetration (mm) and wear at slag level of tested spec.

Tab. 8: Refractory wear (mm) and wear index (%) of tested spec.

Test specimen	AMC1	AMC2	AMC3	AMC4	AMC5	AMC6
Type of AMC brick	Premium	**High grade**	Medium	Low grade	**High grade**	**High grade**
% BFA replacement	0%	**0%**	100% RGB	100% RGB	**50% FBA**	**100% FBA**
Initial height, mm*.....	76,0	75,4	76,0	76,2	76,6	75,8
Final height, mm**......	71,9	73,2	43,7	52,4	69,8	72,9
Refractory wear, mm	4,1	**2,2**	32,3	23,8	**6,8**	**2,9**
Refractory wear index	13%	**7%**	100%	74%	**21%**	**9%**

* Average value of the test specimen initial heights at positions 1, 2, 3, 4 and 5.
** Average value of the test specimen final heights at positions 1, 2, 3, 4 and 5 after testing.

The commercial AMC bricks based on fired bauxite (RGB) exhibit by far the highest refractory wear rate (table 8).
The corrosion resistance of high-grade AMC bricks based on FBA aggregates is at comparable level to premium and high-grade AMC bricks formulated with brown fused alumina (BFA) (table 8).
The results of the rotary slag-test demonstrate that the lower density of FBA-based formulations, which is mainly due to higher closed porosity in the new sintered aggregate, does not negatively impact the corrosion resistance of the AMC bricks based on it.

FBA as BFA replacement in castables for blast furnace runners

Blast furnace runners are a highly demanding refractory application in terms of refractoriness, corrosion resistance (direct contact with molten pig-iron and slag), oxidation resistance, abrasion resistance and thermal shock resistance. A challenge facing operators of blast furnace runners is reducing the loss in production due to the system down-times for refractory maintenance. Thus, the campaign life of the blast furnace runners is a key parameter to evaluate the level of performance of the applied refractory products. The most common refractory aggregates used in the formulation of castables for blast furnace runners are brown fused alumina (BFA) and silicon carbide (SiC).
On-site testing of castables for blast furnace runners based on FBA was conducted at ArcelorMittal Asturias plant (Gijón, Spain). The alternative refractory castables formulations tested in the industrial application trial were based in total replacement of BFA by sintered FBA and applied to the system in the form of following refractory components:

1. Skimmer blocks (2 test specimens, 2 tonnes) and plates (4 test specimens, 1 tonne) for the main through.
2. Pre-cast shape for the pig-iron runner end (1 test specimen, 2.5 tonnes).
3. Pre-cast for the slag runner end (INBA) (1 test specimen, 1.6 t).
4. Wear lining for the slag runner (3.5 tonnes).

The tested castables and pre-cast shapes based on FBA successfully completed the target campaign life of the blast furnace runners or, alternatively, the service life extension between general and partial repairs, which evidence a level of performance comparable to BFA-based formulations, in terms of refractory durability. On this basis, the FBA lower bulk density and competitive price are expected to positively impact on the specific consumption of castable per tonne of pig-iron and the costs for refractory producers and users.

FBA as BFA replacement in high-alumina bricks

An industrial application trial of high–alumina FBA-based bricks in the lining of a cement rotary kiln is also successfully on-going.

CONCLUSIONS

FBA (Fired Bauxite Aggregate) is a new highly-refractory sintered raw material with an Al_2O_3 content > 92% and a bulk density > 3.5 g/cm^3. The major phase of FBA aggregate is corundum (ca. 84% α-Al_2O_3) with mullite (ca. 11% $Al_{2.4}Si_{0.6}O_{4.8}$) and aluminium titanate or tialite (ca. 5% Al_2TiO_5) as minor phases.
FBA grains exhibit inter and intra-granular closed pores, which is a microstructural characteristic of the sintered aggregates. Therefore, the bulk density of FBA (3.5 – 3.6 g/cm^3) is lower when compared to BFA (3.85 g/cm^3). However, it is important to remark that FBA water absorption (0.8%), apparent porosity (2.9%) and volume of accessible pores > 1 µm (2%), which are key factors for corrosion resistance of the refractory formulations, are at comparable levels to BFA. On the basis of FBA lower bulk density, the potential cost advantage by reduction of material consumption should be analysed for each application. Additionally, mullite has a positive impact on thermal shock resistance, mechanical strength and creep behaviour of the refractory products.
The corrosion resistance of Al_2O_3–MgO-C (AMC) bricks based on sintered FBA was found to be at comparable level to commercially available premium and high-grade AMC bricks, which are based on BFA.
FBA-based castables successfully completed the planned campaign life of the blast furnace runners system during the industrial trial at ArcelorMittal Asturias.
An industrial application trial of high–alumina FBA-based bricks in the lining of a cement rotary kiln is also successfully on-going.
The results from the laboratory tests and industrial validation trials of refractory FBA-based products evidence the potential of the new high-alumina sintered aggregate to become a technical alternative for the total or partial replacement of brown fused alumina (BFA) in various refractory applications and also as a raw material to up-grade refractory formulations based on fired bauxite (RGB).
The production process of FBA includes 2 firing stages (calcination + sintering) of BauxST^{AR} ore, the world's highest quality gibbsitic refractory-grade bauxite (Guyana). The installation of the new FBA production line is successfully on-going at ARCIRESA main plant, located in Lugo de Llanera (Asturias, Spain). As the new refractory aggregate will be manufactured in EU and its production process is independent from Chinese raw materials, FBA provides a European strategic alternative to brown fused alumina (BFA) imported from China and ensures refractory producers a long-term, reliable supply and stable product quality.
FBA introduction to the market is scheduled for the first quarter of 2023.

Acknowledgments:

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REFERENCES

[1] Schnabel, M.; Buhr, A.; Schmidtmeier, D.; Chatterjee, S.; Dutton, J.: Perceptions and Characteristics of Fused and Sintered Refractory Aggregates. Refractories Worldforum 7, 2015.