

WHAT AFFECTS EROSION RESISTANCE OF REFRACTORY CASTABLES?

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ABSTRACT

The wear of refractory linings is often a critical problem in process units where transfer lines are subjected to high velocity gas stream containing solid particles. Knowledge regarding erosive wear of refractory linings under these conditions is restricted and, as consequence, the technological development is slow and, in general, carried out in an empirical way.

The objective of the present work is to review relevant aspects related to erosive wear in industrial applications and to investigate the erosion resistance of refractory castables currently used by the aluminum industry and in petrochemical cracking units. Among the erosion variables tested are: the particle impingement angle, line pressure, particle size and hardness, the microstructure of the refractories, the binding agent content, type of aggregate, thermal history and porosity.

It was found that the higher erosion was attained at 90° of impingement and decreased slightly when the angle was close to 30°. The results also pointed out that erosion was proportional to the particle velocity, its hardness and size. In addition, it was observed that the refractory erosion resistance is mostly affected by reducing the porosity.

INTRODUCTION

Refractory castables are commonly used to provide erosion resistance at the working temperature. In the aluminum industry, for instance, they are mainly presented as linings in aluminum hydroxide calciners. In fluid bed stationary calciners, hot transfer lines and cyclone separators have to withstand erosion of particles conveyed at approximately 30 m/s and temperatures as high as 1200°C [1]. Similar conditions are found in cyclones and catalyst transfer lines of petrochemical cracking units [2], where plastic refractories and castables are used. To reduce the maintenance costs and the risk of unplanned production stopping, refractory castables with improved erosion resistance are required.

In this paper, some concepts concerning the preliminary developments of erosion resistance of refractory castables will be presented. Current problems found in the aluminum industry and in catalyst cracking units are shown to provide a basic understanding regarding erosion. Finally, results of erosion testing of refractory castables are shown and discussed.

Erosion in industrial applications

The selection of the suitable wear resistant lining will depend on various factors including the operational life extension provided by the material, overall cost, design parameters of the system, dimensions of the lining area, the media being conveyed, flow rates and chemical attack [3].

Erosion is defined as the progressive loss of original material from a solid surface due to the mechanical interaction between the surface and a fluid, i.e. impinging liquid and/or solid particles [4]. Due to the broad range of these definitions, ASTM suggests that the wear mechanism has to be indicated, which in this work could be stated as erosion by solid particle impingement.

Erosion is detected in industrial applications where high particle velocities and turbulence of flowing liquids and gases are found. Erosion starts to become a problem when the gas velocity is about 3 m/s, and it is very severe, even for low particle concentration, at velocities as high as 36 m/s [5].

In fluid bed stationary calciners for aluminum industry or cracking units in the petrochemical industry, sudden changes in gas flow direction are required. As result, erosive particles impinge on internal walls of transfer lines at high velocities, causing wear. Modifications in the equipment project aiming at reducing particle velocities and improvements in refractory linings helps to increase life expectancy of the equipment. However, these changes are mostly infeasible, pointing out the need for refractory castables with superior wear resistance.

Erosion of materials

Parameters that control wear include the properties of the carrier fluid, those of the particles themselves, and the properties of the target material [1]. This work concerns the last two items.

The particle parameters that influence erosion include particle shape and size, density, the particle velocity, and the angle of the particle impingement. The relevant properties of the target material include the microstructure, the toughness, and the hardness. According to Ruff and Wiederhorn [6], the most important experimental parameter that controls erosive wear is the particle velocity.

Investigations of the properties of the target material are concentrated in two areas of study: the hardness of the target [7] and the

flaws on the surface of brittle materials [1]. Oh [8] suggests that surface cracks are the nuclei for larger ones which are formed during erosion. Therefore, the distribution and depth of the surface crack influence the erosion rate. To support his arguments, the author has related the erosion rate to the Weibull parameters which express the flaw size distribution in the material [9]. Thus, clear evidence that the surface quality is an important factor in erosive wear can be shown.

The influence of the hardness of the target material is the differential factor among the developed models for brittle ones, as presented later in this paper.

Science of Erosion

Impact by sharp particles (angular rather than round) results in a different type of crack pattern in the target surface. Two types of cracks are observed: the first is a radial set of cracks oriented primarily perpendicularly to the target surface; the other is a lateral set of cracks parallel to the target surface (**Figure 1**). The radial set of cracks is primarily responsible for strength degradations, whereas the lateral ones are responsible for erosive wear.

Two of the most accepted models of erosion developed for brittle material were proposed by Evans [11] and by Wiederhorn – Law [12]. Both models assume that particle impact is normal to the target surface and that erosion is the result of cumulative damage of no interacting, single particle impacts. Moreover, the models are based on the assumption that erosion occurs entirely by crack propagation and chipping. The main difference between the models is the contribution of the plastic deformation to the process of crack formation.

The model developed by Evans [11] assumes that the erosion rate is proportional to the amount of material withdrawn by each impact event. The volume lost (V) per impact is calculated from the depth of penetration and the maximum size of the lateral cracks formed during impact. Therefore, the following equation is obtained for the erosion rate:

$$V \propto v_0^{19/6} \cdot r^{11/3} \cdot \rho^{19/12} \cdot K_{IC}^{-4/3} \cdot H^{-1/4} \quad (1)$$

where:

- V : volume lost (m^3)
- v_0 : particle velocity (m/s)
- r : particle radius (m)
- ρ : particle density (kg/m^3)
- K_{IC} : critical stress intensity factor of the target material ($MPa \cdot m^{1/2}$)
- H : hardness of the target material (GPa)

The elastic plastic theory used by Wiederhorn – Law [12] can also be applied to the development of an erosion theory. Assuming that the lateral crack size is proportional to the radial crack size and that the depth of the lateral cracks is proportional to the maximum particle penetration, then the wear rate is given by the following expression:

$$V \propto v_0^{22/9} \cdot r^{11/3} \cdot \rho^{11/9} \cdot K_{IC}^{-4/3} \cdot H^{1/9} \quad (2)$$

This theory is more suitable for high temperatures, considering that the wear is carried out by both mechanisms: ductile, based on the plastic flow; and brittle, with microcrack formation.

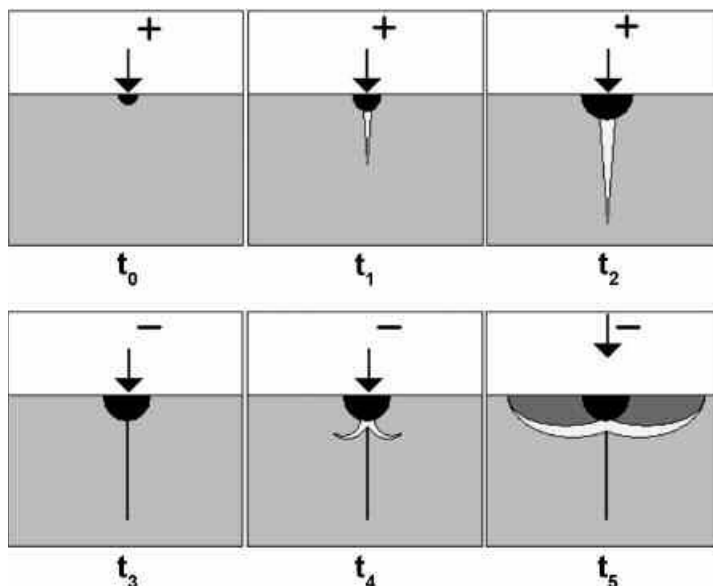


Figure 1. Shows crack growth during sharp impact. (+) indicates loading and (-) unloading. Dark area denotes irreversible strain [10].

Although the theory presented above is supported by erosion data, the functional dependence of this theory on others ceramic materials differs significantly. Considering the complexities of the erosion process, the simplifying assumptions used to derive models of erosion and those concerning dense ceramics, not refractory castables, additional theoretical and experimental work will be needed to further understand the refractory material erosion process. One of the reasons of this inequality is associated with the refractory materials microstructure, multi-phase composites consisting of a matrix paste surrounding a cluster of coarse aggregate grains [13].

“Shadowing Effect”

Fully developed erosion surfaces show a somewhat different behavior from the reported model above. The main theory which describes the erosion of refractory castables is known as the “shadowing effect” [14]. In the present model, the aggregate grains were approximated by spheres. Thus, only the matrix phase among the spheres is eroded by a direct impact of the erosive particles. As the matrix phase is eroded, canals are developed exposing the aggregate grains, which protect the matrix phase through the “shadowing effect”.

This model suggests that the dependence between erosive wear and the impingement angle is determined by the size and spacing to the largest aggregate particles in the refractory, as illustrated in **Figure 2** and according to **Equation 3**.

$$A = 2 \cdot (1 - R/\sin\alpha) \quad (3)$$

where:

- A : total available area (mm^2)
- R : aggregate grain radius (mm)
- α : angle of impingement ($^\circ$)

Erosion and Porosity

It is generally assumed that the wear behavior of the refractory castables is controlled by the strength of the material, and that any

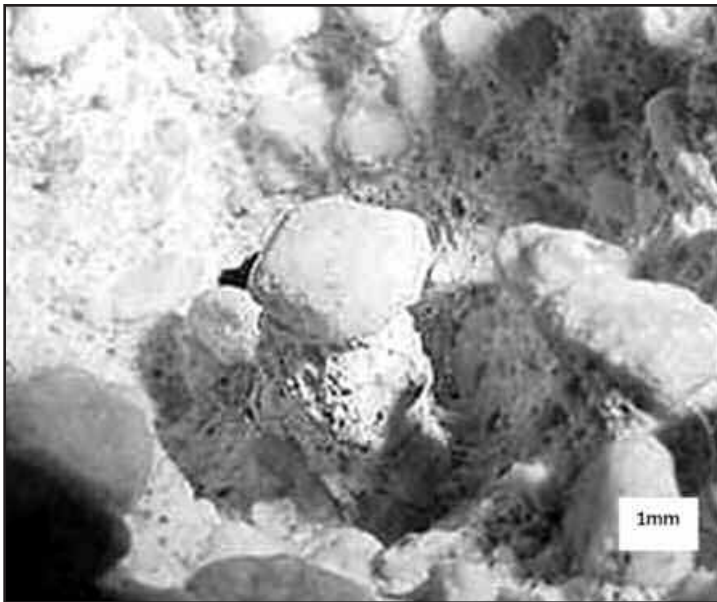


Figure 2. “Shadowing effect” where the aggregate is protecting the underlying matrix.

change in this property will be followed by a corresponding one in the erosion rate [15].

The strength of ceramics can be understood in terms of the Griffith [16] equation of strength:

$$\sigma_f = 1/Y \sqrt{2 \cdot E \cdot \gamma_{eff} / \pi \cdot C} \quad (4)$$

where:

σ_f : strength (MPa)

γ_{eff} : fracture energy per unit area necessary to initiate failure propagation (J/m²)

E: Young’s modulus (GPa)

C: flaw size

Y: dimensionless constant

Equation 4 predicts that the strength of ceramics is mainly controlled by two variables, fracture energy and flaw size. Both parameters depend strongly on the microstructure. Thus, microstructural parameters, such as porosity, fulfill an important role in the strength of the material.

Porosity is deleterious to the flexural strength for two reasons: pores reduce the cross/sectional area across which a load is applied, and they also act as stress concentrators. Experimentally, it has been shown that the flexural strength decreases exponentially with the volume fraction porosity [17].

As a consequence, porosity has also been shown to affect the wear behavior, where increased porosity leads to degradation in the wear resistance [18]. A feasible option to reduce porosity is the use of substances known as glass former, a raw material responsible for the formation of liquid phases during the firing process. A highly effective glass former is the borosilicate frit, a material which has BO₃ planar triangles and SiO₄ tetrahedron linked to form networks, which generates glass with lower melting temperatures and a broader working viscous range. This melt should form a dense layer, reduce porosity and improve the toughness of the material.

MATERIALS AND EXPERIMENTAL PROCEDURE

Four different types of materials were chosen for the present work. Aluminosilicate bricks (B), soda-lime glass (G), erosion resistant commercial available plastic refractories (PA, PB and PC) and a high alumina refractory castable (C) developed by the research group where this work was developed [19].

Erosion tests were conducted at room temperature (ASTM C 704 [20]) using the samples with the following dimensions 115 x 115 x 25 mm³ [21]. The experimental procedure used in this work can be divided into three distinct stages: equipment accuracy, specimens’ preparation and analysis of erosion resistance as a function of some parameters, such as operational characteristics, materials properties and their thermal history.

Equipment Description

The erosion equipment is illustrated in **Figure 3**, where the essential components consist of a metal chamber, a feeding mechanism and the air pressure and sand blast devices. A schematic diagram of the sand blast mechanism is shown in **Figure 4**, consisting basically of an air nozzle (A), an erosion media inlet (B), a stabilizing sleeve (C) and the glass tube (D). The glass tube must be replaced after each test in order to avoid changes of its internal diameter and of the corresponding pressure.



Figure 3. Erosion test equipment [22].

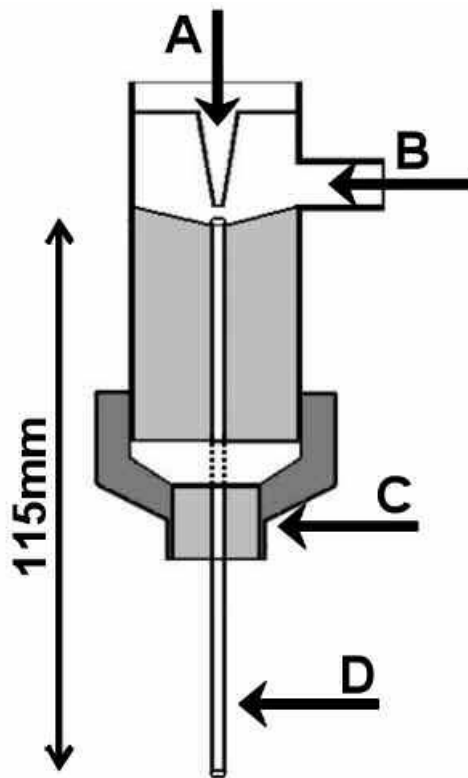


Figure 4. Sand blast device: (A) Air nozzle; (B) Erosion media hole; (C) Stabilizing sleeve; (D) Glass tube.

Equipment Accuracy

In order to ensure the tests' reproducibility, erosion experiments were performed using soda-lime glass standard specimens. This material was chosen due to its homogeneity and zero porosity. Results obtained showed good reproducibility ($4.92 \pm 0.04 \text{ cm}^3$), since the maximum result difference between two tests in this material using the same equipment was 0.5 cm^3 [22].

Silicon carbide particles (EC6-F036, Treibacher Schleifmittel, Brazil) used in this work were dry sieved according to the ABNT standard [23] in the size range of 300 – 600 μm to ensure the correct particle size distribution.

Preparation of Specimens

Plastic refractories were mixed using a rheometer developed for refractory castables [24] and molded. The specimens were cured for 24 h at room temperature and dried for 24 h at 110°C . For castable refractory specimens', curing was conducted for 24 h in an environment kept at 25°C and $\sim 100\%$ relative humidity.

Engman [25] demonstrated that, due to the "shadowing effect", the erosion testing of a heterogeneous material might have different results depending on the region in which the testing takes place. It is suggested that the testing must reach a depth where the measured average wear rate is almost independent of these heterogeneities.

Specimens were wet-ground in order to expose the internal microstructure of the material and to obtain a steady-state erosion behavior [8, 25], as illustrated in **Figure 5**. After that, specimens were dried for another 24 h at 110°C . Based on previous work conducted by the authors, it was concluded that these refractories are not affected by wetting during the grinding process.

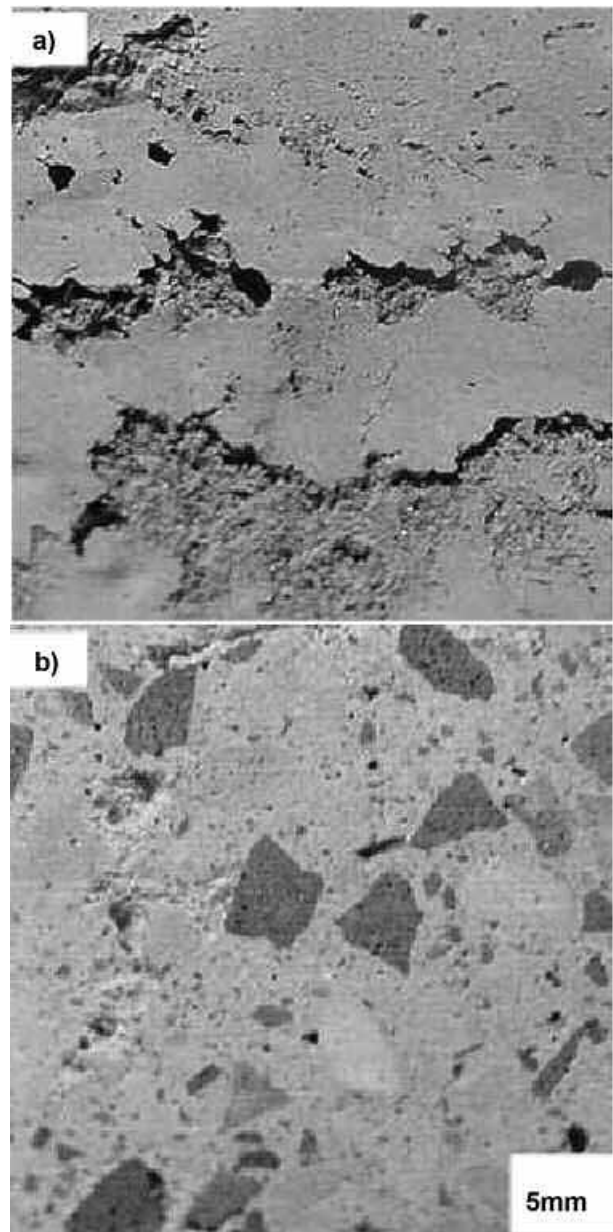


Figure 5. Pictures of (a) not ground and (b) ground surface of the specimens.

Erosion testing parameters

An understanding of how the erosion is affected by its parameters is a primary requirement in the search for knowledge about erosive wear. Therefore, the effect of the line pressure, impingement angle, size and hardness particles on erosion phenomena were examined.

Aluminosilicate bricks (B) and the plastic refractory (PA) – soft and hard materials, respectively – were eroded at a distinct line pressure. In this case, changes in pressure will induce particle velocity shifts. Erosion measurements of this plastic refractory as a function of the particle impingement angle (using a holder that allows the specimen to be tilted to any desired angle) and of the size and hardness of the particles were evaluated, as the importance of the particle hardness has also been recognized in the literature [26]. Silicon carbide, calcined alumina (A1, Alcoa, Brazil) and aluminum hydroxide (C-30, Alcoa, Brazil) were used as erosive media for this study.

Erosion as Function of Materials Properties

In order to understand the influence of binding agent content in the erosion resistance, high-alumina castable compositions were formulated with various calcium aluminate cement contents (2, 5 and 10 wt%). All castables were carefully designed with the software PSDesigner [27, 28].

A comparative study to evaluate the influence of the aggregates on the wear behavior was carried out. Two high-alumina castable compositions were prepared with 10 wt% of calcium aluminate cement and distinct types of aggregate grains: brown and white fused alumina supplied by Elfusa Brazil.

Afterwards, the effect of thermal history of the castables and plastic refractories erosion resistance was evaluated in order to detect whether the materials tested presented any significant change of the binding agent performance. The heating rate and the dwell time were 1°C/min and 5 h, respectively.

In addition, samples of aluminosilicate bricks (B), soda-lime glass (G), erosion resistant commercial available plastic refractories (PA, PV and PC) and a high alumina refractory castable (C) were erode tested and their apparent porosity was measured by water immersion according to the techniques described by the ASTM C-20 standard test method [29]. Specimens of alumina refractory castable compositions with distinct contents of borosilicate frit (0, 1, 3 and 5%) were also evaluated, aiming at a more consistent relation between erosion rate and porosity.

RESULTS AND DISCUSSIONS

Erosion Testing Parameters

Figure 6 presents the effect of the line pressure on the volume loss of different erosion resistant materials (PA and B). Material B is not designed for applications where high erosion resistance is required, as it presents high porosity and crystalline and amorphous phases of low hardness. The harder material – PA – showed less susceptibility to the line pressure [30].

Based on these results, the pressure of 400 mm Hg was selected as a standard value because it imposes a more severe condition among those analyzed. Furthermore, it is the suggested value for ASTM C 704 [20].

The effect of the impingement angle on the volume loss of material PA is shown in **Figure 7**. Erosive wear is the highest when the

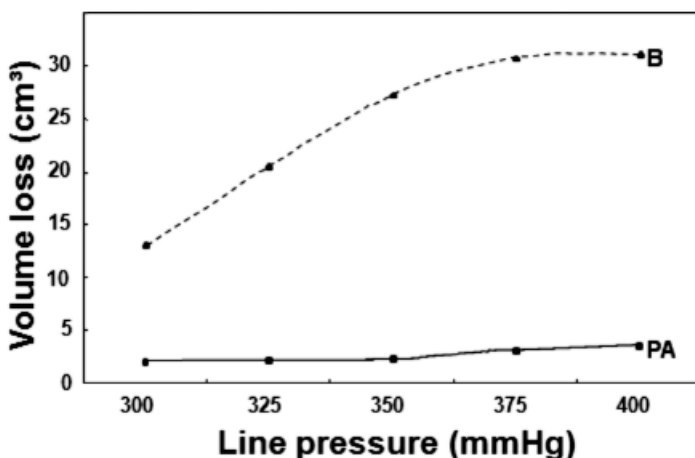


Figure 6. Effect of line pressure on volume loss of distinct erosion resistance materials (B: Aluminosilicate bricks and PA: plastic refractories samples).

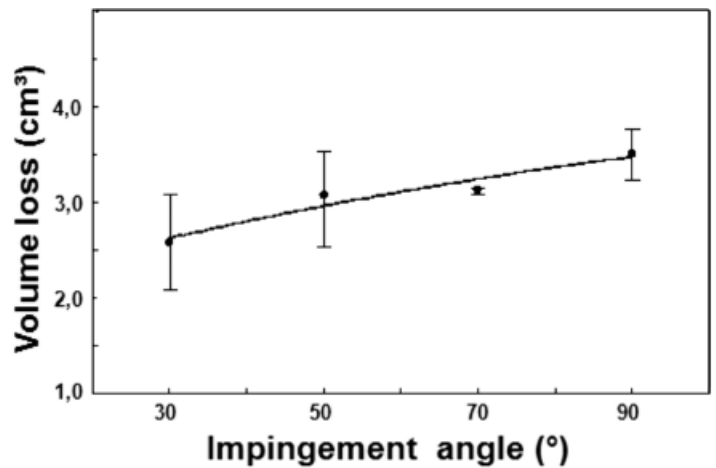


Figure 7. Effect of impingement angle in volume loss of plastic refractory material PA.

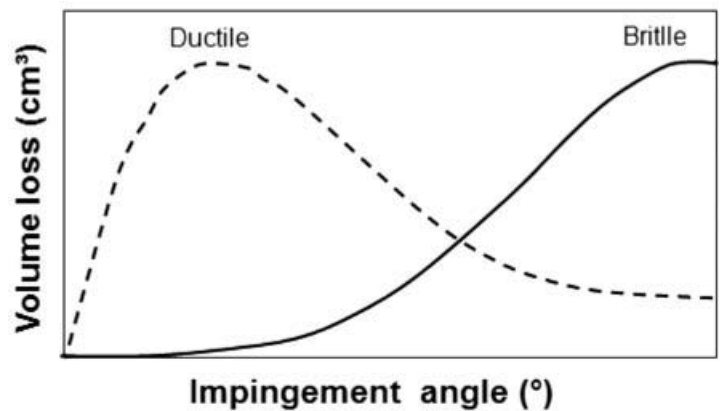


Figure 8. Erosive wear of ductile and brittle materials as a function of the angle of impingement [6].

angle of impingement is 90° and the erosion decreases gradually as the angle changes from 90° to 30°. This behavior is quite similar to that reported elsewhere for refractory castables and for glass [31], although in the case of glass, the erosion rate is observed to decrease more rapidly. Thus, the erosion behavior of the refractory castables is typical of brittle materials (**Figure 8**) showing little or no plastic deformation at room temperature.

Deviations of 10% among the results are acceptable because of the inherent heterogeneity of the castable and plastic refractory specimen microstructure. Materials with superior erosion resistance had a very small weight change, and consequently, the loss of a single grain of aggregate during the test changes its volume loss appreciably. As the impingement angle decreases, usually, increasing deviations were observed, mostly likely due to the smaller volume loss, resulting in not very precise results.

Reduction on the impingement angle leads to the formation of preferential wearing canals among the aggregates, as the matrix is worn out. However, as the impingement angle is below a critical value, these canals are protected by the aggregates – resulting in a decrease in the erosion rate.

Table 1 presents the properties of the erosive media: silicon carbide (SiC), calcined alumina (A1) and hydroxide aluminum (C30) and shows the effect of particle type on the erosion of material PA.

These results show that SiC has a more severe wearing. According to **Equation 1**, one possible reason for this behavior could be its high-

Table 1. Properties of the erosive media

	Bulk density (g/cm ³)	Mohs Hardness	Particle size distribution (μm)			Volume loss (cm ³)
			D10	D50	D90	
SiC	3.17	9.5	310	390	425	3.51
A1	3.5	9.0	55	95	150	0.17
C30	2.42	3.0	60	100	150	0.09

er particle size among the types of erosive media tested, although there is not a large difference in hardness between SiC and the calcined alumina particles. A decreasing particle size usually causes a lower volume loss; which may be associated to the lower kinetic energy of the small particles as they impinge the specimen [32]. The faced morphology of the SiC compared to the rounded ones of the calcined alumina might also have influenced the results.

Even though calcined alumina and hydroxide aluminum are alike in the particle size distribution, the former presents higher hardness and bulk density. Thus, a higher volume of material was eroded by the calcined alumina particles.

Microstructural Parameters

The influence of the binder agent content in the erosion resistance is illustrated in **Figure 9**. Tests performed with 2 wt% calcium aluminate cement were invalid since the erosive agent made a hole through the sample.

Results revealed that the erosion loss decreased with the cement content. This trend can be attributed, partly, to the increase in the matrix phase strength, holding the aggregates in place.

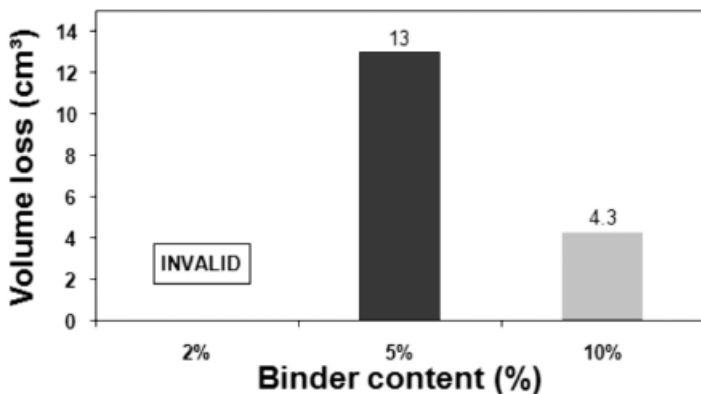


Figure 9. Effect of binder content in the erosion resistance.

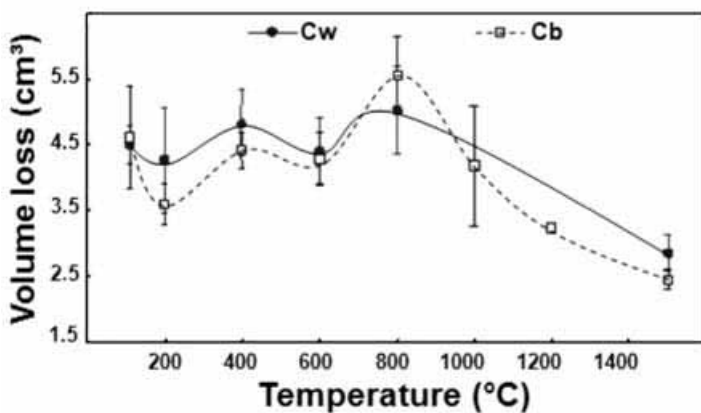


Figure 10. Influence of the thermal history on the volume loss after erosion of two high-alumina castable compositions with distinct types of aggregate grains (Cw: white-fused alumina, Cb: brown fused alumina).

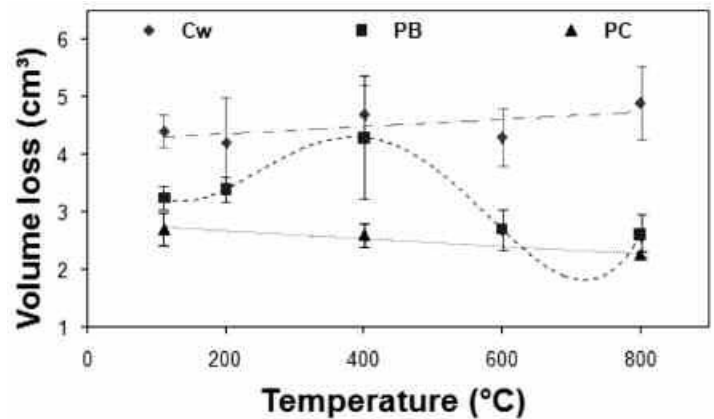


Figure 11. Effect of thermal treatments on erosive wear of a castable (Cw) and plastic refractories (PB and PC).

A comparative study of considering the aggregate nature is shown in **Figure 10**.

The effect of the thermal treatment on the volume loss after erosion was carried out for two high-alumina castable compositions with distinct types of aggregates: brown (Cb) and white (Cw) fused alumina. Although some differences in erosion resistance could be expected due to the distinct porosity of the grains, as shown in **Table 2**, this was not observed. Therefore, castable porosity provides a more consistent correlation with wear loss (**Table 2**).

The effect of the thermal treatment on the erosive wear of the castable (Cw) and the plastic refractories (PB and PC) was analyzed (**Figure 11**). Material PB presented higher volume loss when heat-treated at 400°C and an enhanced erosion resistance after 600°C and 800°C. These results point out the need for thermal treatment at temperatures higher than 400°C in order to maximize the erosion resistance of this material. The use of material C indicates the possibilities of saving energy, since its erosion resistance kept nearly the same level for the evaluated temperatures. However, if heat treatment would be required to fit it with other materials used in the equipment-lining project, heat treatment will not be detrimental. The erosion resistance of PC material had been enhanced by thermal treatment in the temperature range investigated.

Figure 12 illustrates the relation between erosion loss and porosity of tested materials: aluminosilicate bricks (B), soda-lime glass (G),

Table 2. Porosity of the distinct aggregates and of the refractories with these aggregates

Alumina Type	Porosity of aggregates (%)	Refractory castable Porosity (%)
Brown Fused alumina	2.5	6.8
White fused alumina	7.0	7.0

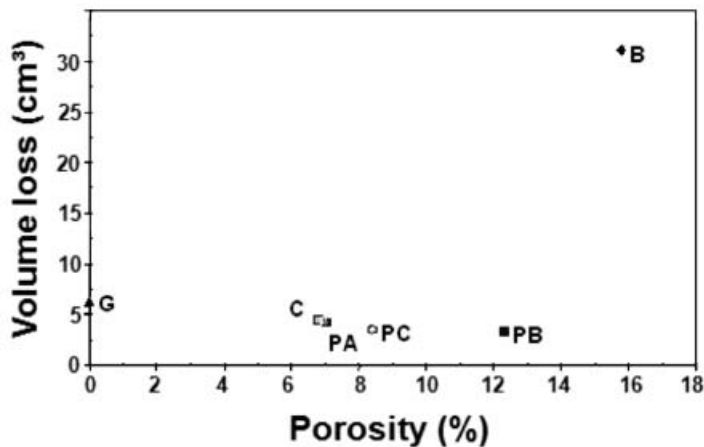


Figure 12. Erosion loss and porosity of tested materials.

erosion resistant commercial available plastic refractories (PA, PB and PC) and a high alumina refractory castable (C).

Even though glass does not present any porosity, the specimens resulted in lower erosion resistance than the evaluated plastic refractories and the volume loss was similar to the castable. Equation 1 can explain this behavior, since this material has lower values of hardness (H) and critical stress intensity factor (KIC), which could result in the formation and propagation of cracks after loading for long time intervals.

Although a close relation between the erosion rate and porosity would be expected, this was not observed. Plastic refractories presented very similar erosion resistance but distinct porosity values. One possible explanation for this behavior may be the different binding agents of these materials and, consequently, distinct hardness. Furthermore, the size and the mean distance among the coarse particles of each plastic refractory can influence the erosion resistance of these materials.

Figure 13 presents the effects of thermal treatment on the volume loss of alumina refractory castable compositions with different contents of borosilicate frit. The results attested the influence of porosity on the erosion for this castable class. Generally, the increase in the temperature leads to higher porosity values in the refractory castables with calcium aluminate cement, due to the dehydration of the binder [33]. This trend was modified by adding borosilicate frit, leading to the improvement of the wear resistance of the castables.

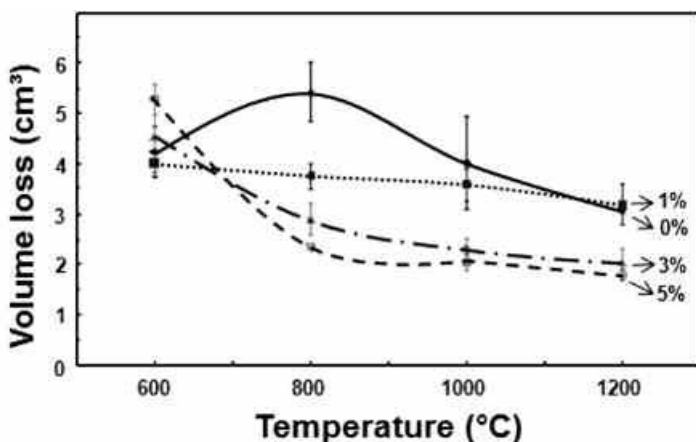


Figure 13. Effect of thermal treatment on volume loss of alumina refractory castable compositions with different contents of borosilicate frit.

CONCLUSIONS

It was observed that some features of the erosion media particles and testing conditions including size, hardness, velocity and impingement angle, and the increase of any of these variables resulted in larger volume loss.

It is believed that the degradation in wear resistance is mostly due to the decrease in matrix bond strength and as a result the increased number of microstructural flaws that act as stress concentrators for nucleation and propagation of cracks. The thermal history of the material may cause changes in the binder efficiency and, consequently, a meaningful change in the erosion resistance.

Erosion resistance in commercial available plastic refractories evaluated in this work presented similar erosive wear resistance values. These materials have been an effective option to control wear by erosion in transfer lines of industrial units.


The addition of borosilicate frit may be an interesting choice for the erosive wear problem when porosity needs to be reduced. However, because at high temperatures it could induce liquid formation, it is important to identify the most suitable glass former type and content in order to avoid any detrimental aspects to the mechanical integrity of the refractory lining.

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