SYSTEMIC ANALYSIS FOR THE SELECTION OF ANODE BAKING FURNACE REFRACTORIES

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Abstract

Purchasing and installing refractory materials are some of the major baking furnaces' costs. Usually, the products are selected considering the corrosion during operation. Nevertheless, other variables may affect their performance and must be evaluated. Because of the height of the flues (and the high temperatures), a load is imposed at the bottom part of the furnace and, thus, creep analysis is important. In parallel, loading and unloading anodes can cause mechanical damages, that may be evaluated. Over-heating is another processing drawback and determining the refractory's maximum service temperature is required, as well as the thermal shock due to constant sections' heating-cooling cycles. Finally, the thermal conductivity may be analyzed as this is a critical parameter to the anodes' thermal treatment. Based on this approach, various materials were evaluated, pointing out the best options, considering not only the technical potential but also the savings on purchasing high-performance but low-cost refractory materials.

Key-words: refractories, baking furnace operations, working life

1. Introduction

Reducing the aluminum production costs is a key issue for the competitiveness of this industry. Considering that refractory materials stands for roughly 40 % of a bake furnace investment cost and 50 % of its maintenance cost [1], the proper selection of these products is critical for the equipment's overall working life and consequent purchasing / maintenance expenses.

The flue and head walls of these furnaces are comprised by aluminosilicate bricks [2, 3], totalizing between 1 and 2 million pieces per baking furnace. The main functions of these products are [4]: to withstand high-temperature flue gases and direct them in the chambers; to provide heat transfer from the flue to the pit to bake the anodes; to keep the desired heat balance of the furnace throughout its lifetime, reducing the energy consumption during the anode production; and to maintain a tight lining to inhibit the evaporation of pitch fumes from the process.

Coupled with the furnace design and the quality of the used bricks, there are processing parameters that influence the flue wall life [5, 6]. First of them is the sodium content in the green anodes, that lead to considerable corrosion of the bricks. In addition, fuel components can result in chemical attack. Moreover, mechanical stresses can be formed during loading-unloading anodes as well during the withdraw of adhered carbon at the surface of the refractory wall. The continuous heating and cooling cycles of the furnace can result in thermal shock, which may be considered as well. Besides this, eventual heterogeneous combustion in the flue walls can cause localized overheating, leading to liquid phase formation in the bricks, reducing its performance. Another thermo-mechanical damage that can be observed is creep, due to the weight of the bricks over the bottom layers. These requirements indicate that the refractory must be evaluated systemically as it withstands a complex environment and must further present suitable thermal conductivity to increase the firing process efficiency [7].

Figure 1 shows a summary of the main wear mechanisms that can damage the bricks and the properties that may be evaluated during their selection. The objective of this work is to evaluate these aspects aiming to find the most promising technical options, increasing the overall number of fire cycles and reducing the related costs for purchasing and maintenance.

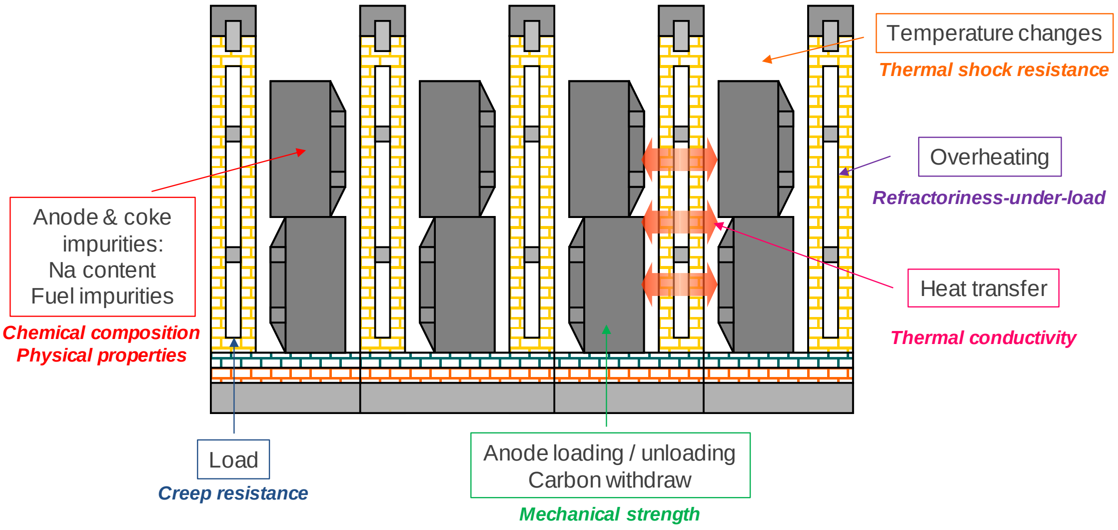

Figure 1 - Correlation between process and design parameters and the refractory properties.

2. Materials and Techniques

Seven refractory products from four distinct suppliers were selected for the proposed characterization. The first evaluated aspect is related to chemical attack and the tests selected were: X-ray fluorescence (ASTM C-573) for the brick chemical composition analysis, apparent porosity / bulk density (ASTM C-20) and permeability (ASTM C-577), for understanding how the physical / microstructural parameters can help to inhibit gas infiltration in the pores.

The mechanical tests used were the cold crushing strength (ASTM C93) at room temperature and the hot modulus of rupture (ASTM C583) at 1370 °C. Further thermo-mechanical tests conducted were the refractoriness-under-load (RuL), using a heating rate of 5 °C/min up to 1600 °C and compressive load of 0.2 MPa (from this test, one can define the initial softening as well as the maximum service temperature) and creep resistance, using again a heating rate of 5 °C/min but now up to 1280 °C or 1427 °C followed by a dwell time of 24h at these temperatures (the linear deformation is measured). These later tests were carried out based on the DIN 51053 standard.

Thermal shock tests were also performed, based on ASTM C1171 standard. The thermal gradient (ΔT) was of 1000 °C and after every two heating-cooling cycles, the elastic modulus values were measured using the bar resonance technique (ASTM C1198). Finally, the thermal conductivity was evaluated using the ASTM C1113 (hot-wire method).

3. Results and Discussion

The chemical composition of the bricks is presented in Table 1. Except for B and F all materials have a high content of silica, which is relevant to withstand alkali attack. Regarding the impurities, it is worth keeping the iron amount lower, which is attained for all of them. Nevertheless, TiO_2 amount is excessive (> 2 wt%) for samples C and D, whereas the alkali oxide ($Na_2O + K_2O$) contents is high for B, E, F and G. The presence of these oxides can not only induce additional corrosion, but also lead to liquid phase formation, reducing the bricks' refractoriness and affecting the overall properties, imparting a negative effect to the expected working life of the flues and furnace.

Figure 2 shows the porosity level and the bulk density of the products. A maximum of 15 % of porosity was set as a good reference, whereas the minimal density should be 2.3 g/cm^3. Materials A, B, C, D and G were suitable, but E and F (same supplier) were not. This can indicate a certain processing drawback of the producer related to pressing, leading to lower density and higher porosity, or can be related to the formulation itself (particle size distribution). Even though the porosity was higher in this later case, the permeability level (for all products) was acceptable (Darcian parameter, k_1, below 3 x 10^{-13} m^2), which is favorable to inhibit the infiltration of vapors. Thus, although the amount of pores (apparent porosity) can be greater in some cases, the lower size and / or the pore distribution (related to the tortuosity) is adequate to withstand gas penetration.

Table 1 - Chemical composition of the evaluated bricks.

Oxide content (wt%)							
Bricks / Oxides	**A**	**B**	**C**	**D**	**E**	**F**	**G**
SiO_2	> 49	> 45	> 46	> 47	> 47	> 46	> 47
Al_2O_3	> 47	> 46	> 48	> 48	> 49	> 50	> 49
Fe_2O_3	< 1	< 1	> 1	> 1	> 1	> 1	< 1
TiO_2	> 1	> 1	> 2	> 2	> 1	> 1	> 1
Na_2O	< 0.2	> 0.5	-	-	< 0.2	< 0.2	-
K_2O	-	> 0.5	> 0.1	> 0.1	> 0.3	> 0.3	> 0.3

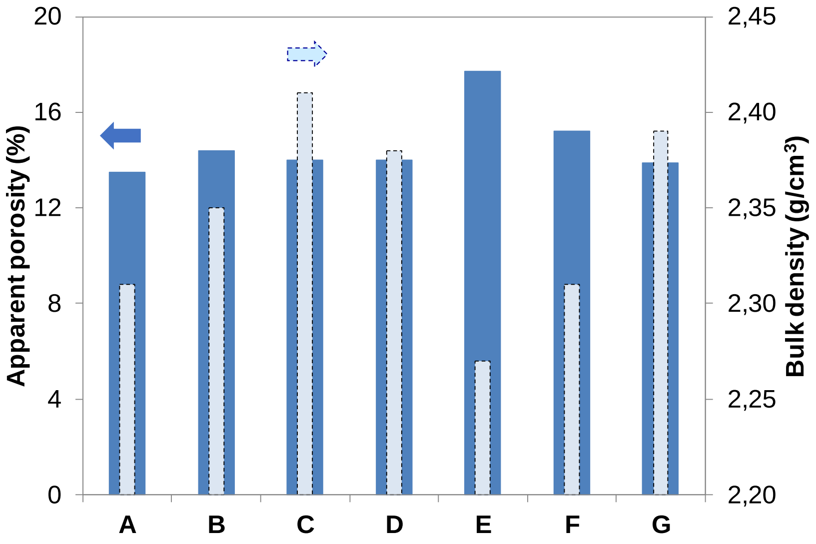

Figure 2 - Apparent porosity and bulk density of the bricks.

Concerning the mechanical properties, the creep linear deformation (Table 2) was evaluated at two distinct temperatures (1280 and 1427 °C) after 24 h of dwell time and under a compressive load of 0.2 MPa. Brick E had the highest linear deformation in both temperatures, indicating that it is not appropriate to withstand loads (such as the flue weight itself). Product C also considerably deformed at the highest testing temperature (1427 °C). Conversely, brick A had an outstanding behavior, with the lowest deformation levels. Although bricks B, D, F and G deformed more than A, they are still good options, as deformations below 3 % are acceptable, considering the high testing temperatures.

Table 2 - Creep resistance of the bricks, measured by the linear deformation after 24 h of dwell time at 1280 or 1427 °C.

Bricks / Testing temperatures	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1280 °C	- 0.1	- 0.3	- 0.2	- 0.4	- 0.6	- 0.3	- 0.2
1427 °C	- 1.2	- 2.9	- 4.1	- 3.0	>> - 5.0	- 3.0	- 2.8

Another parameter that may be evaluated is the mechanical strength, due to the process practices such as anode loading / unloading and flue wall cleaning or because of design issues, for instance, the configuration of the tie bricks that lead to bending during use. Standard values of 50 MPa for the cold crushing strength and 8 MPa for the hot modulus of rupture at 1370 °C are set as suitable numbers. As shown in Figure 3, bricks A, C, F and G attained this condition, whereas B, D and E presented an inappropriate behavior, which could reduce the bricks' working life during use in the furnace.

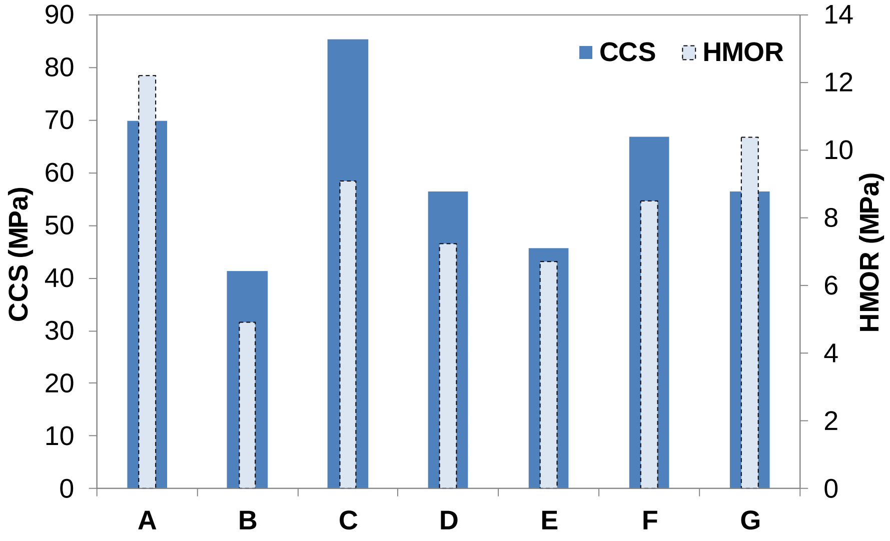

Figure 3 - Cold and hot mechanical strength of the bricks.

Considering the cycling temperature changes in the furnace's sections, it is necessary to evaluate the thermal shock resistance of the bricks. Figure 4 presents the elastic modulus evolution (MOE) with cooling and firing cycles considering a thermal gradient of 1000 °C. There are two aspects that may be considered: the initial MOE value, which indicates the rigidity of the brick before the thermal shock, and the percentage drop after 6 cycles, that is related to the material's ability to withstand the damage caused by thermal shock (the lower the MOE loss, the lower the formation of cracks is and, thus, the higher the resistance to temperature changes). Absolute initial MOE values above 20 GPa are already suitable and the only material that did not present it was brick D. Regarding the MOE loss (Table 3), it can be observed in the figure that brick A, for instance, has very high initial elastic modulus, but a considerable drop after initial 2 thermal shock cycles (75 % after 6 cycles). On the other hand, brick G has also high initial MOE, but lower decay after 6 cycles (33 %), pointing out a better thermal shock resistance.

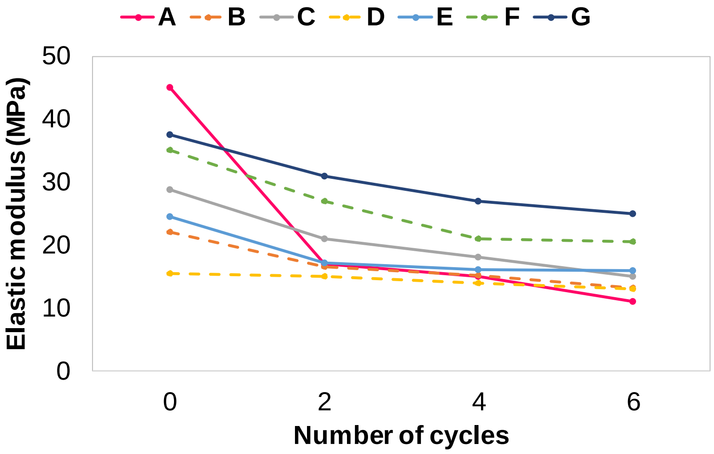

Figure 4 - Elastic modulus of the bricks as a function of the number of thermal cycles (for a ΔT = 1000 °C).

Over-heating is another cause of reduction in the flue wall lifetime. In this sense, evaluating the maximum service temperature of the bricks is of utmost importance and this can be measured by the refractoriness-under-load technique (continuous heating up to 1600 °C under compressive load of 0.2 MPa). To attain this value, one may consider the temperature at which the deformation starts (called softening temperature, $T_{softening}$) and the one when 0.5 % of linear deformation takes place ($T_{0.5\%}$). Table 4 shows these temperatures and highlights the suitable behavior of bricks A, F and G, presenting

$T_{softening}$ > 1250 °C and $T_{0.5\%}$ = 1500 °C. Brick C has the most concerning condition, due to the lowest values for both measurements.

Table 3 - Elastic modulus loss (%) of the bricks after 6 thermal cycles.

Bricks	**A**	**B**	**C**	**D**	**E**	**F**	**G**
% MOE decrease	75	40	49	16	35	41	33

Table 4 - Softening and maximum service temperatures of the bricks.

Bricks / temperatures	**A**	**B**	**C**	**D**	**E**	**F**	**G**
$T_{softening}$ (ºC)	1300	1290	1196	1220	1220	1270	1284
$T_{0.5\%}$ (ºC)	1500	1455	1450	1470	1470	1500	1500

To finalize the technical analysis, the thermal conductivity - K (Figure 5) is presented. It is very common in the refractory area to look for materials with low K, to save energy. Nevertheless, for anode baking furnace, a distinct approach may be used as the primary role of the bricks is the heat transfer to the anodes to bake them. Thus, K values higher than 2 W/m.K are considered appropriate for this objective. This level was attained for bricks C, D and G, being then good alternatives to provide an efficient heating to the carbon blocks.

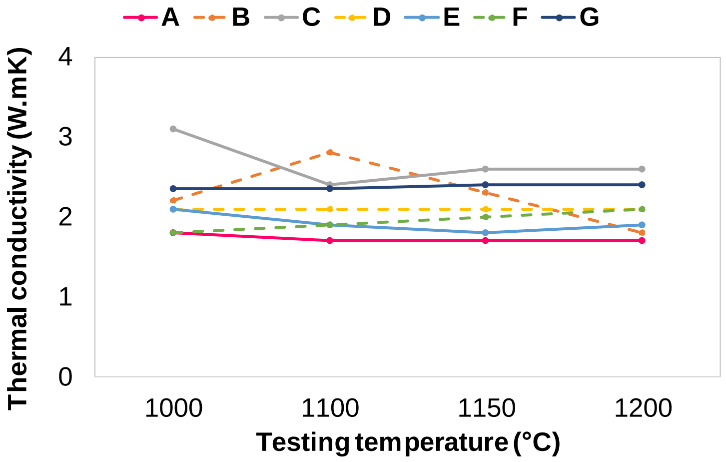

Figure 5 - Thermal conductivity (K value) of the bricks in the temperature range of 1000 to 1200 °C.

4. Final remarks

Based on this systemic evaluation, it was possible to identify the bricks that can present high performance during use in anode baking furnaces. Table 5 presents a technical ranking of these products based on the evaluated properties. Compositions A, F and G have better properties and thus are the most suitable options, whereas products C and D can also be considered if they have attractive purchasing prices. Conversely, products B and E did not show good properties and must then not be considered during the selection of bricks for this application. This analysis, coupled with commercial evaluation, can be very useful to increase the working life of the flues and the furnace and, thus, contributes to reduce the overall aluminum production costs, which is the final objective of the work.

Table 5 - Overall analysis of all bricks based on the attained laboratory results.

Bricks / Properties	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Chemical composition	2	0	1	1	1	1	1
Porosity	2	2	2	2	0	1	2
Density	2	2	2	2	1	2	2
Permeability	2	2	2	2	2	2	2
Creep resistance	2	1	0	2	0	2	2
Cold crushing strength	2	0	2	2	1	2	2
Hot modulus of rupture	2	0	2	1	1	2	2
Thermal shock	0	1	1	1	1	2	2
Refractoriness-under-load	2	1	0	1	1	2	2
Thermal conductivity	1	1	2	2	1	1	2
Sum	17	10	14	16	9	17	19

5. References

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