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Unlocking the Recycling Potential of Fine Refractory Breakout Materials

RHI Magnesita and MIRECO are deeply committed to advancing sustainability and promoting a circular economy within the refractory industry. However, the wide variety of refractory products and the presence of impurities arising from various industrial processes pose significant challenges for the reuse of spent materials in refractories. These challenges become even more pronounced when dealing with fine breakout materials generated through dismantling, transport, handling, and comminution. The reuse of such fines in refractory production is constrained by narrow composition tolerances, limited availability of fine-sorting technologies, and restrictive physical properties such as grain size. Currently, the use of these fine breakout materials in iron and steelmaking—as circular metallurgical additives—is well established, with considerable potential for further expansion. However, the substantial volumes of available materials, which can vary in quality and supply, necessitate exploration for new application fields to avoid expensive landfill disposal and its associated environmental impact. This article provides an overview of the challenges associated with fine breakout materials, their current applications, and the emerging opportunities for alternative applications beyond refractories and circular metallurgical additives. These advancements, driven by research and development activities, demonstrate significant potential for future value creation.

Introduction

In today's rapidly evolving industrial landscape, sustainability and circular economy principals are at the forefront of innovation. From a technical perspective, RHI Magnesita and MIRECO are taking a leadership role in innovating material recovery by combining artificial intelligence (AI)-driven classification, advanced analytics, and cross-sector reuse strategies. These efforts not only optimise the life cycle of refractory materials but also contribute directly to CO_2 emission reductions and industrial decarbonisation, aligning with EU policy targets. The generation of refractory fines (i.e., grain size <70 mm) can reach up to 50% depending on how the material is dismantled and presorted. In line with an industry-specific interpretation of the European Union Waste Framework Directive [1] and recent developments in EU waste shipment regulations [2], the "no-out, no-in" principle reflects a legal preference for keeping materials within the cycle ("no-out") and minimising the input of new raw materials ("no-in") by prioritising reuse and recycling. However, increasing the recovery of high-grade circular raw materials for refractory applications inherently results in the generation of secondary fractions that do not meet the strict specifications required for reintroduction into refractories. Therefore, the logistical challenge of material management must be taken into careful consideration. In addition, due to their lower financial value, fines are highly sensitive to freight costs, making local processing and deployments essential. Within the CERO Waste framework (Figure 1), the customer, MIRECO as the recycling company, and RHI Magnesita as the refractory producer form a mutually interdependent, long-term partnership focused on avoiding landfill practices.

Figure 1.

The closed CERO Waste cycle, illustrating the mutually interdependent value chain formed through collaboration between all business partners, with MIRECO at the centre enabling the recycling process.

The refractory-using industries, such as customers at the top of the value chain, generate spent refractories, which are subsequently transferred to MIRECO for processing. There, the materials are sieved, sorted, and cleaned, resulting in two main material streams: The fine fraction (<70 mm), which is discussed in this article and typically used for nonrefractory applications, and the coarse fraction (>70 mm), which is primarily recycled into refractory products. However, one of the most pressing challenges lies in the reuse of fine breakout materials. The key difficulty in recycling these fines is the need for a creative "matchmaking" process to align the various material properties with the specific requirements of potential applications. The matchmaking process for circular metallurgical additives, illustrated in Figure 2, can also be applied to other suitable material streams.

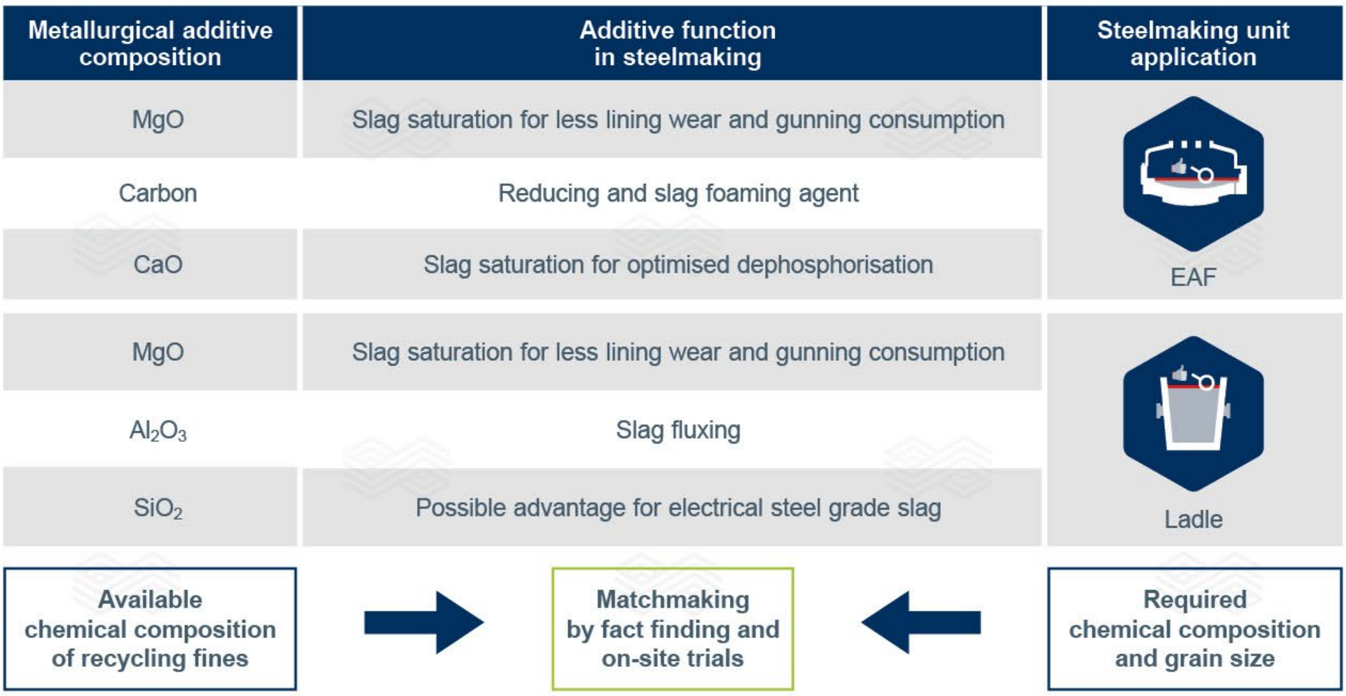
This article explores the challenges, current applications, and emerging opportunities to further unlock the value of this fine mineral resource, driving both environmental and economic benefits. The collaborative research and development efforts undertaken by RHI Magnesita, together with MIRECO, and partners from the EU-funded ReSoURCE (Refractory Sorting Using Revolutionising Classification Equipment) initiative [3], demonstrate that the longstanding challenges related to fine breakout materials can be successfully addressed by technological innovation, material analytics, and cross-sector application development.

Technical Challenges of Recycling Fine Breakout Materials in Refractories

The critical properties of refractories—such as thermomechanical behaviour and corrosion resistance—depend primarily on the raw materials used in their production. Therefore, to ensure the required refractory performance, raw material parameters including chemical composition, mineralogy, and grain size must meet strict specification limits. One key technical obstacle in the sustainable reuse of spent refractory fines in high-quality refractories is achieving these stringent specifications. Unlike coarse fractions, which can be manually sorted with acceptable accuracy, fine materials typically present significant challenges due to their inherent heterogeneity. In many cases, this chemical inhomogeneity directly conflicts with the stringent specifications that refractory products must meet, as each product class has precise compositional limits for key oxides such as MgO, Al_2O_3, CaO, SiO_2, Fe_2O_3, Cr_2O_3, and C. Variability in these parameters, especially within fine fractions, poses a significant barrier to their reuse without extensive pretreatment and/or sorting. For example, the fine circular raw materials used in sustainable basic gunning mixes are derived from the comminution of presorted reclaimed materials, typically >70 mm, with the fines undergoing a subsequent drying step [4]. This also highlights a further technical challenge in reusing fines for refractory production, namely the high moisture content of certain materials, which makes material handling more complex or can lead to the complete disintegration of some refractory components (e.g., circular raw materials derived from doloma products) due to the associated volume expansion.

Moreover, inherent processing limitations further restrict the proportion of fine materials that can be incorporated into refractory formulations. In particular, the use of material with a particle size <0.3 mm is often limited to approximately 30%, as exceeding this threshold can cause issues in both pressing and casting processes, leading to defects in the final product quality and reduced performance. As a result, despite the substantial volumes of fine breakout material generated, its reintegration into refractory production

Figure 2.
Matchmaking procedure for circular metallurgical additives.



remains extremely limited under current conditions and is dependent on extensive research and development activities and industrial field trials. Therefore, innovative approaches in sorting technology and material characterisation are urgently needed to overcome these challenges and unlock the value embedded in fine reclaimed materials.

Recycling Fine Breakout Materials in Circular Metallurgical Additives

Despite the difficulties of reintegrating fine breakout materials into refractory production, promising circular economy applications have already been established, particularly in the field of metallurgical slag engineering (see page 49). Metallurgical additives play a fundamental role in iron and steelmaking, where they serve to optimise slag properties and enhance various processes such as dephosphorisation, slag foaming, and desulfurisation. These additives are generally classified into two groups: Basic oxides that aid in CaO and MgO slag saturation, and nonbasic fluxing oxides, which help to fluidise the slag [5].

Through targeted quality control, MIRECO transforms fine refractory residues into circular metallurgical additives, offering significant benefits from both an economic and environmental standpoint. One of the key advantages of using fine breakout materials in slag applications is their high content of refractory oxides—especially MgO and Al_2O_3—which are valuable components for slag conditioning. Despite the fact that refractories are designed to withstand high-temperature corrosion, industrial studies have shown that circular metallurgical additives dissolve appropriately in basic oxygen furnace (BOF) and electric arc furnace (EAF) slags, improving basicity and contributing to slag foaming behaviour [5,6].

MIRECO provides a comprehensive portfolio of circular metallurgical additives and Table I summarises the standard basic and nonbasic grades, which can be tailored to meet the specific demands of individual steel plants. These customised solutions not only enhance operational efficiency but also contribute significantly to reducing the carbon footprint (CFP) of steel production. The CFP values for these recycled materials, which account for transport and processing steps and are averaged across the entire product portfolio, are up to 40 times lower (i.e., 0.05 tonne of CO_2 equivalent per tonne of metallurgical additive) than those of virgin raw materials, reflecting the environmental benefits of using circular metallurgical additives.

Currently, more than 100000 tonnes of MIRECO's circular metallurgical additives are sold on the European market every year. Of this volume, approximately two-thirds consist of basic oxides, while one-third comprises nonbasic fluxing oxides. An EAF steel plant typically uses approximately 15 kg of dololime per tonne of produced steel, in addition to lime, to ensure proper slag formation. If a high-MgO recycled material such as MIRECO's MgO 75 is used instead, the required amount can be decreased to approximately 7 $kg/tonne_{steel}$. Although, due to its lower CaO content, additional lime must be added to maintain the overall slag balance, industrial trials have shown multiple benefits from adopting this sustainable approach including reduced MgO pickup from the brick lining and reduced gunning mix consumption [5]. A further advantage of MgO 75 is the carbon content serves as an energy source and slag foaming agent, reducing anthracite injection during the refining period. Currently, the use of fines in slag engineering is particularly well suited for material fractions that are chemically stable and largely free from critical impurities. Pre-processing steps, including magnetic separation, drying, and partial screening, are commonly employed to tailor fines for specific metallurgical applications. However, while industrial case studies on circular metallurgical additives demonstrate that valuable outlets exist for fine refractory residues, certain material streams remain unsuitable due to chemical incompatibilities or very fine particle sizes, which can lead to dust generation and handling issues. As a result, significant untapped potential remains—particularly for finer particle sizes and more complex material mixtures. This underscores the need to explore additional innovative fields of application, as outlined in the following sections.

Table I.

Examples of MIRECO's standard circular metallurgical additives, which can be tailored to customer requirements.

	Product Name	MgO [%]	CaO [%]	SiO_2 [%]	Al_2O_3 [%]	Fe_2O_3 [%]	TiO_2 [%]	C [%]	CaF_2 [%]
Basic oxides	MgO 55	55	20	5	10	5		8	
	MgO 75	75	6	5	5	5		5	
	MgO 80 A7	82	1.5	0.5	8	0.7			
Nonbasic fluxing oxides	TE 80	3	2	11	78	2.5	2	2	
	TE 85	2.5		7.5	85	0.7	0.4	6	
	TE 90	2.5	2.5	1.8	90	0.8	0.1		
	Rehcal 10	6	15	9	55	2			10
	CFA 40–60	2.5	20	5	20	0.6	0.5		50

Alternative Applications Beyond Refractories and Slag Forming Additives

To fully realise the potential of fine refractory residues, a multi-faceted approach is essential—one that goes beyond traditional metallurgical reuse. This includes exploring advanced material applications such as functional fillers and surface coatings, developing low-carbon construction materials based on geopolymers, and improving material quality through advanced sorting technologies and integrated quality monitoring systems. Together, these strategies enable a more circular and value-driven use of fine fractions, aligning with both technical performance requirements and sustainability targets.

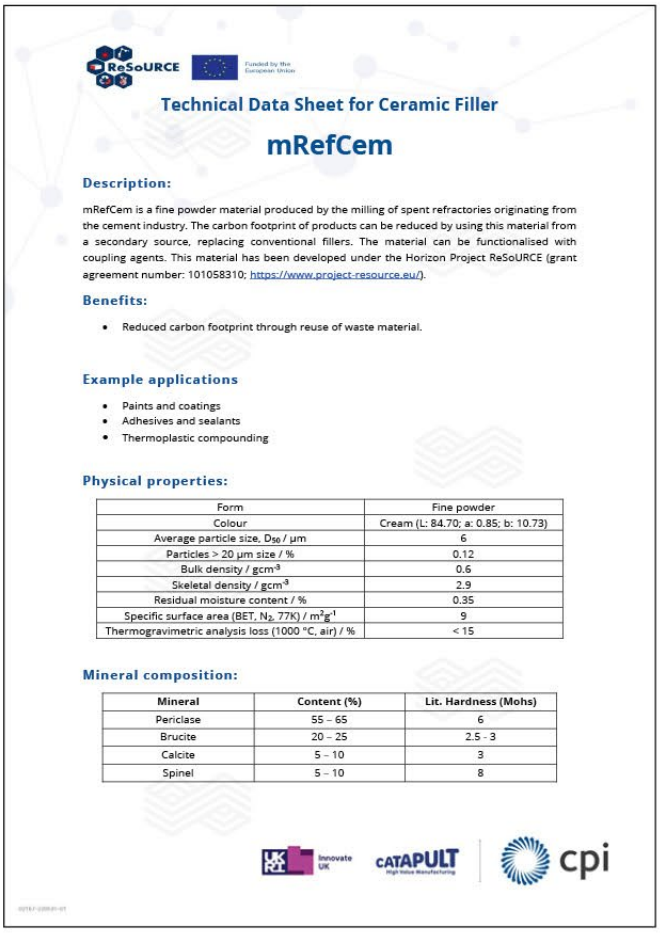
Advanced material applications

One such approach is currently being explored within the EU-funded ReSoURCE project, which aims to develop automated sorting solutions for refractory breakout materials, identify nonrefractory application opportunities, and conduct life cycle and techno-economic assessment as part of a holistic spent refractory management strategy [3]. As part of this initiative, RHI Magnesita, in collaboration with the Centre for Process Innovation (CPI)—a leading technology centre based in the UK [7]—is investigating the suitability of fine refractory residues as functional fillers in polymer composite systems. These composites, which combine a polymer matrix with inorganic fillers, are widely used across industries for their tailored mechanical, thermal, and electrical properties. Conventionally, fillers such as kaolin, glass fibres, or calcium carbonate are used. However, refractory residues—due to their thermal stability, mechanical hardness, and altered microstructure from service life—offer unique advantages. Initial studies conducted by CPI, show that, at an optimal dosage, refractory fillers can enhance thermal resistance, dimensional stability, and mechanical strength of polymer composites. The viability of these applications has been strengthened through the development of a dedicated material passport, including technical datasheets (Figure 3) and end-user safety considerations, in accordance with EU circular economy guidelines.

These materials could potentially replace conventional fillers like marble powder or low-grade clays, thus creating both cost and resource-efficiency benefits. By enabling the creation of engineered fillers from waste, these innovations extend the circular economy beyond the boundaries of traditional refractory applications. They also open the door to future use cases in thermal insulation or high-performance coatings areas that are being actively explored within ongoing collaborative projects. The early-stage results suggest that refractory residues may play a meaningful role not only in metallurgical processes but also in advanced materials science. The continued development of such high-value alternative applications will be essential in turning reclaimed refractories from a disposal challenge into a strategic secondary raw material resource.

Figure 3.

Technical data sheet for mRefCem, a ceramic filler derived from reclaimed refractory materials.



ReSoURCE — Funded by the European Union

Technical Data Sheet for Ceramic Filler

mRefCem

Description:

mRefCem is a fine powder material produced by the milling of spent refractories originating from the cement industry. The carbon footprint of products can be reduced by using this material from a secondary source, replacing conventional fillers. The material can be functionalised with coupling agents. This material has been developed under the Horizon Project ReSoURCE (grant agreement number: 101058310; https://www.project-resource.eu/).

Benefits:

- Reduced carbon footprint through reuse of waste material.

Example applications

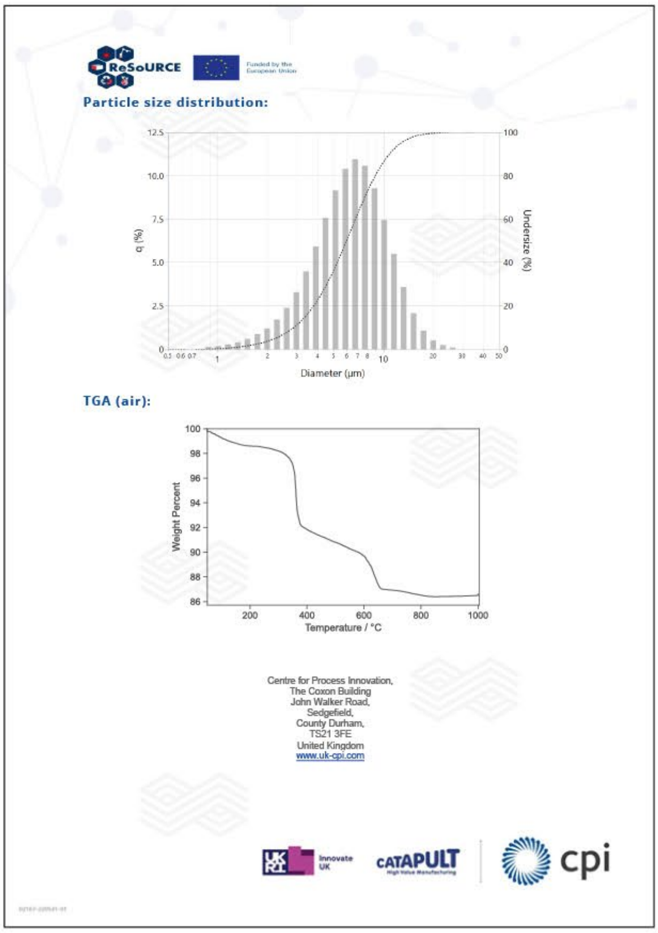
- Paints and coatings
- Adhesives and sealants
- Thermoplastic compounding

Physical properties:

Form	Fine powder
Colour	Cream (L: 84.70; a: 0.85; b: 10.73)
Average particle size, D_{50} / µm	6
Particles > 20 µm size / %	0.12
Bulk density / gcm^{-3}	0.6
Skeletal density / gcm^{-3}	2.9
Residual moisture content / %	0.35
Specific surface area (BET, N_2, 77K) / m^2g^{-1}	9
Thermogravimetric analysis loss (1000 °C, air) / %	< 15

Mineral composition:

Mineral	Content (%)	Lit. Hardness (Mohs)
Periclase	55 – 65	6
Brucite	20 – 25	2.5 - 3
Calcite	5 – 10	3
Spinel	5 – 10	8



Advanced Sorting Technologies

As previously outlined, grain size and effective material sorting remain critical bottlenecks in the efficient recycling of spent refractory materials. While manual sorting is economically viable for materials >80 mm, finer particles—especially <5 mm—are typically downcycled or landfilled due to their inhomogeneous composition and impurity content [8]. To overcome this challenge, RHI Magnesita and partners within the EU-funded ReSoURCE project initially developed the fully automated mobile sorting unit, RAPTOR (Refractory Automated Precision Technology for Optimised Recovery) [9], shown in Figure 4. This equipment is capable of identifying and classifying materials in the 5–120 mm range using sensor-based technologies. However, particles <5 mm still fall outside the scope of existing sorting solutions. To address this gap, a next-generation demonstrator system is being developed to sort and analyse spent refractory materials <5 mm into distinct particle size fractions and chemically defined classes. This modular system integrates optional direct sorting functionality and in-line bulk chemical analyses via laser-induced breakdown spectroscopy (LIBS), providing a real-time assessment of key oxide concentrations (e.g., MgO, Al_2O_3, SiO_2, CaO, Fe_2O_3, and C). At any separation point, the material can either exit the system and be deposited in big bags, proceed to further processing via a direct sorting method, or be routed to the LIBS system. A multi-chamber fluidised bed classifier [10,11] separates particulate solids in the 0–1 mm range based on density, shape, and size, exploiting the interaction of gravity, aerodynamic drag, centrifugal force, and particle collisions (Figure 5).

Initial trials on various feedstocks have shown highly encouraging results, particularly in terms of material recovery rates, process reproducibility, and the selective concentration of either valuable minerals or unwanted impurities. Depending on the material input characteristics, the system can either enhance the value of both fine and coarse fractions or concentrate impurities into the fine stream, thereby producing a purified coarse fraction. When combined with LIBS and integrated powder handling logistics, this approach significantly increases the recycling potential of spent refractory materials <5 mm.

Figure 4.

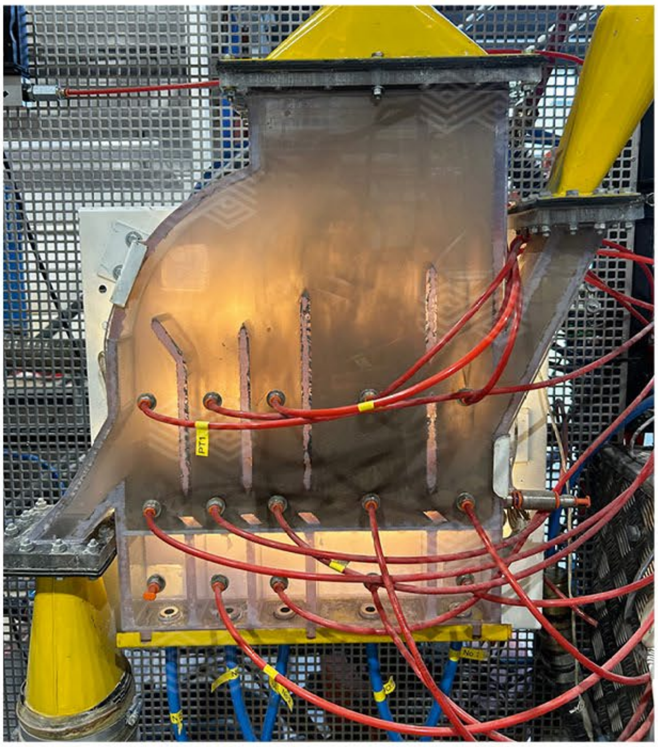
RAPTOR—RHI Magnesita's automated sorting unit for spent refractories.

Low-Carbon Construction Materials

To further expand the application potential of sorted fine fractions, RHI Magnesita recently joined the Christian Doppler Laboratory for Waste-Based Geopolymer Construction Materials in the CO_2-Neutral Circular Economy ($GECCO_2$) [12] as an industrial partner. This cutting-edge initiative focuses on developing next-generation, waste-based geopolymer construction materials as an important step towards CO_2-neutral building material solutions. The CD laboratory brings together interdisciplinary expertise from waste, material, environmental, geo-, and civil engineering sciences to transform industrial residues—including slags, ashes, mineral wool, and clay-rich demolition materials, and now reclaimed refractories—into high-performance binders and building materials. Additionally, by integrating carbon-rich waste materials such as used oils, organic fibres, and biomass residues, the 7-year project aims to drastically reduce the environmental impact of construction materials. Through its involvement in $GECCO_2$, RHI Magnesita is exploring how spent refractory fines can serve as functional components in geopolymer matrices or as raw materials in alternative activator developments, extending the value chain of recycled materials into high-end construction applications.

Figure 5.

Multi-chamber fluidised bed classifier showing air inlets, solids inlet, gas/fine particle outlet, coarse solids outlet, and pressure taps.



Conclusion

RHI Magnesita and MIRECO continue to lead the refractory industry in transforming the way refractory materials are recycled—particularly the complex, high-volume segment of fine breakout materials. Established applications such as circular metallurgical additives already provide effective and scalable solutions in slag systems, demonstrating the value of fine fractions in industrial processes. Building on this foundation, the company is investing in advanced sorting technologies, LIBS-based analytics, and modular classification systems to unlock further potential in sub-5 mm materials. Through strategic collaborations in projects like ReSoURCE and the Christian Doppler Laboratory for Waste-Based Geopolymer Construction Materials in the CO_2-Neutral Circular Economy (GECCO_2), new application fields—such as polymer composites and CO_2-neutral geopolymer construction materials—are being developed. These efforts reflect RHI Magnesita's and MIRECO's strong commitment to circularity, innovation, and decarbonisation, and reinforce its position as a global leader in sustainable refractory solutions.

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