Matheus Moraes, Alexander Leitner, Gustavo Nogueira, Barbara Zocratto, Stefan Heid and Jürgen Mühlhäußer

Technical Challenges for Refractory Recycling and Innovative Processing Solutions

RHI Magnesita is driving the refractory industry towards a carbon-neutral production footprint and in order to achieve this ultimate target, recycling is one of the most important strategic initiatives. Nevertheless, to drastically increase the recycling rate, adaptations to processing and product design are necessary. This article presents an overview of the current challenges to increase recycling utilisation, from sourcing to processing and use. Additionally, innovative solutions under development at RHI Magnesita are discussed, including sorting during or after dismantling, the removal or stabilisation of contaminants, as well as fragmentation methods to increase mineral circularity. These technology developments are providing customers from different industries with a low carbon footprint refractory product portfolio that offers high performance at competitive costs.

Introduction

RHI Magnesita has the objective to significantly reduce its carbon footprint, with intermediate targets clearly set towards this goal [1]. The use of recycling is an immediate approach to significantly decrease the CO_2 footprint of refractory products. Table I presents the carbon footprint of a representative lining concept for the cement industry (basic and nonbasic monolithics and fired bricks), exemplifying the raw material contribution to the overall CO_2 footprint.

Since the carbon footprint of recycling is substantially lower than the original raw material (depending on logistics and processing steps) [2], replacing a primary raw material source by a circular mineral has the potential to save almost 60% of a mixed refractory lining carbon footprint and the value could be close to 90% for an unshaped material (no brick heat treatment necessity), such as a basic monolithic (see page 39). Additionally, the use of recycling can reduce the dependence on imported aggregates, simplify complex logistics, lower the amount of waste to be landfilled, and provide a competitive advantage by offering full circular solutions for customers [4,5]. Therefore, the benefits of recycling are clear and it's a latent opportunity with plenty of materials available on the market. However, only refractory companies with a clear strategy and dedicated investment in innovative technologies will be able to achieve significant recycling usage alongside appropriate performance, with RHI Magnesita leading the market towards a circular business model.

Table I.

Example of the carbon footprint per production step for a representative cement industry lining concept (basic and nonbasic monolithics and fired bricks) [3].

Processing Step	CO_2 footprint [%]
Raw material	59.9
Processing (batch preparation and shaping)	2.0
Brick heat treatment	28.8
Finishing and packaging	2.3
Transportation	7.0

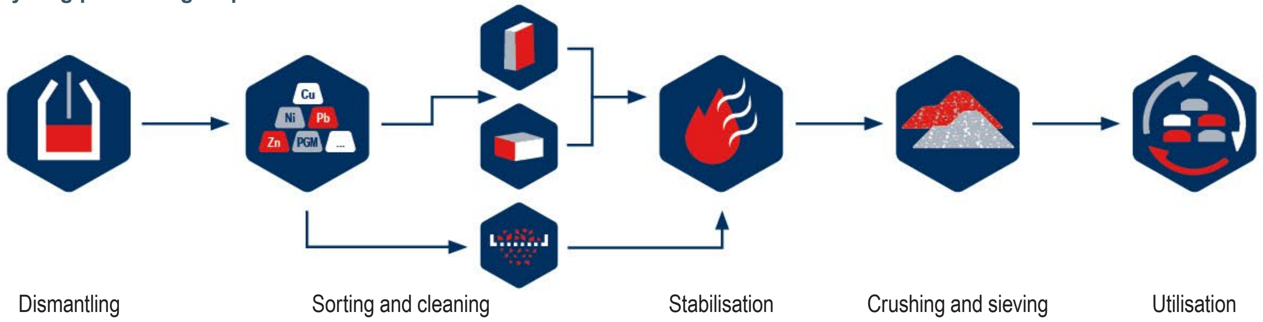
Challenges and Opportunities for Refractory Circularity

The maximum amount of recycling that can be returned to refractory compositions is highly dependent on material sorting as well as the process efficiency to remove contaminants, thereby reducing variability of the chemical and physical properties. Furthermore, the R&D capability regarding product and process design for refractories is also a major contributor.

The recycling process starts with the customer agreement and dismantling the lining, in addition to establishing the legal framework required to transport spent material to the processing plant. After these steps, the logistics and storage are key for the economic feasibility. After arriving at the processing plant,

Figure 1.

Recycling processing steps.



preprocessing (e.g., screening and metallic shell removal), sorting, stabilisation, crushing, and sieving are normally necessary before the materials can be reintroduced into the refractory production. Finally, determining applications for the leftover materials are necessary in order to keep the process both economical and truly sustainable. Figure 1 illustrates the recycling processing steps.

Sourcing and legal framework

The sourcing strategy of spent refractories is essential to ensure stable volumes and quality for the downstream processes. The agreements vary from simple spot purchasing to a full circular contract, linking the return of spent material to product supply. An important factor for sourcing quality is effective dismantling at the refractory user. The better the separation during an equipment dismantling, the higher the overall yield and stability achieved after processing. Additionally, licenses to transport and process waste materials are necessary for some refractory recycling, with special attention on dolomitic goods. Hence, the cost and timeframe to establish a recycling operation can vary according to source location and the material to be processed. Even though some regions, such as the European Union, try to foster circularity and a low carbon footprint economy, there is still conflicting legislation regarding waste handling and management for circular operations, which is a key topic to be addressed.

Sorting

After establishing a source of spent refractories, sorting the different products is essential to achieve the necessary chemistry range to reuse the materials in refractories or to direct them for further processing. This step is currently the most important challenge to be addressed since the operations are mostly carried out manually and dependent on workforce experience to identify the various classes. In the vast majority of cases, an operator is responsible for deciding which refractory product the recycling originally came from, relying on colour, fracture characteristics, sound upon impact, density, and lustre according to the light applied. Figure 2 illustrates a manual sorting operation.

However, the main constraint of this process is the limited distinction possible with human senses (especially for carbon-containing materials), leading to suboptimal sorting of certain material types. Moreover, training a sorting expert requires extensive hands-on experience. Finally, the process productivity is low, leading to high operational expenditures, particularly in places with high labour costs. In order to avoid reducing the productivity even further, only the coarse fraction (normally above 80 mm) is sorted, making it necessary to find an application for the unsorted finer fraction. This is another major challenge regarding cost and landfill reduction, given that the more mixed the materials, the higher the variability in properties and the more difficult it is to find a use.

Stabilisation and beneficiation

The removal of contaminants such as iron and slag infiltration for materials coming from the steel industry and alkalis in infiltrated cement rotary kiln bricks, as well as the stabilisation of carbides that have formed in antioxidant-containing bricks are examples of essential steps required before spent materials can be returned to refractories. However, while the necessary processes are available in the market, they have to be upscaled according to the utilisation ramp up, posing a challenge for the design footprint, investment, and operational costs. Figure 3 illustrates a process for carbide stabilisation (i.e., weathering method), currently with a 3-month lead time and high storage area required.

Sizing and utilisation

After processing and appropriate quality control, the recycling material must be crushed, sieved, and prepared for reuse in refractory products. The design of high-performance product formulations optimised for the chemistry and physical properties of the available recycling is highly dependent on the R&D capability from a refractory company. RHI Magnesita relies on its five R&D centres around the globe and more than 140 masters and doctors among the 500 experts, to develop formulations and exchange knowledge on production processes to support its recycling strategy and targets.

Figure 2.
Manual sorting operation at RHI Magnesita in Brazil.

Figure 3.
Carbide stabilisation using the weathering method.

RHI Magnesita's Innovation Roadmap

The development of recycling processing is part of RHI Magnesita's technology roadmap, reflecting the company's strong commitment to the topic. Currently, several novel processes and techniques are being developed to improve the business circularity.

Sourcing pool

The rapid increase of recycling utilisation by RHI Magnesita highlights the innovation capability of the company, but it also poses a challenge for sourcing to keep up with the demand. Therefore, the company has developed new circular business models with refractory consumers, benefiting the customer with a proper destination for the residues and ensuring reliable sources of spent refractories for RHI Magnesita, with both sharing the benefit of reverse logistics. Additionally, symbiosis with other industries and players is fundamental to further develop solutions. For example, recently RHI Magnesita announced the joint venture with Horn & Co. Group, creating MIRECO, a key recycling material supplier and processing technology hub, accelerating the value creation and environmental benefits from refractory recycling.

Automated sorting

The priority focus for recycling process R&D is on a fully automated identification and separation of materials and RHI Magnesita has been developing a prototype to be implemented in Austria that will completely change the status quo of spent refractory sorting [6]. Figure 4 shows the device design being constructed.

The prototype is just the first stage of a full sorting solution, comprising all size fractions (also addressing the fines) and difficult materials (carbon containing are not a constraint for the process). In this direction, RHI Magnesita is leading a consortium of 9 members from industry and academia, including 30 experts from 10 different nationalities. This project, called ReSoURCE, is funded by the European Union's Horizon Europe Framework Programme (HORIZON) under the Grant Agreement Number 101058310. Core developments comprise tailor-made multisensor solutions (e.g., laser-induced breakdown spectroscopy and hyperspectral imaging), artificial intelligence based analysis algorithms, and advanced material processing steps. Overall, these will set new standards for automated sorting of spent refractories.

Carbide stabilisation

Carbide stabilisation is essential for recycling markets where antioxidant utilisation in magnesia-carbon bricks is high (e.g., North America, South America, India, and China) because the aluminium added to reduce carbon oxidation is transformed into Al_4C_3 at temperatures ranging from 700 °C up to 1400 °C, according to equation 1.

$$4Al + 3C \xrightarrow{(700\ °C–1400\ °C)} Al_4C_3 \quad (1)$$

While the in-situ formed Al_4C_3 is highly refractory, at ambient temperatures it hydrates to form $Al(OH)_3$ (leading to an approximately 110% volume increase) and methane (equation 2). Therefore, the Al_4C_3 in reclaimed material must be stabilised before being recycled in refractories or it will promote cracks and result in scrap production.

$$Al_4C_3 + 12H_2O \rightarrow 4Al(OH)_3 + 3CH_4 \quad (2)$$

Figure 4.
Fully automated sorting prototype being implemented by RHI Magnesita.

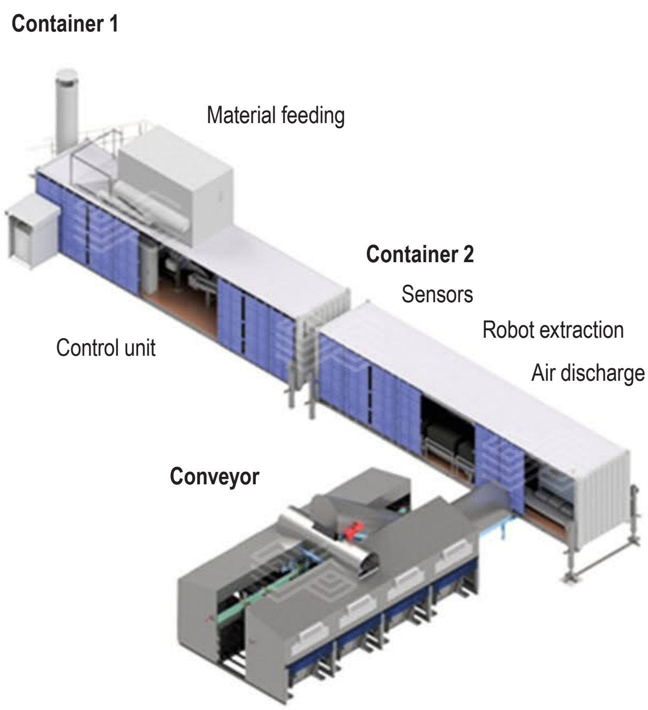


Figure 5.

Aluminium carbide measurement device.

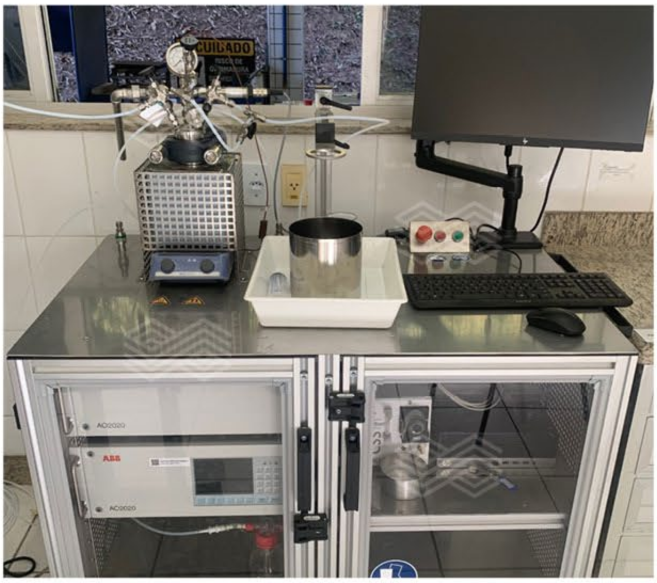


Figure 6.

Novel carbide stabilisation device under implementation.

Currently, this is mostly performed using a weathering process, which is achieved by spraying water over a brick pile and waiting for several months before recovering the material. In addition to the long processing time, process quality control is not possible using commercially available testing methods. Therefore, RHI Magnesita R&D worked on both fronts, developing a novel carbide measurement device (Figure 5) and an innovative stabilisation process (Figure 6) [7]. The carbide measurement can quantify the process efficiency, ensuring the final product quality delivered to customers is guaranteed [8].

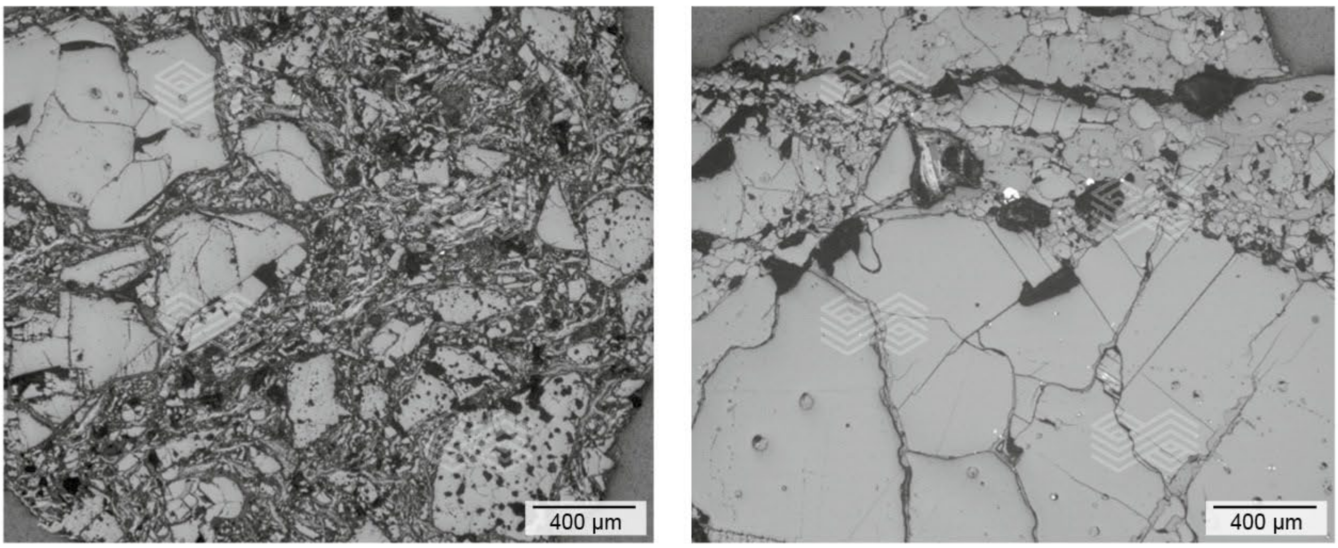
Alternatives to the weathering process were developed by RHI Magnesita to reduce the processing time, operational costs, and footprint necessary for production ramp up. Moreover, these novel processes ensure the stabilisation efficacy since it is possible to have a real-time measurement of the carbide transformation. This new processing already has a prototype in the ramp-up stage at RHI Magnesita's recycling plant in Brazil, reducing the processing time from 3 months to approximately 12 hours.

Grain separation

A defined goal in RHI Magnesita's technology roadmap is the effective fragmentation of used bricks to enable recovery of the original raw materials, theoretically removing any constraints for achieving full circularity. Therefore, RHI Magnesita is dedicating time and research on the liberation and separation of the original raw materials from spent refractories. The R&D centres from different regions are working on proof of concepts and prototypes to test different technologies. Promising results, as illustrated in Figure 7, have already been observed, such as separating high carbon containing grains from fused magnesia aggregates in magnesia-carbon recycling.

Figure 7.

Proof of concept for separation techniques. (a) high carbon containing particle and (b) fused magnesia particle.



(a) (b)

Product carbon footprint

Another important innovation introduced by RHI Magnesita to the refractory market is reporting the carbon footprint of its products (see page 39). This transparency to customers is key to foster the selection of low carbon footprint products as well as to lead industry awareness and encourage partnerships with customers for circular business models. Figure 8 illustrates the section of a technical datasheet presenting the carbon footprint of a cement refractory brick.

Impact of Innovation, Strategy, and Business Models

Due to the clear strategy to ramp up recycling utilisation, targeting a lower carbon footprint intensity, RHI Magnesita has been able to constantly increase its recycling rate. In 2022, the company already reached the target set for 2025, replacing at least 10% of the virgin raw materials with circular minerals. Figure 9 shows the evolution of RHI Magnesita's recycling rate compared to the values published by the second largest refractory producer [1,9]. By reaching a recycling rate of 10.5%, RHI Magnesita avoided landfilling approximately 150000 tonnes of spent refractories and 300000 tonnes of CO_2 emissions.

Conclusions

RHI Magnesita has a strong commitment to sustainability, with defined targets and a recycling strategic initiative to reduce the carbon footprint of refractory products. However, developing significant recycling utilisation depends on overcoming various challenges including sourcing, logistics, legislation, processing, marketing, and product design.

Figure 9.

Recycling rate evolution of RHI Magnesita compared to the second largest refractory producer [1,9].

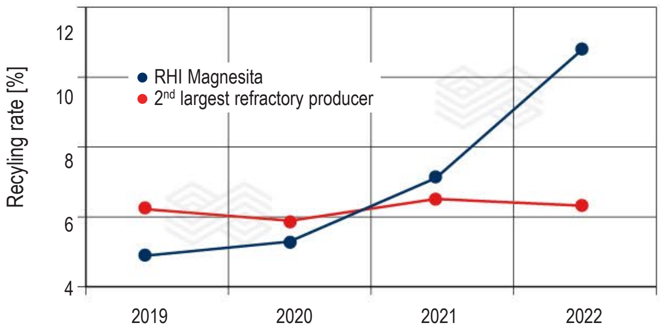


Figure 8.

Technical data sheet detailing the product carbon footprint.

ANKRAL R1

General Information	
Classification	Magnesia-spinel product type MSp80 ISO 10081-2
Main raw material components	High grade sintered magnesia, high purity sintered magnesia, MA-spinel
Bonding type	Ceramic
Type of brick	Fired
Mortar to use	ANKERFIX NS60

Environmental Indicators		
Product carbon footprint	2.211 [lt. CO_2e/t prod.]	ISO14067
The carbon footprint of the product (CFP) has been calculated following the principles of ISO14067		

Therefore, RHI Magnesita has been actively developing strategies and technologies to constantly, and significantly, increase the adoption of circular products.

For the recycling sourcing, partnerships are being established with customers to improve the quality of dismantling and material separation. Additionally, RHI Magnesita is working with recycling processors to expand the supplier pool and set up a joint venture with Horn & Co. Group, founding MIRECO as a key player in the European market.

Recycling sorting is a key technology to be explored and improved. ReSoURCE is a European Union funded consortium that is led by RHI Magnesita to address automated sorting techniques, targeting quality improvements and yield of separation. The main goal is to develop sensors specifically developed for the refractory recycling challenges, overcoming the limitations of off-the-shelf devices. Important advancements have also been achieved for contaminant stabilisation and quality control. For example, a new analytical method for aluminium carbide quantification was developed as well as novel process techniques for its stabilisation.

Longer-term developments are also included in the recycling technology roadmap, with techniques being explored to liberate and separate raw material aggregates from the matrix of recycled refractories. On the one hand this is a challenging approach, but on the other hand success in this area would remove several bottlenecks for recycling utilisation.

RHI Magnesita's strategy and focus on sustainability topics, taking advantage of the expertise of the R&D centres and process experts worldwide, is already bringing benefits and a record recycling rate of 10.5% was achieved in 2022. This value represents a landfilling reduction of around 150000 tonnes of used refractories and avoiding CO_2 equivalent emissions close to 300000 tonnes.

References

[1] RHI Magnesita 2022 Sustainability Report. https://ir.rhimagnesita.com/wp-content/uploads/2023/03/42705-rhi-sustainability-report-2022-web.pdf

[2] Moraes, M.N., Nogueira, G.G.R. and Silveira, F.T. Desafios Técnicos no Processamento de Reciclados. 42nd Alafar Conference Proceedings. Foz do Iguacu, Brazil, November 7–12, 2022.

[3] Strubel, S. *Developing a Model to Calculate the Carbon Footprint of Refractory Products*, Master's thesis, Leoben University, Austria, 2012.

[4] Moraes, M.N., Nogueira, G.G.R., Lopez, M., Silveira, F.T. and Bonadia, P. Refractories Recycling—Challenges and Opportunities in a Path Towards CO_2 Footprint Reduction. 4th EMECR - International Conference on Energy and Material Efficiency and CO_2 Reduction in the Steel Industry Conference Proceedings. Sao Paulo, Brazil, June 7–9, 2022, 1–9.

[5] Schutte, M. Refractory Recycling Earning Your Environmental Brownie Points. The Southern African Institute of Mining and Metallurgy Refractories 2010 Conference Proceedings. Johannesburg, South Africa, March 16–17, 2010, 75–86.

[6] Leitner, A. Innovating Refractory Recycling – A Technology Review with Focus on ReSoURCE. Mineral Recycling Forum Proceedings. Dubrovnik, Croatia, March 28–30, 2023.

[7] Heid, S., Leitner, A. and Königshofer, S. Innovative Aluminium Carbide Detection and Treatment Technologies to Increase Magnesia-Carbon Recycling. *Bulletin*. 2022, 11–16.

[8] Niedermayer, S. and Ellersdorfer, M. Combination of Autoclave Treatment and NDIR Process Analytics for Quantification of Aluminum Carbide in Powder Samples. *Analytica*. 2022, 3, 106–199.

[9] Vesuvius plc Sustainability Report 2022. https://www.vesuvius.com/content/dam/vesuvius/corporate/Sustainability/2023-update/Vesuvius_SR22_Interactive_FINAL.pdf

Authors

Matheus Naves Moraes, RHI Magnesita, Contagem, Brazil.
Alexander Leitner, RHI Magnesita, Leoben, Austria.
Gustavo Nogueira, RHI Magnesita, Contagem, Brazil.
Barbara Zocratto, RHI Magnesita, Rotterdam, Netherlands.
Stefan Heid, RHI Magnesita, Leoben, Austria.
Juergen Mühlhäußer, RHI Magnesita, Leoben, Austria.
Corresponding author: Matheus Naves Moraes, Matheus.Naves@rhimagnesita.com