REFRACTORIES TECHNOLOGICAL EVOLUTION FOR STEEL LADLE*

Ângelo Cristante[1]
Roselaine Magalhães[2]
Santiago Barrios[3]

Abstract
Steel ladle is the steelmaking process pillar, it participates in all steps of secondary refining, from BOF/EAF liquid steel receiving to casting it into the tundish. For this reason, the refractory lining, mainly precast bottom, underwent various development to withstand the severe operating conditions, due to the strictest quality requirements, such as: chemical reactions, temperature changes during the process, oxygen blowing, and vacuum conditions. In order to meet operational requirements, Vesuvius has directed efforts towards the development of high-performance lining associated with technological solutions, which combine a high installation rate, low cost, operational safety, and good ergonomic conditions for employees. Additionally, extending bottom life for more than one campaign, using carbon-free castable and reduction of metal loss due to design enabled significant gains in relation to sustainability. In this context, results of laboratory and industrial tests are presented and discussed, as well as the precast bottom benefits of steel ladle as a replacement for the standard brick lining.
Keywords: PRECAST LADLE BOTTOM; REFRACTORIES; SECONDARY REFINING.

[1] *Engenheiro de Materiais, M.Sc.; Engenheiro de Desenvolvimento, Vesuvius Research Pittsburgh; Pittsburgh, PA, EUA.*
[2] *Engenheira de Materiais, PgDip.; Engenheira de Produto, Vesuvius; Rio de Janeiro, RJ, BR.*
[3] *Engenharia Metalúrgica/ Engenharia Extrativa, M. Sc.; Gerente de Produto, M&T, Vesuvius; Rio de Janeiro, RJ, Brasil.*

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1 INTRODUCTION

Steel ladle is an important vessel that has the function to transfer molten steel between 1500°C to 1700°C from the Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF) to the continuous or ingot casting process. In addition to being used as a transport vessel with a capacity of 160-300 tons for plates and 50-100 tons for rolling steel billets, this ladle is also used as a secondary refining reactor to enhance the quality of the steel and as a controller of the steel flow being poured into the tundish [1,2]. With the advent of the use of ladles as secondary refining equipment, its refractory lining becomes decisive in the efficiency and productivity of the process.
The transformation of transfer vessels to process vessels has made the steel ladles vessels the highest cost/ton for refractories in the steelmaking process [1]. This transformation created a complex combination of steelmaking processes (thermal-chemical-mechanical loads) and mechanical loads from the movement of the ladle. Steel ladles can be in service from 25 to more than 150 heats and with partial repair these values can reach even higher values [1]. The refractory lining of these vessels varies from steel shop to adapt to local requirements and local restrictions. The slag line has the highest breakout statistics followed by the slide gate area [1].
High silicate bricks were initially used in steel ladles, followed by zircon bricks because of their better performance in the secondary refining and continuous casting process [3]. Steel quality improvement and easier/cost-effective installation methods allowed alumina-magnesia spinel monolithic refractories to be employed by the end of the 1980s [3]. During the 1990s, alumina-magnesia monolithic refractories were employed to increase performance [3,4,5].
Technological advantages in the development and installation of refractories have allowed a significant increase in safety and performance. This trend is particularly higher for unshaped refractories [5,6]. This type of refractory can be shaped into molds and then placed into the steel ladle with a crane within hours compared to the time and resourceful consuming use of bricks. Currently, precast shapes of refractories have been used for steel ladle bottoms because of their performance, easy and fast installation, and safety [1,4].
Steel ladle bottom is exposed to higher erosion due to the pouring and treatment of the steel, higher pressure of the molten steel, slag attack after pouring, and thermal cycling. Therefore, ladle bottom refractories must have thermal-mechanical stability, resistance to thermal and mechanical cyclical loads, and corrosion and erosion resistance [1,4,6].
The combination of technological advantages in developing and installing monolithic refractories has allowed the development of enhanced yield ladle bottoms. These ladle bottoms are precast with a tailored made refractory developed to sustain the harsh environment of the ladle bottom while enhancing the molten steel usage.
Vesuvius in partnership with the steel industry directed efforts to combine high-performance material, low water consumption, high density, and low porosity with technological solutions that combine high installation rate, low cost, great operational safety, and favorable ergonomic conditions for the operators.
This work analyzed three different refractories used in steel ladle bottoms and correlated its laboratory results with industrial tests showing the benefits of the precast bottom benefits of steel ladle as a replacement for the standard brick lining.

2 DEVELOPMENT

Table 1 shows the identifications and main characteristics of refractories for steel ladles analyzed.
In this study, the main characteristics, and properties of two high-alumina castables that are used in the manufacture of precast parts were determined, one of them with cement binder and the other without cement. The obtained results were compared to the MgO-C system brick, which is traditionally used for lining steel ladles. Post-mortem samples taken from different areas of a precast ladle bottom after 119 heats were also evaluated.

Table 1. Refractories for steel ladle bottom.

	B1	M1	M2
Shape	Brick	Monolithic	Monolithic
Id	MgO-C Brick	Criterion 92 SR	Numax SL
Chemical	MgO-C	Al_2O_3-MgO-CaO	Al_2O_3-MgO
Binding	Resin	CAC	HA
Thermal Treatment	Tempered	Dried	Dried

2.1 Hot Modulus of Rupture (HMOR)

Hot modulus of rupture (HMOR) were measured at 1400°C and 1550°C with a holding time of five hours. 25x25x160mm samples and 127mm span size were used. The procedure was based on ASTM C583 (2021).

2.2 Apparent Porosity and Bulk Density (AP/BD)

After the hot modulus of rupture test, samples were cut into 25x25x25mm for apparent porosity (AP) and bulk density (BD) test. A pressure container and Isopar were used as the liquid medium. The procedures were based on the ASTM C830 (2016).

2.3 Thermal Shock

Thermal shock test was performed in 25x25x160mm samples immersed in molten steel between 1600°C and 1630°C in an induction furnace. Samples were immersed for two minutes and then cooled down under a fan for 20 minutes. Then, samples were visually analyzed.

2.4 Oxidation Test

Oxidation test was performed in 51mm cubic samples exposed to 640°C for five hours. The samples were cut and the cross-section was visually analyzed.

2.5 Correlation with Industrial Trial

The industrial experiment consisted of lining the bottom of a 350-ton capacity steel ladle in 5 parts. In regions of greater demand, parts “A” and “D” were used, made with M2 castable. For regions with moderate and low wear, conventional castable was used to manufacture the precast.

3 RESULTS AND DISCUSSIONS

Table 2 shows a summary of the main properties of the evaluated materials used in steel ladle bottoms and their characteristics.

Table 2. Analyzed refractories.

	B1	M1	M2
	1400°C		
HMOR (MPa)	+	+++	++
AP (%)	++	+++	+
BD (g/cm3)	+	+	++
	1550°C		
HMOR (MPa)	+	+++	++
AP (%)	++	+++	+
BD (g/cm3)	+	+	++
Thermal Shock	Good integrity, oxidation.	Good integrity penetration.	Good integrity.
Oxidation	Oxidation layer	None	None

3.1 Hot Modulus of Rupture (HMOR)

Figure 1 shows the hot modulus of rupture of the analyzed samples at 1400°C and 1550°C. M1 showed the highest values after 1400°C and 1550°C while B1 showed the lowest values. Spinel formed bonded with calcium aluminate cement (CAC) monolithic refractories are known for their high hot strength values [4,7]. The difference in values for M1 and M2 is associated with the phase transformations, including spinel forming for M2 and CA_6 for M1. B1 otherwise, when exposed to an oxidation atmosphere in higher temperatures has carbon oxidation.

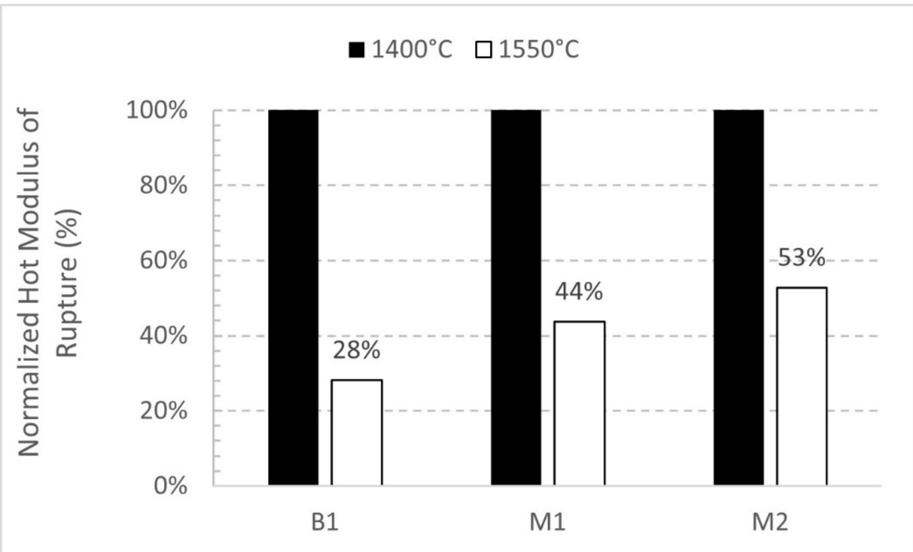


Figure 1. Hot modulus of rupture.

3.2 Apparent Porosity and Bulk Density (AP/BD)

Figure 2 shows the apparent porosity (AP) and bulk density (BD) of the analyzed samples at 1400°C and 1550°C. M2 had the lowest apparent porosity and higher bulk density values. M1 showed the highest values of apparent porosity. This is associated with the CAC phases. Lower porosity is linked to lower corrosion and penetration by molten metal and slag.

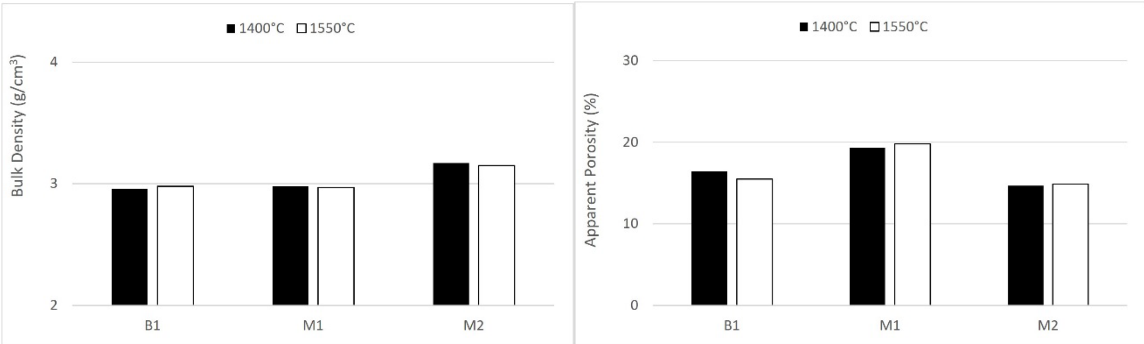


Figure 2. Apparent porosity and bulk density.

3.3 Thermal Shock

Figure 3 shows the thermal shock samples before and after one thermal cycle consisting of immersing samples in molten steel above 1600°C. All samples showed good physical integrity. B1 showed visual signs of oxidation and M1 showed visual signs of corrosion near the interaction between molten steel and air.

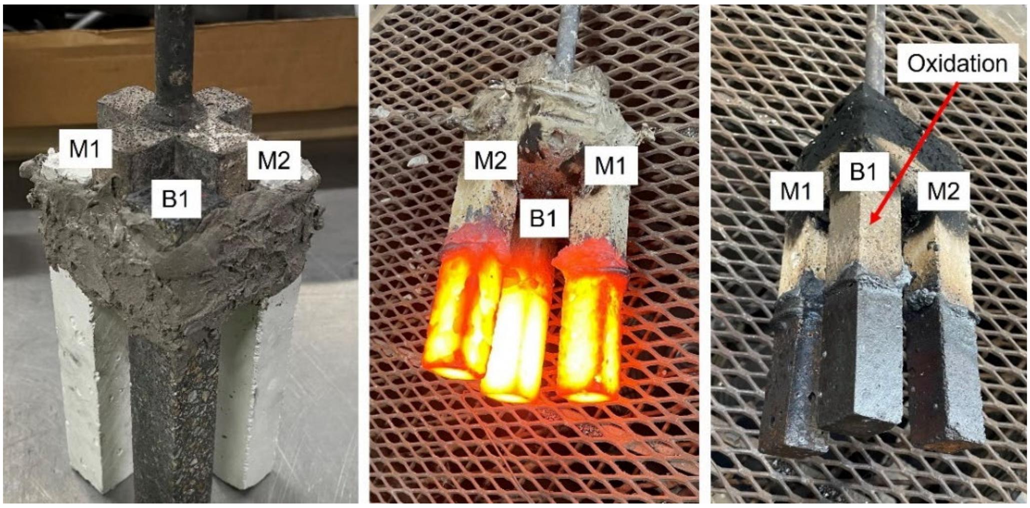


Figure 3. Thermal shock test.

3.4 Oxidation Test

Figure 4 shows the cross-section of the samples after the oxidation test. There was no significant visual difference in the samples M1 and M2. Sample B1 showed oxidation signs. The loss of carbon is associated with higher porosity, potential carbon dissolution into steel, higher heat loss, and higher CO_x release [7].

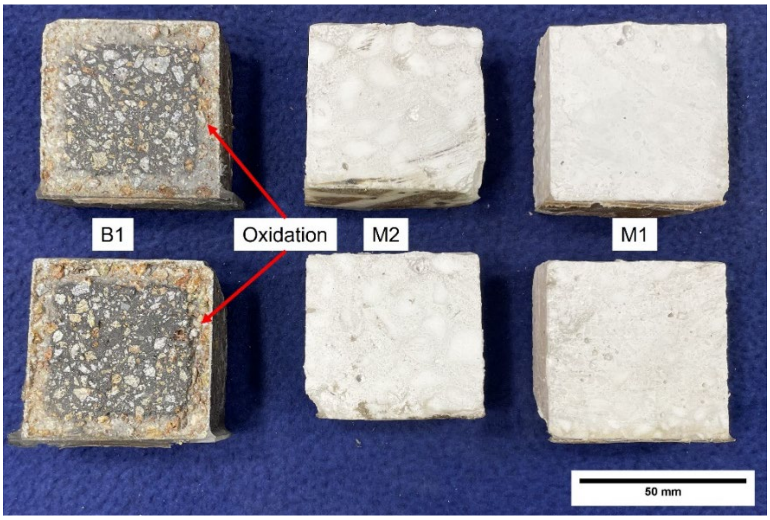


Figure 4. Oxidation test.

3.5 Correlation with Industrial Trial

3.5.1 Assembly Trials

The steel ladle bottom is the region that requires the highest workload because of the bricklaying work. The bricklayer crew must crouch which can cause ergonometric problems. In this context, the precast shapes settled with an overhead crane showed significant gains in operational safety and improved ergonomics.

Figure 5 shows the assembly of a 350-ton steel ladle bottom divided into five parts. First, the sole was prepared with the insulator and leveled with mortar. Secondly, an application template was placed to guarantee the correct position of the parts. The installation started with parts “A” and “D”, followed by “E”, “B”, and “C”, respectively. Finally, the channels were sealed using M1 castable.

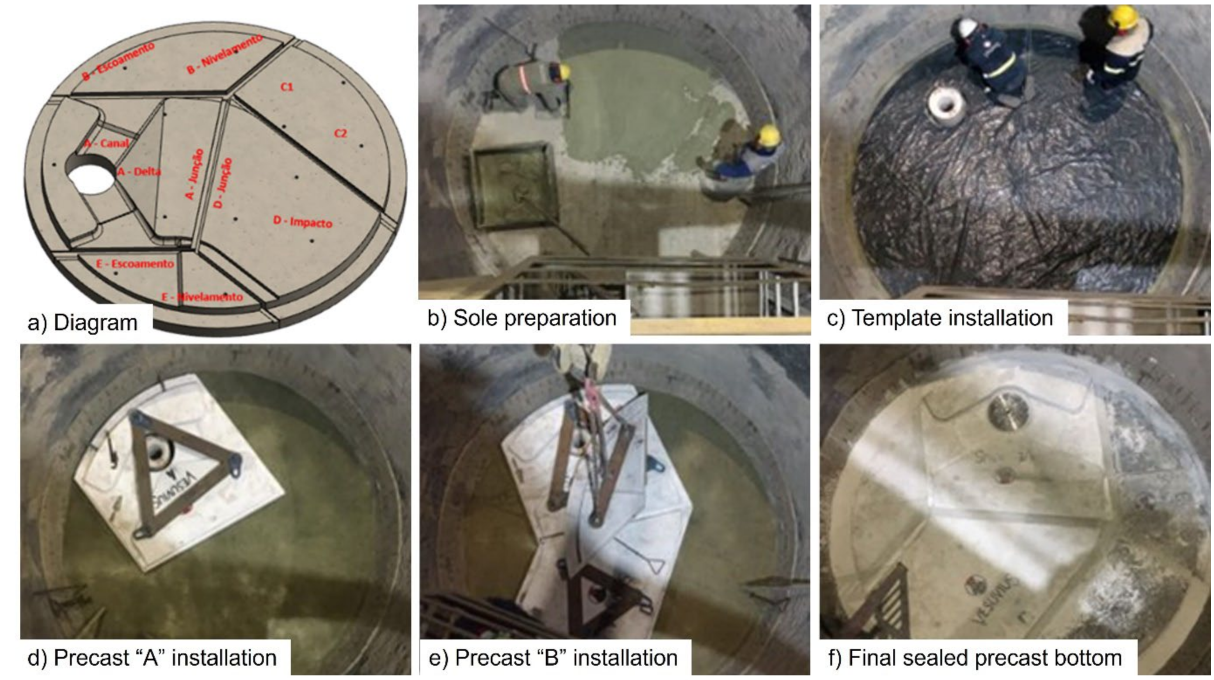


Figure 5. Photographs of the assembly stages of the pre-molded bottom in a 350-ton ladle.

Figure 6 shows the estimated reduction in man/hours by replacing the brick ladle bottom with the precast. In addition to the reduction in installation time, there are significant ergonomics improvements and the reduction of employees exposed to the risk conditions. The bricklaying of a 350-ton ladle bottom requires six operators while for the precast shape, only six operators were employed (50% reduction).

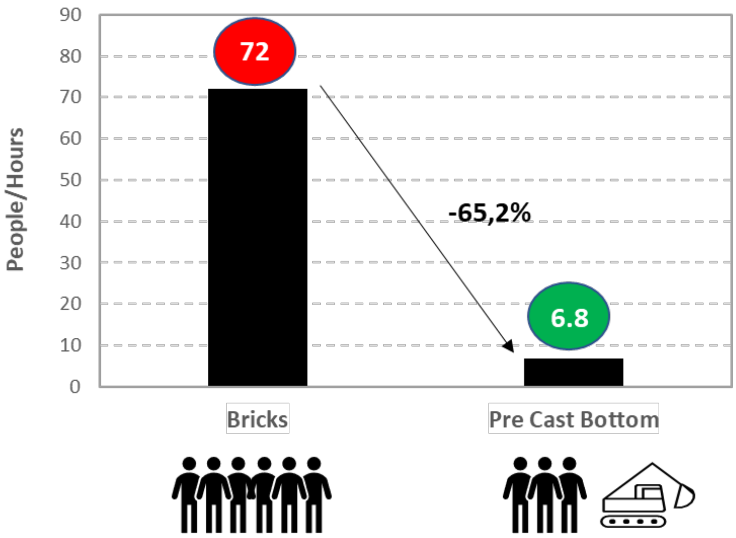


Figure 6. Estimated productivity gains in assembling ladles with precast bottoms.

Figure 7 shows the time to install precast parts in a steel ladle bottom of 350 tons. The average time was monitored among five steel ladle bottoms with an average time of two hours and 11 minutes. The longest installation time was three hours and 15 minutes, in which 49 minutes more were spent in the installation stage and 15 minutes on the channel sealing stage.

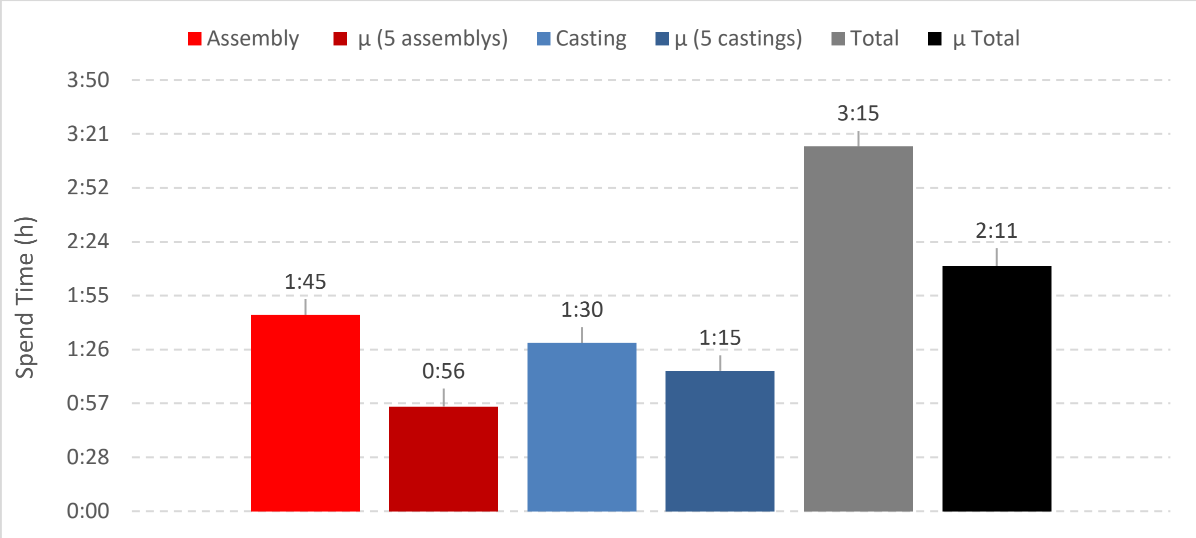
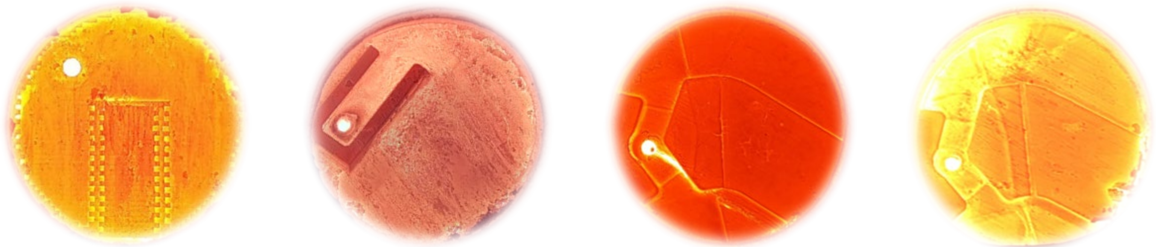


Figure 7. Assembly time for 5 pieces in steel ladle with a capacity of 350 ton.

3.5.2 Industrial Trial

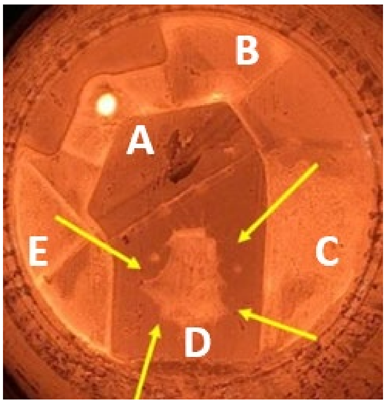
Figure 8 shows the evolution of the ladle bottom. The steel ladle studied is traditionally lined with bricks from the MgO-C system and is limited by the wear of the slag line. Currently, the target campaign is set at 120 heats. In this context, the challenge of the project was to reduce installation time and maintain equipment performance.

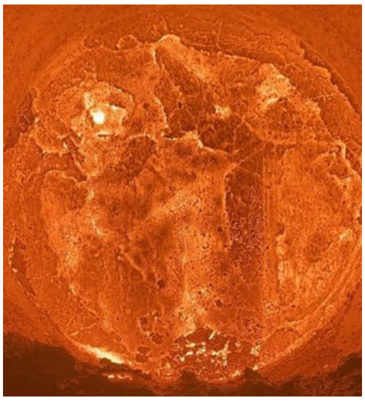


Brick = 90 heats (a) | Precast = 120 heats (b) | Precast = > 120 heats (c) | Precast = > 120 heats (d)

Figure 8. Ladle bottom evolution.

Figure 9 shows the visual aspect of the precast ladle bottom after seven and 118 heats. It was verified that the greatest wear of the refractory occurred in the impact zone and at the beginning of the operation. However, after the wear was stabilized, the lining reached the end of the campaign with a higher residual lining thickness than required, as shown in item 3.5.3.





(a) (b)

Figure 9. Precast bottom after: (a) 7 heats and (b) 118 heats.

3.5.3 Remaining Thickness

Figure 10 shows the schematic representation of the precast bottom, indicating the remaining thickness measurement positions.

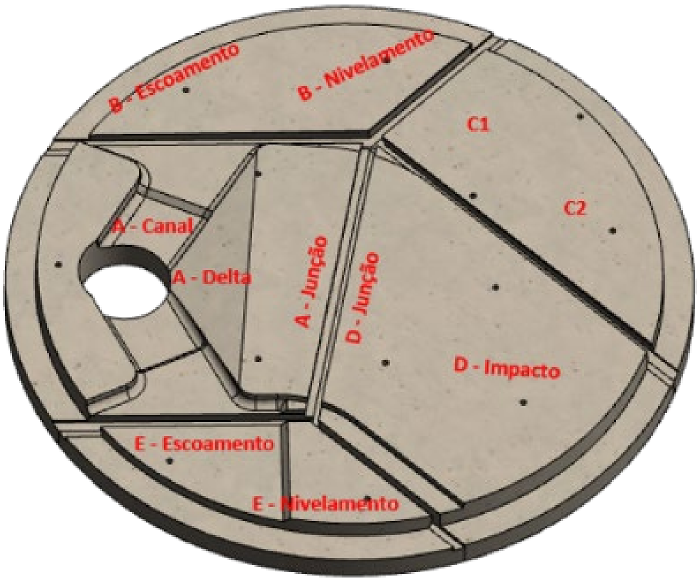


Figure 10. Schematic representation of the precast bottom used in test.

Figures 11 and 12 show, respectively, the remaining lining thickness after 119 heats and the estimated life of the precast bottom based on the wear rate. The results showed that the minimum residual found was 170 mm located in part “A”. This means that after eliminating the security thickness, the bottom showed a remainder of 90 mm.

Regarding the wear rate, the values indicated that the region with the greatest wear could operate for 181 heats, thus having a 52% increase in the life of the lining. However, as the increase in the life of the ladle bottom does not affect the campaign of the steel ladle, which is determined by the slag line performance, gains can be obtained by repairing the lining at the end of the campaign to extending the useful life. fund for more than one campaign. Thus, for each ladle bottom, two linings would be used, thus obtaining gains in terms of sustainability with waste refractory reduction.

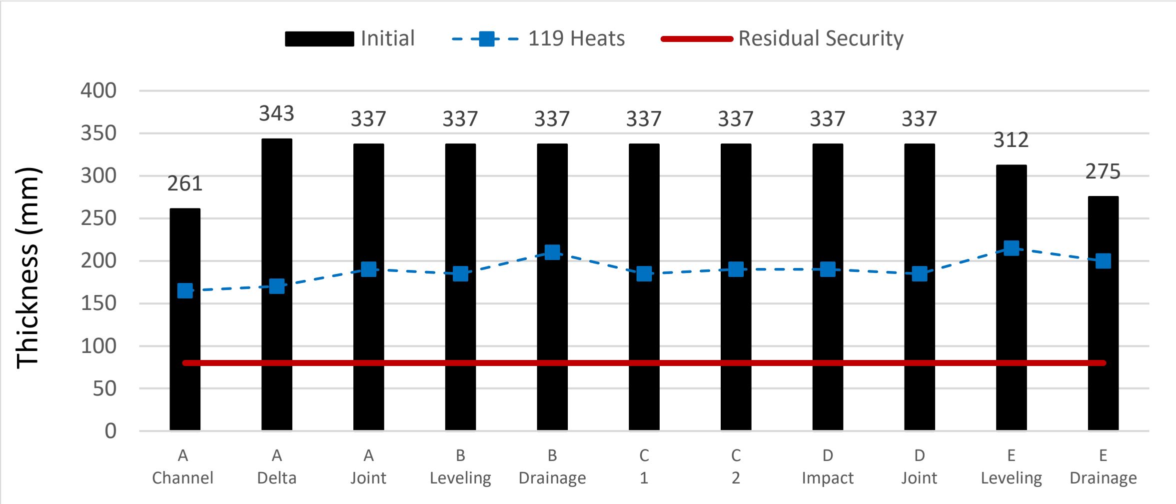


Figure 11. Lining thickness: initial, after 119 heats and residual security.

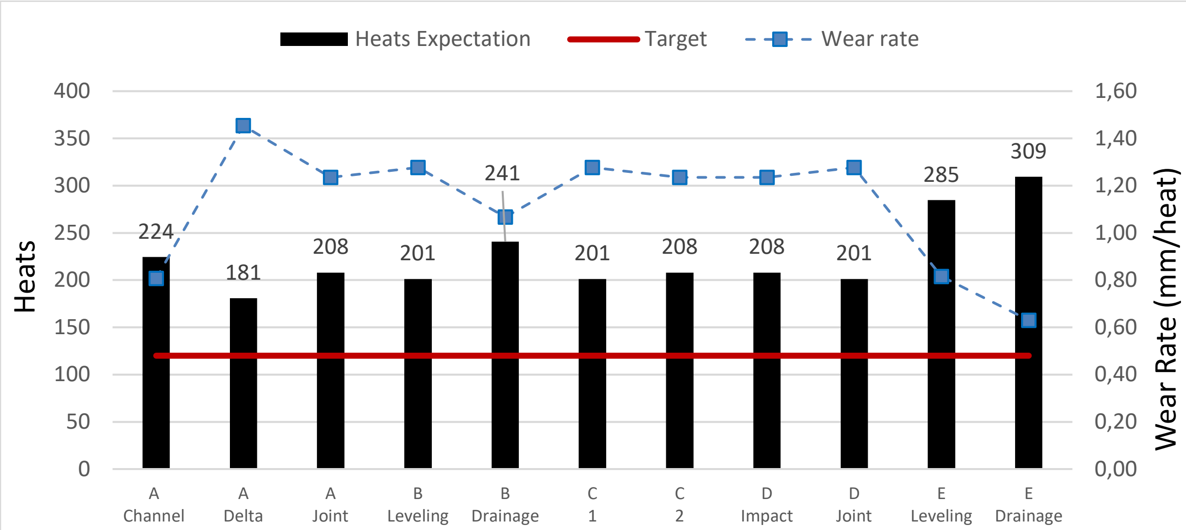


Figure 12. Heats expectation, target, and wear rate.

3.5.4 Post-Mortem Samples

Figure 13 shows photographs of post-mortem samples after 119 heats. The dimensions of the evaluated samples corroborate the results of the wear measurement and revealed that the ladle bottom lining showed substantial progress in terms of remaining thickness when compared to the conventional brick lining. In addition, it is noteworthy that the samples did not show visible damage, that is, no cracks or infiltrations were found in the internal structure of the part.

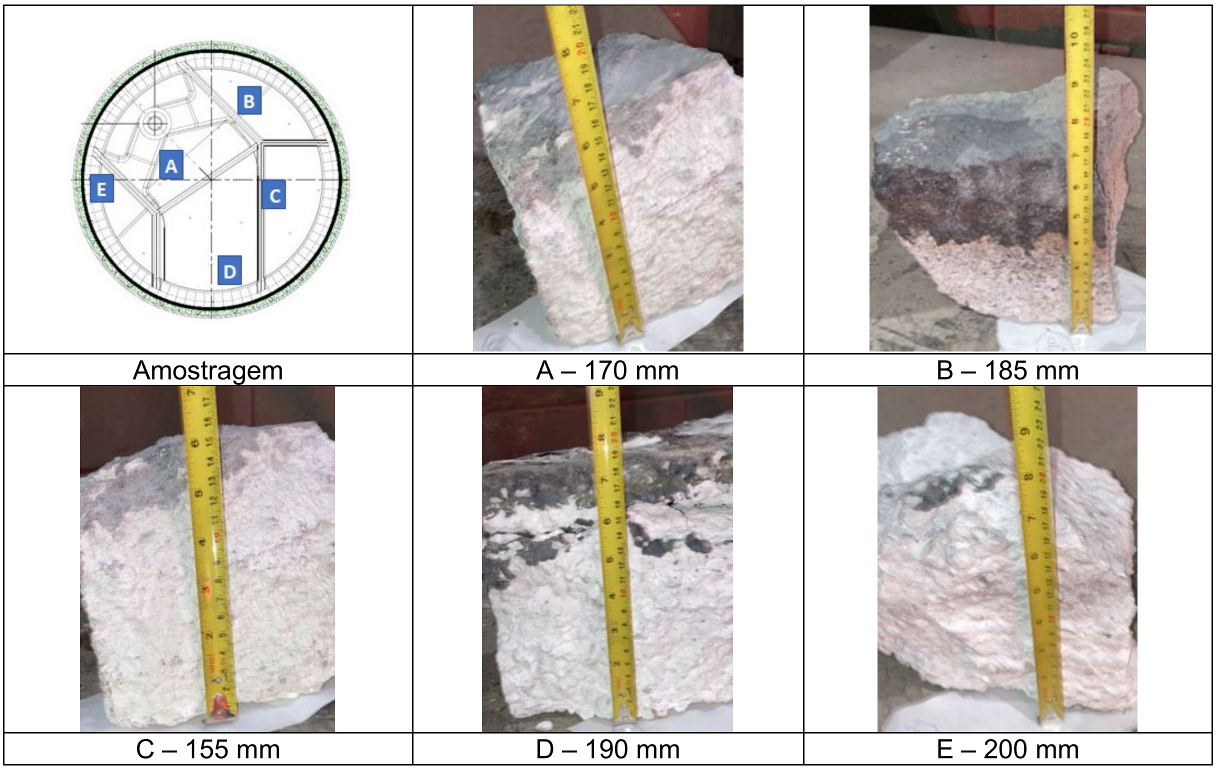


Figure 13. Lining thickness after 119 heats.

3 CONCLUSION

Three refractories commonly used for steel ladle bottoms were analyzed and compared in laboratory testing. These results were then analyzed and correlated to desired properties of the state-of-the-art ladle bottom application with high performance, fast installation, and safer.

Monolithic refractory M1 showed higher values of hot modulus of rupture and apparent porosity but lower resistance to molten iron interaction and thermal cycling. Brick B1 showed lower apparent porosity compared to M1 and hot modulus of rupture values like M2. However, oxidation, potential carbon picks up, higher thermal conductivity, and longer installation time are some of its drawbacks. Monolithic refractory M2 showed lower values of apparent porosity and a microstructure with important characteristics to sustain thermal mechanical and chemical loads during application.

Industrial trials of precast steel ladle bottoms showed good results with higher performance and economic gains for the customer. The use of precast refractories for steel ladle bottoms showed faster installation time and a safer environment with a reduction in operators. In addition, the higher-performance of the M2 refractory developed by Vesuvius showed improvement in performance for precast ladle bottom refractories. This showed Vesuvius's commitment to safety, faster turnaround time, and performance.

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