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Analysing material flows and final fate distribution of spent refractories from steel casting ladles and cement rotary kilns in Europe

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ABSTRACT

Refractories are used in high-temperature applications, consuming 35 to 40 Mt globally each year and generating 28 Mt of spent refractories (SR), primarily from steel and cement production. This paper addresses knowledge gaps in SR material flows from steel casting ladles (SCL) and cement rotary kilns (CRK) by collecting data from respective industry interviews, reports and trade balance sheets, to estimate Europe's annual refractory demand. Additionally, an approach is presented to easily estimate the amount of SR generated. In 2022, Europe consumed 2.7 Mt of refractories, with 1.36 Mt for steel and 0.14 Mt for cement production, resulting in 326 kt of SR from SCL and 74 kt from CRK. Compared to dated literature, recycling of CRK breakout material increased to 42 %, whereas no data was provided in 2003. Contrary, 52 % of SCL material is being landfilled nowadays compared to no landfilling reported in 2003. Spent refractories recovered by recyclers is utilised in novel refractory production at rates of 64 % for SCL and 81 % for CRK. This study provides the first in-depth analysis of SR handling from cement production, including an average process loss of 45 %. The findings improve the overall knowledge about the final fate of SR.

1. Introduction

"All economically used materials were once taken from natural resources and eventually become emissions and waste" (Kranert, 2010). This quote highlights the importance of a functional waste management system for modern society, as increasing consumption inevitably leads to an increasing waste generation. This general conclusion noticeably effects all areas among the value chain. To manage those waste streams, the European Union (EU) introduced various regulations to address current and upcoming waste challenges. Accordingly, the EU implemented policies for environmentally sustainable waste management, establishing principles such as the "waste hierarchy" (Directive 2008/98/EC of the European, 2008), which comprises prevention, preparation for re-use, recycling, recovery, and disposal. To monitor these measures, the Waste Statistics (Regulation (EC) 2150/2002, 2002) requires documentation and continuous reporting of reliable statistics on waste generation, recovery/recycling, and disposal. This documentation includes reporting on waste quantity, characteristics, source, destination, collection frequency, transportation mode, and intended treatment method. Additionally, each waste has to be assigned a waste code number defined at European level, which has recently been updated by EU: Commission Decision (2014). However, these waste categories can be overly broad, complicating the accurate determination of specific waste material volumes.

This complexity also applies to spent refractories (SR), which generate from high process temperature industries, where they are employed to ensure a safe production. According to standards (DIN 51060), refractory products are non-metallic ceramic materials characterised by their refractory properties, specifically a softening point (cone fall point) exceeding 1500 °C. High temperature production processes are often accompanied by harsh environmental conditions caused by corrosive liquids and/or gases, which reduce the refractory lifetime. The annual worldwide production of refractories is estimated to 35 - 40 Mt (Horckmans et al., 2019). In cement production, refractories are used primarily as lining within cement rotary kilns (CRK). In steel production, they are utilised at each metallurgical stage, including the furnace, converter, ladle, and tundish, as well as in the transportation of molten metal. Steel casting ladle (SCL) linings usually generate the largest SR

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stream in steel production due to the highly corrosive production environment and the resulting frequent renewal of the lining (Smith et al., 1999; Viklund-White et al., 2000). Other refractory applications are glass production, the chemical industry and waste incineration.

Although waste codes distinguish between carbon-based refractories (16 11 02 – 16 11 04) and those used in non-metallurgical processes (16 11 05 and 16 11 06), further differentiation (possibly through a subsequent sorting step), based on varying chemical composition is required to enable efficient and effective recycling. Carbon-based bricks used in steelmaking can be subdivided into, e.g., alumina-based and magnesia-based bricks. The blending of these material types significantly influences the usability of the recyclate. Moreover, secondary raw materials (SRM) derived from carbon-based bricks, can only be utilised for the production of novel carbon-based refractories as conventional processing methods limit the separation of individual grains (e.g., magnesia) from the carbon-containing matrix. The recyclate utilisation rate can reach up to 87 wt% with today's available qualities (Kunanz et al., 2022).

A similar challenge is encountered for carbon-free bricks used in cement production. These bricks can be categorised based on their iron content, and mixing these subclasses is highly detrimental for the use as SRM in the production of new refractory products. Correctly sorted and treated spent refractories from cement applications can make up to 20 wt% of a novel refractory (Klitzsch et al., 2021).

This work is part of the EU-funded project ReSoURCE (**Re**fractory **So**rting **U**sing **R**evolutionising **C**lassification **E**quipment), which develops an automated sorting solution for SR. The objective is to effectively manage all SR breakout materials, including the fine fraction, with a focus on reliability, robustness, and accuracy while maintaining mobility to enable on-site sorting at the point of SR origin. This requires a comprehensive understanding of the occurrence and properties of SR as a fundamental basis. Contemporary literature on the topic is limited and comprehensive statistical data is lacking. The most thorough study on this topic was carried out by Eschner (2003). However, considering that the study was conducted 21 years ago, it is uncertain whether the distribution of SR among various end-of-use categories (hereinafter referred to as final fate distribution) is still accurate.

This study addresses knowledge gaps concerning the quantity and material flow of SR. It employs a multi-step methodology that integrates correlation-based estimation of refractory consumption in Europe with material flow analysis techniques. The results are compared to relevant, but mostly dated, technical literature, highlighting shifts in material flow over the past two decades.

Material flow analysis (MFA) is a systematic approach documenting material flows and storage within a spatially and temporally defined system and is based on the fundamental principle of the law of conservation of mass (Trinkel et al., 2015). Furthermore, the MFA is a quantitative method to track material flows from the source via intermediate to final sinks, allowing for the identification of potential improvements, e.g. in recycling (Brunner and Rechberger, 2017). The present analysis focuses on SCL and CRK, as a large proportion of refractory materials are used in these applications and their breakouts represent a regular and plannable source of SRM. Ultimately, this will allow a more accurate assessment of the economic feasibility of large-scale SR recycling programs.

2. Lifecycle of refractories

Refractories utilised in Europe are manufactured by refractory producers both within and outside of Europe, subsequently distributed to customers. The lifespan of refractories is contingent upon material loss during processes, due to wear. Wear is caused by mechanical and chemical erosion such as abrasion, alteration, infiltration and dissolution and is an imperative area of research as understanding these degradation features could contribute to a longer period of use. Wear reduces the thickness of the refractory lining and the material lost in the process (process loss) can be determined by calculating the ratio of the thickness after and prior to the use phase (eq.1). Wear has a significant effect on the SR volume generated. Reported losses of refractories in steel production vary between 33 and 75 % (Eschner, 2003; Gueguen et al., 2014; Madias, 2018; Muñoz et al., 2020; Nakamura et al., 1999), with Eschner (2003) reporting a loss of 60 % specifically for refractories in SCL. Gueguen et al. (2014) state that a material loss of 75 % applies to CRK. Roberts and Saxby (2014) report a total refractory process loss of 35 % as an estimation, without specifying an industry of use. This variability arises from regional and technological differences, from varying product qualities of the refractory manufacturers and also from differing process conditions.

$$Process\ loss\ (PL)\ [\%] = \left(1 - \frac{Thickness\ of\ spent\ refractory\ lining\ [cm]}{Thickness\ of\ unused\ refractory\ lining\ [cm]}\right) * 100\ \% \quad (1)$$

After reaching the end of their lifetime, SR are broken out during a maintenance period of the plant. This is usually done monthly for SCL (Lule et al., 2005) and once a year for CRK (as deducted from survey data, see 3.2.2) or even after longer periods of time. Typically, SR are broken out indiscriminately to reduce downtime (Horckmans et al., 2019), however companies with successful refractory recycling processes often establish selective breakout processes to minimise subsequent sorting efforts (Hanagiri et al., 2008; Maza, 2019; Ortega, 1998; Viklund-White et al., 2000). Horckmans et al. (2019) estimate that up to 28 Mt of SR are generated annually worldwide.

According to Eschner (2003), the final fate of SR can be divided into three groups: Landfilling, use in non-refractory applications ("downcycling"), and use in refractory applications ("recycling"). Landfilling is considered to be the least desirable option due to land consumption and the loss of highly valuable SRM. Internal utilisation is common practice, e.g., as slag additive (Lule et al., 2005) or as SRM in cement production (Eschner, 2003). In many cases, the material is sent to an external recycler or refractory manufacturer. According to earlier investigations, about half of this material is then used as SRM for refractories (Eschner, 2003). Further applications are aggregates in concrete or road construction, as SRM in glass production or as soil stabiliser and conditioner (Viklund-White et al., 2000). Alternatively, SR can be internally recycled in unshaped (e.g., refractory concrete) or shaped (e.g., bricks) refractory applications or reused in the form of a pre-wall application, where used bricks are placed in front of the new refractory lining (Hanagiri et al., 2008; Muñoz et al., 2020). However, this requires significant investments on the part of the refractory user and is currently not standard practice. Eschner (2003) provides an in-depth analysis on the final fate distribution of SR in Europe from the beginning of the 21st century, stating that about one third (650 kt) was recycled at that time (Table 1).

3. Refractory consumption in steel and cement production

The annual global production of refractories is estimated at 35 - 40 Mt (Horckmans et al., 2019), and the share of iron & steel production in this amount is estimated at 65 - 70 % (Buhr et al., 2016; Buhr, 1999; Horckmans et al., 2019; Jankovits et al., 2016; Madias, 2018; Pirker et al., 2012; Sarkar, 2023). According to Eschner (2003), about 11 % of refractories consumed in iron and steel production can be attributed to iron production, which indicates that 54 - 59 % of refractories are actually consumed by steel production. According to the same reference, 42 % of refractories consumed in steel production are utilised in SCL, while the cement and lime production consumed 8 % of the annually produced refractories. In the case of the Spanish steel producer SIDENOR, 35 % of all required refractory products are applied in SCL (Larzabal, 2020). Briggs (2005) states a 52 % share of refractory consumption for the steel industry and 7 % for the cement industry in

Table 1
Final fate distribution of spent refractories from different industries, adapted after Eschner (2003).

Use case	Final fate						Industry total
	Internal use or non-refractory application		External recycling for refractory applications		Landfill		
Iron and steel	630 kt	46 %	500 kt	36 %	250 kt	18 %	1380 kt
Utilised in a) Steel casting ladles	155 kt	50 %	155 kt	50 %	–	–	310 kt
Non-steel	180 kt	29 %	150 kt	24 %	300 kt	48 %	630 kt
Utilised in b) Cement/lime production	54 kt*	90 %	–	–	6 kt*	10 %	60 kt
Total	810 kt	40 %	650 kt	32 %	550 kt	27 %	2010 kt
Utilised in: a) + b)	209 kt	56 %	155 kt	42 %	6 kt	2 %	370 kt

*Calculated with data taken from Eschner (2003), using the process loss of 75 % from Gueguen et al. (2014).

western Europe in 2002. According to Kreuels (2009) the values are 52 % for integrated steel plants and mini-mills and 15 % for cement and lime production in Europe.

An important key figure in relation to refractories is the specific consumption. This ratio correlates the required quantity of refractories and the quantity of the produced final product (e.g., steel or cement) (eq.2). The specific consumption has been decreasing continuously in recent decades, from approximately 50 kg/t of produced steel in the 1950s to about 10 kg/t in modern plants (Domínguez et al., 2010; Guéguen et al., 2014; Jankovits et al., 2016; Kreuels, 2009; Pirker et al., 2012). For cement production, the specific consumption is generally lower and decreased from about 2 kg/t to about 1 kg/t in average (Guéguen et al., 2014; Pirker et al., 2012; PRE, 2009) or even below 0.2 kg/t in modern large-scale kilns (Guéguen et al., 2014; Scheubel, 2019). This value strongly depends on the regional technological level, as denoted by the difference in specific consumption of 20 kg/t in steel plants in China, 10 kg/t in American and European plants, and only 8 kg/t in Japanese plants (Jankovits et al., 2016). However, the steelmaking route (blast furnace or electric arc furnace) has an additional impact on the specific consumption, with electric steel mills exhibiting lower refractory usage (Jankovits et al., 2016). The specific consumption in steel production further changes with respect to the produced steel grade, the specific know-how and technology employed at the individual plant (Jankovits et al., 2016). Significant impact on the specific refractory consumption is evident through process enhancements like transitioning from Thomas-Process to Basic-Oxygen-Furnaces and from Open-Hearth-Furnaces to Electric-Arc-Furnaces. However, the rate of decrease has plateaued since the mid-1990ś (Guéguen et al., 2014). The mean specific consumption in SCL in 2010 has been calculated with 3.3 kg/t (Pirker et al., 2012). Similar numbers for SCL are stated by Buhr (1999), with a specific consumption of 1.5 to 4.0 kg/t. A specific consumption of 4.2 kg/t for SCL can be deducted from data published by Eschner (2003).

$$\textit{Specific consumption}\left[\frac{kg}{t}\right] = \frac{\textit{annual refractory demand}\ [kg]}{\textit{annual production of product}\ [t]} \tag{2}$$

4. Methodology

4.1. Estimation of the refractory consumption and SR generation

Statistics on refractory consumption up to 2014, as well as on steel and cement production, are publicly available. Since a MFA requires defined boundaries in time and space (Brunner and Rechberger, 2017), data from 2014 cannot be used directly to calculate the current material flow of refractories in Europe. In the absence of more recent data, it is necessary to estimate the consumption of refractories. The following statistics were used as the basis for the estimation of refractory demand:

- Refractory production figures are partially published by the European refractories producers association PRE (PRE, 2015; 2014, 2013, 2011), with latest numbers pertaining to 2014.
- Refractories trade balances, published on the website of the PRE (PRE, 2021).
- Steel production in Europe, published by the European steel producers association EUROFER (Eurofer, 2023, 2022, 2020, 2015, 2010).
- Cement production in Europe, reported by the European cement producers association Cembureau (Cembureau, 2023, 2022, 2020, 2017).
- The Development of clinker-to-cement ratio in Europe, summarised by the Alliance for low carbon cement and concrete (Alliance LCCC, 2023).

To provide a reliable estimate, it must first be assumed that refractories as bulk goods are not produced on stock but are consumed within their year of production. In this way, the production data published by PRE can be harmonised with the trade balances of refractories in Europe and the resulting quantity can be interpreted as the consumption of refractories in Europe. Furthermore, the production figures for steel and cement are multiplied by the respective specific consumption to be able to estimate the consumption of refractories. This result can then be multiplied by the respective process loss either according to literature values or of a specific productions site, to calculate the amount of generated SR (eq.3). Specific consumption values were taken from literature (see chapter 1.2). The percentage of material lost in the process could be partially updated with the help of the survey (see chapter 2.2). Dated literature values were only used if no recent data could be acquired (see supplementary material). If assuming that the shares of steel and cement production on overall refractory consumption as well as the trade balance are roughly constant, it then is possible to estimate the overall refractory consumption in Europe based on its correlation with refractory consumption in steel and cement production.

$$SR\ [kg] = \left(\textit{Specific consumption}\left[\frac{kg}{t}\right] * \textit{annual production of product}\ [t]\right) * (1 - PL\ [\%]) \tag{3}$$

4.2. Analysis of the refractory material flow

To analyse the material flow of refractories in recent years in Europe, data was collected through a survey. The survey was distributed digitally via email and social media (e.g., LinkedIn) and supplemented by direct telephone interviews.

The questionnaire was distributed to 34 contacts within the European steel industry. In total, 14 steel producers responded, however, only one survey was completed and coherent answer was provided.

Additionally, 15 steel plants in Austria and Germany were contacted via telephone, however only one of these producers was ready and able to provide data. According to the published work of McCarten et al. (2021a, 2021b), who presented a global dataset encompassing 70 % of the iron and steel, as well as 90 % of the cement production facilities worldwide, the European continent hosts 504 steelworks with 132 steelworks producing crude steel and are therefore within the scope of this report. Due to the incompleteness of this dataset, actual numbers might be slightly higher. In relation to the total number of steelworks in Europe, 36 % were addressed. Considering all contacts via email and telephone, usable reaction quote is at 4 %. The low reaction quote in steel production can possibly be attributed to the large company structures in steel industries. Some steel manufacturers stated that they do not have the data available and that the process of refractory maintenance is organised by a contractor. Additionally, three recyclers (two on-site and one off-site) for SR from SCL were interviewed regarding the final fate distribution of SR after processing. During all further interpretations, the low reaction quote has to be considered as a factor limiting the certainty of the results. To counteract this fact, five incomplete answers could be used to verify the complete answers for reliability. They generally confirm them on average but also show higher variance.

Furthermore, the questionnaire was sent to 32 European cement producers via email. In total, seven cement manufacturers responded, three of which provided answers that were complete and coherent and therefore could be used for further evaluation. In addition, nine out of 17 contacted cement producers were ready and able to provide the data in question via telephone. When considering all contacts made via email and telephone, the usable response rate is 24 %. No usable answers could be generated through distribution via social media. It has to be noted that the data is concentrated on Austrian and German cement producers and might therefore be biased towards countries with rather strict waste management regulations.

All acquired data was anonymised. The survey aimed to gather the following information:

a) How high is the annual demand for refractories and how high is the amount of SR that are generated annually in the companies' CRK/SCL?
b) What is the final fate distribution of SR from the companies CRK/SCL (internal use, external recycler/manufacturer, landfill)?

Moreover, on- and off-site refractory recyclers were interviewed to gain further insights into the final fate of SR.

According to Bringezu and Moriguchi (2002), a MFA can be related to a substance, a material or a product. The investigated system includes the material flow of SR as a product group, indifferent of their chemical and physical properties, within Europe in 2022 originating from SCL and CRK.

The material flow is analysed from the consumption of refractories in different industries to the final fate of SR (refractory SRM, alternative use cases, landfill). This paper focuses on SCL and CRK, which, according to the literature review, make the largest contribution, other processes and industries are not further considered at this point. Based on the considerations outlined in chapter 2.1, it is expected that there is no long-term storage of SR on the refractory consumer's premises.

Survey and interview data from cement and steel producers and interviews with recycling companies are used to calculate an updated process loss, the amount of SR generated and the further fate of this material. The results are compared with dated literature values to gain insight in changes of refractories material flow over the last 20 years.

5. Results and discussion

5.1. Estimation of refractory consumption

The specific consumption of refractories is reported to be 10 kg/t of

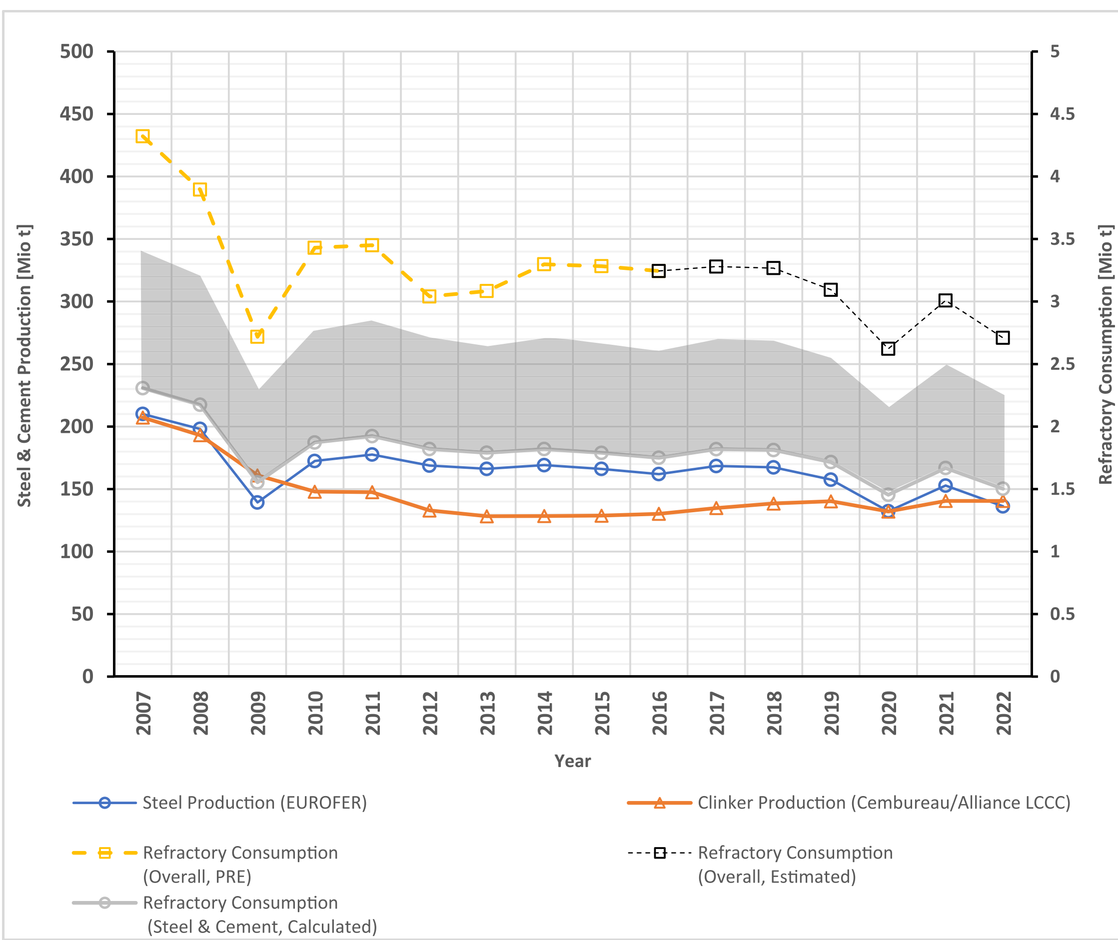


Fig. 1. Development of EU steel and cement production and refractory consumption with time. Refractory consumption in 2022 can be estimated at 2.7 Mt, with 1.36 Mt being attributed to steel and 0.14 Mt to cement clinker production.

steel and 1 kg/t of cement clinker (see chapter 1.2). These values have been confirmed as realistic by a global refractory manufacturer. Multiplying steel and cement clinker production figures with their respective specific consumption value yields the respective estimated refractory consumption. The resulting curve (Refractory Consumption (steel & cement, calculated) in Fig. 1) correlates significantly (Pearson-coefficient > 97 %, significance $p < 0.01$) with the trade-balance adapted overall refractory consumption (PRE, 2021, 2015, 2014, 2013, 2011), indicating that the share of steel and cement industry on refractory consumption was roughly constant. Steel production was reported by Eurofer (2023) at 136.2 Mt in 2022, while cement production was listed at 182.5 Mt by Cembureau (2023). With an average clinker-to-cement ratio of 77 % as proposed by (Alliance LCCC, 2023), the clinker production in Europe can be calculated at around 140.5 Mt.

Based on the observed correlation, it is estimated that approximately 2.7 Mt of refractories were consumed in Europe in 2022 (Fig. 1), indicating a reduction of 0.4 Mt (13 %) within the last two decades compared to the figures reported by Eschner (2003). Of these 2.7 Mt, 1.36 Mt (50 %) can be attributed directly to steel and 0.14 Mt (5 %) directly to cement clinker production. This further indicates that the industry share of steel and cement clinker production is 12 % lower than the 59 % in steel plus 8 % in cement and lime production compared to the findings of Eschner (2003). However, a minor amount of the deviation can be attributed to lime production, which is considered together with cement production by Eschner (2003) but does not fall within the scope of this study. For steel production, the shares are closer to the values provided by Briggs (2005) and Kreuels (2009), who state 55 % and 52 % respectively. On the one hand, this might indicate a decreasing share of steel production over time, but on the other hand may also be due to differing calculation bases.

Further uncertainty is introduced with the use of specific consumption values representing modern plants. This is because not all steel and cement works might reach a specific consumption as low as 10 kg/t (steel) and 1 kg/t (cement) respectively. If the specific consumption is set to 12 kg/t and 1.2 kg/t, the respective shares are 61 % for steel and 6 % for cement industry or even 76 % and 7 % if the specific consumption is set to 15 kg/t and 1.5 kt/t. This variability is indicated by the curve area in Fig. 1. However, this would mean to exceed literature values on specific consumption by about 20 - 50 %. Therefore, shares of 50 % (1.36 Mt) and 5 % (0.14 Mt) for steel and cement clinker production respectively are conservative estimations.

5.2. Analysis of SR flow

5.2.1. SR form SCL

To obtain new data for the MFA, a questionnaire, as described in chapter 2.2, was distributed to contacts within the European steel industry.

The data obtained directly from steel producers suggest that about 40 % of refractories consumed in steel production are utilised in SCL. It can be assumed that there is a process loss ranging from 30 % to 40 % in this application. Approximately 50 % of breakout material is disposed of in landfills, while the remainder is either completely transferred to external recyclers or partially (20 %) reused internally, for instance, as slag additive as presented by Kwong and Bennett (2002). Since the sample size is very low, no derivations on representativity can be made. However, the proportion of landfilled material is relatively high, unveiling the potential for improvement of the waste management practices in these two plants.

The information provided by the recyclers indicate that breakout from SCL is partially pre-sieved by the steelworks, allowing the medium-sized fraction to be used as a slag conditioner. However, the sieving process may also be outsourced to on-site recyclers. The same applies to the handling of scrap metal adhesions, which might be sorted out by steelworks or on-site recyclers and then is used again in steel production processes. The use of SR as slag additive is considered good metallurgical practice, the decision criteria are extensively described in other works (Avelar et al., 2012; Conejo et al., 2006; Kwong and Bennett, 2002; Lule et al., 2005). Sieving prior to sorting can be considered optional, even though it is generally recommended by the interviewed recyclers. This occurs because manual sorting often entails the segregation of specific grain sizes (e.g., > 80 mm), and preliminary sieving serves to reduce the conveyor belt's throughput rate. Sorting performance should additionally improve, as staff will no longer have to differentiate between grains that are too small and those that fall within the size limit. Within the manual sorting process, SR are typically divided into three to four different fractions, including (1) material used for the production of recyclate for new refractory products, (2) material which will be utilised in metallurgical processes or is going to be downcycled in any other way, (3) fine fraction which cannot be sorted at the moment and is therefore landfilled, and optionally (4) steel scrap. Sorting criteria are generally defined in coordination with potential customers with regard to the respective utilisation route e.g., refractory manufacturers and depend especially on material type, purity, and grain sizes. For example, very fine or very coarse material is not suitable when using SR as slag additive, as fine particles would be discharged by the ascending hot air and exhaust ventilation while very coarse particles would dissolve to slowly in the molten steel bath. Impure material is not suitable as refractory SRM, as quality standards of refractory producers are high. The provided data suggests that on average, 63 % of SCL breakout material is recycled in refractory applications, 25 % is downcycled in metallurgical applications and 10 % is landfilled (Table 2). SCL breakout contains on average 2 % scrap metal adhesions. Selective breakout and precise handling of the breakout material is important for the successful implementation of a recycling program, as already described by other authors (Hanagiri et al., 2008; Maza, 2019; Ortega, 1998; Viklund-White et al., 2000). This fact is emphasised by the rationales provided by the recycling companies for the decision to landfill materials. Mixing of SR during breakout and material handling within the steelworks might increase the share of material landfilled. This is due to the fact that mixed materials are generally more difficult to sort.

In addition, a high proportion of specific grain sizes — too small for sorting but large enough to be used as slag additive — can lead to a higher share of material being landfilled if the steelworks do not use this material as metallurgical correction measure. This is mainly influenced by the company's sustainability strategy. Due to the current practice of predominantly manual sorting, SR that are not within the size limitation are presently not suitable for recycling purposes.

5.2.2. SR from CRK

The questionnaire was sent to 32 European cement producers via email. In total, seven cement manufacturers responded, three of which provided answers that were complete and coherent and therefore could be used for further evaluation. Furthermore, nine out of 17 contacted cement producers were ready and able to provide the data in question via telephone. When considering all contacts made via email and telephone, the usable response rate is 24 %. No usable answers could be generated through distribution via social media. It has to be noted that the data is concentrated on Austrian and German cement producers and

Table 2
Case studies presenting handling of SR from steel casting ladles by recycling companies. Figures from 2022.

Final fate	Case study 1	Case study 2	Case study 3	Weighted average
Recycling in refractory applications	33 %	71 %	79 %	63 %
Use in metallurgical application/downcycling	38 %	23 %	13 %	25 %
Landfill	22 %	6 %	8 %	10 %
Scrap metal adhesions	8 %	–	–	2 %
Total amount	3.7 kt	10 kt	2.25 kt	–

might therefore be biased towards countries with rather strict waste management regulations. Cement producers stated that disagreements on the price of breakout material and concerns for legal security (material formerly used internally would have to be declared as product or waste) were the biggest obstacles onto increasing the share of recycling. Additionally, one off-site recycler for SR from CRK has been interviewed and provided data on the final fate distribution after the recycling process.

The installed capacity of clinker production of the interviewed cement plants accounts for roughly 7 % of European clinker production (see also chapter 3.2). However, since plants are unlikely to be running constantly at their production limit, the share of the investigated plants on European clinker production is estimated to be slightly lower. Cross-validation is possible by dividing the refractory consumption within the interviewed plants by the total refractory consumption in European cement production, leading to a value of roughly 3 %. Therefore, the actual contribution of clinker production to the total European clinker production for the investigated plants might range between 3 % to 7 %, with a probable value around 5 %. The survey indicates a process loss of 45 %, an internal reuse as cement SRM of 30 %, a rate of material provided to external recyclers or the manufacturers of 23 % and a share of landfilled material of only 2 % (Fig. 2).

Data provided by an off-site recycler for SR from CRK indicates a high share of material being recycled in refractory applications: 81 % are recycled in refractory applications, 14 % are used as cement SRM or other non-refractory applications and 5 % are landfilled. Challenges are essentially equivalent to those presented for SCL (chapter 3.2.1). However, a large proportion of cement manufacturers have the option of grinding the breakout material directly in their plant and using it as a SRM for cement. Thereby the share of this fraction at the recycler is reduced.

5.2.3. Comparison of the results with literature

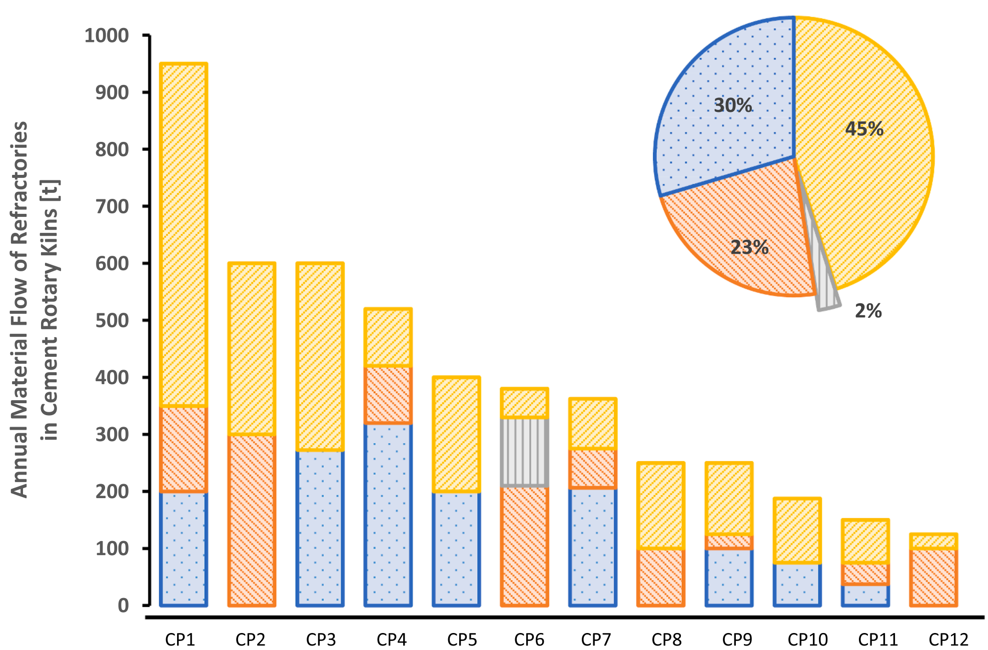
As outlined in section 3.1, 2.7 Mt of refractories were consumed in Europe in 2022, with 1.36 Mt (50 %) allocated to steel production and 0.14 Mt (5 %) being attributed to cement clinker production. These values are used as a basis for all further calculations. The calculated numerical values are presented in Table 3 and are visualised in Fig. 3.

Eschner (2003) reported that 42 % of refractories consumed in steel production are used in SCL, with a process loss of 60 %. During this study, it was found that approximately 40 % of refractories were indeed used in SCL, but results indicated a lower process loss, thereby suggesting a higher proportion being generated as SR. A process loss of 40 % is conservatively estimated based on the available survey data. Using eq.3 (chapter 2.1) this results in 326 kt of SR generated from SCL in Europe in 2022.

According to the survey, half of the breakout material is disposed of in landfills. This finding contrasts sharply with Eschner's (2003) assertion that no breakout material from SCL would be landfilled due to its high material quality.

The survey data indicates a process loss of 45 % within CRK, which is considerably lower than the 75 % stated by Gueguen et al. (2014). Eschner (2003) suggests that no material from cement production was recycled, 10 % were landfilled and most of the SR are milled and used in small proportions as SRM in cement production, although specific values are not provided. This situation has changed, as deduced from the survey. Results indicate that 55 % of breakout material is used as a cement SRM, 42 % are passed over to recyclers and the rest (3 %) is landfilled.

According to interviews conducted, 64 % of SR from SCL that are handed over to recyclers are recycled in refractory applications. This is consistent with the 66 % stated by Eschner (2003). Furthermore, 10 % of this material is landfilled according to our investigations, while Eschner (2003) stated the share to be 20 %. The remaining material is used in metallurgical or other non-refractory applications.



	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8	CP9	CP10	CP11	CP12
Refractory Demand	950	600	600	520	400	380	363	250	250	188	150	125
Process Loss	600	300	327	100	200	50	88	150	125	113	75	25
Fate: Landfill	0	0	0	0	0	120	0	0	0	0	0	0
Fate: Recycling	150	300	0	100	0	210	69	100	25	0	38	100
Fate: Internal Reuse	200	0	273	320	200	0	206	0	100	75	38	0

Fig. 2. Fate of installed refractories at interviewed cement plants (1-12) (bar chart) and average fate (pie chart, total ≈ 4.8 kt).

Table 3
Fate of refractories from steel casting ladles and cement rotary kilns in 2022 in Europe. Values of internal use and landfill, are split according to their origin.

	Final Fate								Total SR
	Internal use non-refractory applications			Landfill			Recycling		
	breakout	recycler	% of Total SR	breakout	recycler	% of Total SR	refractory SRM	% of Total SR	
Steel casting ladle	81.5 kt	21 kt	30 %	163 kt	8 kt	52 %	52.5 kt	16 %	326 kt
Cement rotary kiln	42 kt	4 kt	60 %	2 kt	2 kt	6 %	25 kt	32 %	77 kt

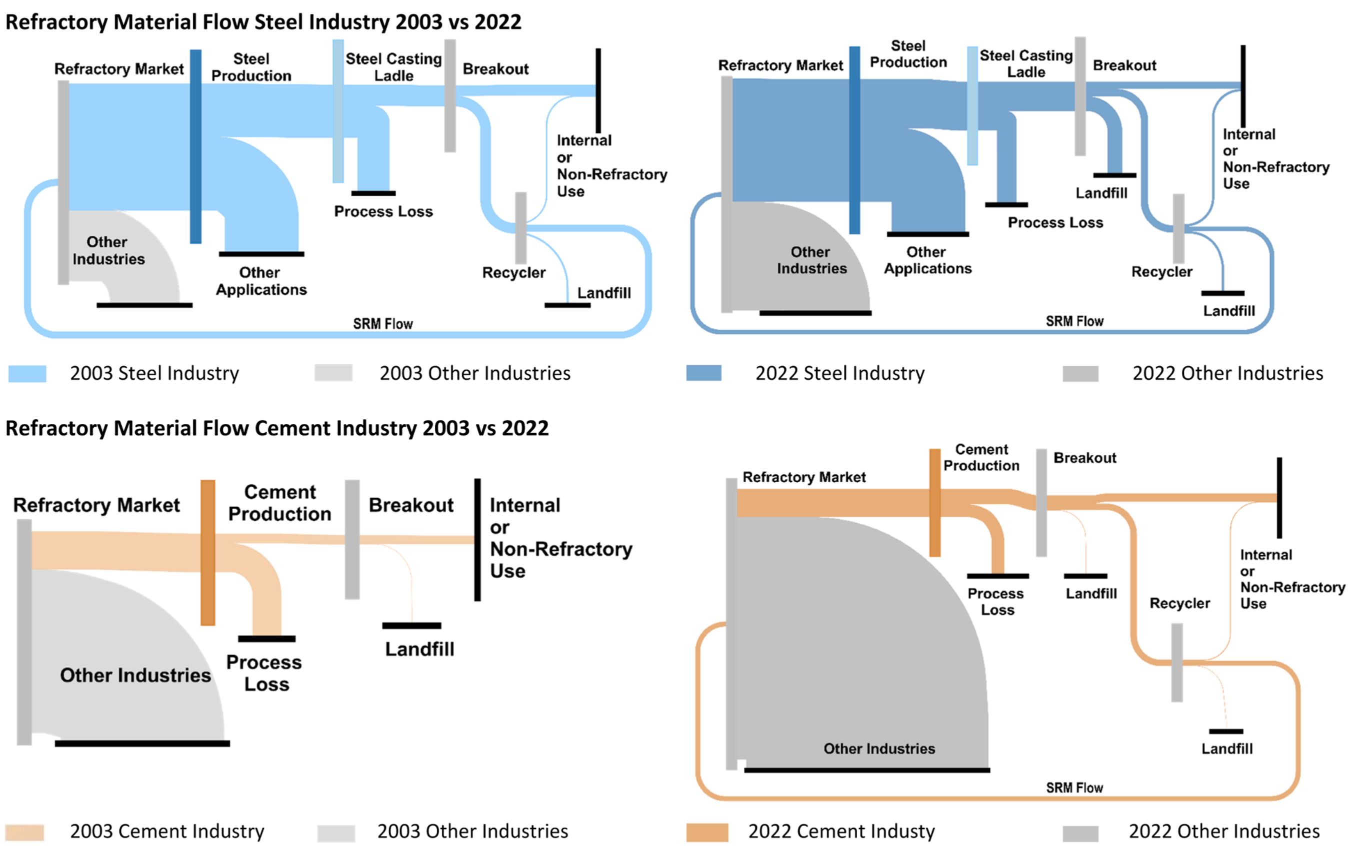


Fig. 3. Material flow of refractories, showing the development of recycling rates for refractory linings in SCL and CRK during the last two decades. Data acquired during this and earlier (Eschner, 2003, adapted with refractory process loss in cement production after Gueguen et al., 2014) works.

For cement production, a recycler stated that 81 % of SR from CRK are recycled in refractory applications. In total, 14 % are used as cement SRM or within other non-refractory applications with the rest (5 %) being landfilled.

6. Conclusion

During this investigation, we analysed the material flow of refractories in Europe in 2022 focusing on SCL and CRK. The required data was obtained through a combination of evaluating annual reports from steel, cement and refractory manufacturers, a survey of cement and steel producers via email and telephone, and interviews with refractory recyclers.

The refractory production has been estimated at 2.7 Mt with 1.36 Mt being attributed to steel production, of which 40 % is used in SCL, and 0.14 Mt being attributed to cement production. Process losses for SCL (40 %) and CRK (45 %) are calculated to be lower compared to previous publications. The results indicate that in 2022 in Europe 323.5 kt (81 %) of SR were generated from SCL and CRK but not recycled in refractory applications. This reveals the immense potential for the implementation of large-scale recycling programs.

Contrary to expectations, the results indicate a shift towards a lower recycling- and higher landfill share. However, this is particularly influenced by steel production, where results must be interpreted cautiously due to the limited number of participants. Further investigations on specific consumption rates and material fate in steel production should be conducted to increase certainty of the results. The presented approach to calculate generated SR volumes can be applied to analyse refractory consumption and material flow for SCL and CRK in Europe and can also be expanded to other industries, adapted to other continents and be used for forecasts on SR generation.

This endeavour will enhance comprehension regarding the fate and quantity of SR. Subsequent research aims to investigate the bulk composition of SR, thereby facilitating a more refined evaluation of technical feasibility.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Perplexity AI in order to increase readability and clarity of the text. After using this service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Florian Feucht: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard Moderegger:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Simone Neuhold:** Writing – review & editing, Investigation. **Klaus Philipp Sedlazeck:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Florian Feucht reports financial support was provided by European Union. Simone Neuhold reports a relationship with RHI Magnesita GmbH that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108158.

Data availability

Data will be made available on request.

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