SUSTAINABILITY ASSESSEMENT OF RECYCLED CEMENT AND HIGH-QUALITY RECYCLED AGGREGATES PRODUCTION FROM CONCRETE WASTE

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ABSTRACT

The present study estimates the energy consumption and greenhouse gas (GHG) emissions of a magnetic separation-based technology developed to produce recycled cement (RC) from concrete waste. Past studies identified two critical aspects for the environmental performance of the method: i) the need to process a substantial amount of concrete waste to obtain a limited amount of RC; and ii) the energy consumed in the thermoactivation of the hydrated cement paste. The present study allocates the impacts by the various products obtained, which include high quality fine recycled aggregates (HQRA), and uses operational data from real aggregates and construction and demolition waste plants. Furthermore, the enthalpies of the dehydration reactions of the hydrated cement paste are used to estimate the thermoactivation energy. The results estimate that RC emits between 13% and 23% of the GHG of Portland cement and HQRA GHG emissions are 41% to 86% lower than crushed fine aggregates.

Keywords

Recycled cement, magnetic separation, energy consumption, greenhouse gases emissions

1 INTRODUCTION

Studies on the fire behaviour of concrete structures found that rehydration of the dehydrated cement paste exposed to high temperatures was possible (Crook and Murray 1970; Alonso and Fernandez 2004). This observation formed the basis of the first studies on the potential for cement recycling (e.g., Splittgerber and Mueller 2003). The definition of recycled cement (RC) is broader and includes the following categories (Shivaprasad et al. 2024): i) mechanically and chemically activated RC, which consists of simply grinding and sieving concrete waste, possibly with the addition of chemical admixtures, to enhance the use of unhydrated cement contained in the concrete (Kulisch et al. (2023) indicate that the proportion of unhydrated cement ranges from 36% for concretes with a water–cement ratio of 0.2, to 6% for concretes with water–cement ratios above 0.4); and ii) thermally activated RC, in which, after mechanical processing involving grinding and sieving of concrete waste, the hydrated cement paste is subjected to thermal treatment that removes hydration water and reactivates the material's hydraulic binding properties.

However, only more recently has the topic received renewed and intense interest (Serpell and Zunino 2017; Carriço et al. 2020a). In the last decade, studies on RC have multiplied, exploring various factors that influence its performance, namely (Xu et al. 2022): i) characteristics of the waste used to produce RC, including aspects such as the degree of hydration (Wang et al. 2018; Xuan and Shui 2011) and carbonation (Zhutovsky and Shishkin 2021; Lu et al. 2018; Ouyang et al. 2020), and the presence of supplementary cementitious materials (Vyšvařil et al. 2014; Baldusco et al. 2019), inert siliceous fines (Florea et al. 2014; Serpell and Lopez 2013) or fine aggregate powder (Florea et al. 2014; Kim et al. 2021; Algourdin et al. 2020); ii) thermoactivation conditions, which include variables associated with thermal processing—such as temperature and processing time (Real et al. 2020; Shui et al. 2009) and heating and cooling rates (Castellote et al. 2004)—and those related to the preparation of the material prior to thermal processing, particularly the grinding method (Zhang et al. 2018; Florea and Brouwers 2012) and the particle size distribution of the hydrated cement paste (Letelier et al. 2017; Bogas et al. 2019); iii) the rehydration process, specifically the phase development (Bogas et al. 2020, 2022), water/binder ratio (Zhang et al. 2018; Baldusco et al. 2019; Shui et al. 2009; Xuan and Shui 2011), the combination of RC with supplementary cementitious materials and other mineral additives (Vyšvařil et al. 2014; Wang et al. 2018; Zhang et al. 2018), and the effect of chemical admixtures (Zhang et al. 2019).

Compared with Portland cement (PC), the main drawback of RC reported in the literature is its higher water demand, which adversely affects concrete workability and applicability (Shui et al. 2009). The amount of mixing water needed is related to the temperature of the thermal treatment, increasing up to 800ºC (Vyšvařil et al. 2014). From the standpoint of RC use, this aspect is critical because the water-cement ratio governs the mechanical strength and porosity, and consequently the durability of concrete. However, by using superplasticizers and partial replacement of PC with RC, several studies have demonstrated the technical feasibility of RC as a substitute for PC (Meng et al. 2021b). Real et al. (2020) highlight the influence of treatment temperature on the mechanical properties of RC, with the best characteristics observed for RC produced with thermal treatment at 650ºC. Below 600 °C, dehydration and formation of reactive α'H-C_2S are insufficient, whereas above 750 °C this phase progressively transforms into a less reactive C_2S polymorph (Real et al. 2020).

The differences between RC and PC are broader, ranging from chemical composition (Zhang et al. 2022) and physical characteristics (Wang et al. 2018; Zanovello et al. 2023) to microstructure (Bogas et al. 2020), which affects hydration (Carriço et al. 2020b; Li et al. 2023) and the properties of hardened concrete. Nevertheless, RC hydration yields the same types and comparable volumes of hydration products as PC (Bogas et al. 2022).

Until recently, most thermally activated RC studies used hydrated cement paste to simulate concrete waste (Baldusco et al. 2019; Mao et al. 2024) or concrete waste itself (Letelier et al. 2017; Kim et al. 2021). In the second group of studies, the cement paste was obtained through mechanical processes, by selecting the finest fractions resulting from concrete grinding. However, the finest fractions of concrete waste are a mixture of hydrated cement paste and aggregates in variable proportions, which limits the practical application of this approach. Recently, a patented technology (Bogas et al. 2021) was developed that enable to effectively separate the cement paste waste from aggregates. The technology exploits the different magnetic properties of cement paste and aggregates to separate these two fractions. Using this process, a cement paste stream with a contamination level of 10–20 vol% can be obtained (Carriço et al., 2021).

Several studies using this technology have demonstrated the technical feasibility of the RC produced (Bogas et al. 2019; Real et al. 2020; Carriço et al. 2021). However, by separating the cement paste from the aggregates, this technology also makes it possible to obtain recycled fine aggregates with cement paste contents below 5 wt%. This is a crucial aspect, considering that the main limitation to the use of recycled aggregates from concrete waste in new concrete production is precisely the detrimental effect of the adhered hydrated cement paste, as evidenced in the many reviews already carried out on this topic (e.g., Evangelista and Brito 2014; Shi et al. 2016; Silva et al. 2018; Verian et al. 2018; Nedeljković et al. 2021; Wang et al., 2021). This technology effectively contributes to a circular economy in the concrete and cement industries by reducing natural resource and energy consumption, lowering GHG emissions, and increasing CDW recycling rates.

Previous research (Sousa and Bogas 2021; Real et al. 2022; Sousa et al. 2023a,b) used the PC production as a proxy to estimate the performance of the RC. However, this analogy entails two major drawbacks: i) the temperature required for the sintering reactions (1450ºC) in PC production is much higher than the temperature required for the thermoactivation of RC (650ºC); and ii) some of the chemical reactions during PC production are exothermic, while the dehydration taking place during the RC thermoactivation is endothermic. These differences affect both the energy balance of the reactions (theoretical energy required) and efficiency of the production process (e.g., energy losses). Additionally, RC is not the only product obtained in the process. High-quality fine recycled aggregates (HQRA), normal fine recycled aggregate (NFRA) and normal recycled filler (NRF) are also produced in the process. The environmental assessment presented herein attempts to address all these limitations from previous studies by: i) establishing an analogy with lime production, which involves a thermal treatment of a temperature closer to RC; ii) quantifying the thermal energy needs based on the enthalpy of the dehydration reactions; and iii) distributing the energy consumption and carbon emissions in each stage of the process by the products produced. Complementarily, the assessment uses operational data from real aggregates and construction and demolition waste (CDW) plants to model the release stage, which entails the larges fraction due the volume of material that needs to be processed.

2 MATERIAL AND METHODS

2.1 PRESENTATION

The novel technology developed under the EcoHydb project (Bogas et al. 2021; Carriço et al. 2021) allows the extraction of hydrated cement past from concrete waste by resorting to magnetic separation.

The novel technology entails three stages, namely: i) release; ii) separation; and iii) reactivation. The release stage aims at disaggregating the cement paste from the aggregates, which is achieved by mechanical gridding and milling the concrete waste. The material is then separated into four fractions:

i) 0.5 to 1 mm; ii) 0.25 to 0.5 mm; iii) 0.15 to 0.25 mm; and iv) less than 0.15 mm. The two middle fractions, 0.25 to 0.5 mm and 0.15 to 0.25 mm, were found to be the most adequate for obtaining the cement paste waste, because of the high proportion of pure hydrated cement paste particles present. The smallest fraction (less than 0.15 mm) is difficult to process with the magnetic separator and can be regarded to be similar to a recycled concrete waste filler (NRF), as defined in EN 197-6 (2023). The majority of cement paste on the particles of the largest fraction (0.5 to 1.0 mm) are still adhered to aggregates, so is identical to typical fine recycled concrete aggregates (NRFA). In laboratory conditions, the fraction of particles over 1 mm was between 5% and 10% (8% in average) and is also identical to typical NFRA.

Using high-intensity permanent rare-earth magnets, cement paste particles can be separated from aggregate particles due to their differing magnetic properties. Before this, the particles are cleaned with compressed air to remove dust that impairs the magnetic separation performance (Sousa et al. 2023a,b). In addition to the hydrated cement paste, this separation process also produces fine recycled concrete aggregates with less than 5 wt% of hydrated cement paste (HQRA). HQRA, with low absorption properties (<1–2 wt%), are comparable to fine crushed aggregates from natural rock and avoid the drawbacks associated with conventional recycled aggregates (e.g., see Nedeljković et al. 2021 for a review). More HQRA can also be obtained by separating the largest fraction (0.5–1.0 mm) of crushed concrete waste using the same magnetic separation process. This step is optional and only serves to increase the quantity of HQRA, since no further hydrated cement paste is recovered.

Thermoactivation involves heating the cement paste to 600–700 °C to produce RC (average 650 °C; Bogas et al. 2019, Real et al. 2020). This treatment dehydrates the cement paste waste, reducing its mass by approximately 20%, on average, but it depends on its degree of hydration. Before the thermal treatment, the cement paste waste is milled to a particle size comparable to conventional cement to optimize its binding properties.

Table 1 presents the mass fluxes of the laboratory-scale process, showing that only 5% of the concrete waste is converted into RC. Given that cement accounted for approximately 15% of the concrete waste by mass, the process achieved a recovery rate of about 33%. This recovery rate was found to be relatively constant regardless of the cement dosage. Alternatives 1 (ALT1) and 2 (ALT2) reflect the option of focusing only on obtaining RC or also maximizing the HQRA amount, by also submitting the 0.5-1 mm coarser fraction to magnetic separation.

Table 1 – Mass fraction of each product obtained with the novel RC production technology

Product	ALT1 [%]	ALT2 [%]
Release and Separation		
HCP - Hydrated Cement Paste	6	6
HQRA - High Quality Recycled Aggregates	18	39
NRA - Normal Recycled Aggregates	48	27
NRF - Normal Recycled Filler	23	23
Loss	5	5
Reactivation		
RC - Recycled cement	5	5

2.2 METHODOLOGY

Within the scope of this case study, a cradle-to-gate analysis is performed, encompassing stages A1 (Raw material extraction and processing), A2 (Transportation to manufacturer) and A3 (Production), as defined on EN 15804+A2 and ISO 21930. A hybrid methodology was adopted involving analogy, when similar industrial processes exist, and simulation. Results from different sources and methods,

when available, are presented and discussed to validate the estimates and provide an indication regarding the magnitude of the associated uncertainty.

To limit the impact of using PC production process as a proxy, herein the analogy is established with the production of lime. In the release stage, complementary comparisons are made with recycled aggregates and natural aggregates production since the comminution of concrete waste is not identical to raw material production for concrete. The separation stage can only be simulated, since it does not exist in the production of the quicklime. A theoretical estimation of the energy required for the thermoactivation is done considering dehydration energy for the main hydrated cement components. The production efficiency of the thermoactivation is estimated by analogy with the lime production assuming that: i) the reaction time in both processes is the same; and ii) the energy losses are similar. A comparison with the energy consumption of the lime production is also done considering a linear relation between temperature and energy.

The production is assumed to take place at two distinct locations: i) the release and separation stages at the CDW treatment plants; ii) the reactivation at a centralized plant, either by utilizing existing lime or cement plant facilities with process adjustments or at a dedicated plant. Producing RC at CDW treatment plants is highly inefficient, requiring investment in various small kilns that will be hard to operate continuously. Centralizing the release and separation stages at a specific site result in longer transportation distances for CDW. In this context, an average distance between the RC thermoactivation plant and the CDW treatment plants of 75 km is assumed This corresponds to a journey of 150 km for transporting the separated hydrated cement paste waste to the location where the thermoactivation is carried out (truck full from the CDW treatment plant and empty in the return).

Another distinctive feature of the present study is to take into account that the RC production also allows obtaining HQRA, NRA and NRF (Table 1). Therefore, the environmental assessment was performed considering the following allocation scenarios: i) S1 – all impact is allocated to RC; ii) S2 – the impacts are distributed over RC and HQRA for each stage involved in their respective production proportionally to the amount produced; and iii) S3 – the impacts are distributed over the all products depending on the amount and stages involved in their production. RC is the only product that requires the reactivation stage, HQRA requires both the release and separation stages, while NRA and NRF require only the release stage.

2.2.1 Energy consumption

The baseline for assessing the environmental performance of RC adopted herein was an analogy to the lime production. This shift from previous research based on analogy with cement production was motivated by the greater similarities of the production processes, particularly in terms of: i) the similarity of the reactions involved (both include a release reaction, with CO_2 in lime and water in RC); ii) the need to prevent the inverse reaction (CO_2 in lime and water in RC); iii) the closer temperature range of the thermal treatments (900-1200ºC for lime and 600-700ºC for RC); and iv) the production technologies, with vertical kilns, more adequate for smaller plants, being more frequent in lime production, while rotary kilns, capable of higher production rates, dominate Portland cement production.

Table A 1 in Appendix presents the information on the energy consumption and direct combustion emissions reported by Schorcht et al. (2013) and Stork et al. (2014) for lime production in Europe. Complementary information from other sources is indicated in the table. The reported values are consistent with average sector values observed in other regions worldwide. For instance, in Brazil, the lime industry average electrical and thermal energies consumptions are 15 kWh/t CaO and 4.3 kWh/t CaO, respectively (CNI et al. 2010).

The experimental work used lab-produced concrete cubes as a source of concrete waste, which does not fully represent the production process of recycled concrete aggregates from CDW. Furthermore, the crushing and grinding processes in laboratory were not optimized and limited to using the existing equipment, hindering the use of the operational data for extrapolating to industrial-scale applications. Therefore, in addition to the analogy with the lime production process, the specific energy was also estimated using the Bond's law (Bond 1952):

$$W = W_i \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}} \right)$$

where W_i is the work index (kWh/t); F is the 80% passing size of the feed material (10^{-3} mm); and P is the 80% passing size of the closing screen (10^{-3} mm). Authors, such as Morrel (2004), have proposed corrections to the Bond's law used herein, but their use requires experimental parameters that are not available for the concrete waste. The work index is determined experimentally and tends to increase exponentially for closing screen sizes below 0.25 mm (Menéndez et al. 2018). This exponential increase occurs in most types of materials and the threshold varies between 0.06 mm and 0.10 mm (Martins 2020). No data was found for concrete waste, so it was assumed that the energy required for crushing and grinding the concrete waste is driven by the coarse aggregate's strength. For limestone, which is the most commonly used coarse aggregate in Portugal, a value of 12.7 KWh/t is indicated in Wills and Finch (2015), consistent with the values of 12.6 KWh/t (for sieve 0.074 mm) to 13.9 KWh/t (for sieve 0.15 mm) obtained by Todorović et al. (2017), but substantially higher than the 5.9 KWh/t to 9.5 KWh/t reported by Petrović et al. (2016). A range between 9 KWh/t and 14 KWh/t, with an average value of 12 KWh/t was adopted. This value is higher than the maximum reported by Menéndez et al (2018) for limestone. Moreover, in normal aggregate concrete, strength is practically independent of aggregate type (Vishalakshi et al. 2018) and remains lower than the strength of the aggregates themselves. Therefore, this assumption is conservative and overestimates the energy required for the comminution of concrete waste.

Complementarily to the theoretical energy consumption estimate for the crushing and griding of the concrete waste, the operational data from a recycled aggregates production plant (SGR) and a natural crushed aggregates production plant (SECIL) were also obtained. This data provides not only realistic information on the crushing and grinding processes, but also account for the energy consumed in material handling during the release stage.

The separation stage is not part of any industrial process related to either lime or cement production, as it involves a newly patented technology. Therefore, the process was simulated extrapolating the laboratory data and manufacturer specifications. The energy required for cleaning the concrete waste was estimated based on the specific energy consumption of air compressors reported by Mousavi et al. (2014), assuming an air demand of 10 m³ per kilogram of cleaned concrete waste. Permanent rare-earth magnetic separators are the most energy-efficient magnetic option (Tripathy et al. 2017), as they do not require electricity to generate the magnetic field. Electricity is consumed only to rotate the magnet, which also drives the conveyor belt. According to the manufacturers, energy consumption is only 1.5 kWh per ton of material processed. Considering the two cycles of magnetic separation, this corresponds to less than 3.0 kWh/t. Material separated in the first cycle does not undergo the second cycle, so the energy consumption for the second cycle is less than 1.5 kWh/t.

The theoretical estimation of the energy required in the reactivation stage is based on the enthalpies of the major reactions involved, namely the dehydration of the C-H-S gel (1440 kJ/kg water) and calcium hydroxide (5660 kJ/kg water) (Bentz and Prasad 2007), considering the following assumptions: i) the cement paste is fully hydrated and non-carbonated; and ii) any moisture present in the cement paste is evaporated by the exhaust heat from the kiln.

In addition to the energy required for the reactions, the reactivation requires energy to heat the material up to 650°C. The heat capacity of the hydrated cement paste ranges between 0.9 kJ/kg °K and 2 kJ/kg °K (Wolterbeek and Hangx 2023), decreasing with the hydration degree (Qomi et al. 2015). Since the cement paste was assumed to be fully hydrated, a value of 1 kJ/kg·K was adopted. A partially hydrated cement paste would increase the energy needed for heating the material, but would decrease even more the dehydration energy required.

To account for the energy efficiency of the thermoactivation process, an analogy with the best technology for lime production was established. The minimum theoretical energy required for complete decarbonation is roughly 3.2 GJ/t CaO (Bes 2006), which, comparing with the energy consumption reported for the PFRK kilns, would imply a 100% efficiency. However, commercial lime is not pure and for the degree of purity of the commercial lime the minimum theoretical energy is around 3.0 GJ/t CaO. This implies an energy efficiency of the kiln is 94%, which was adopted herein.

The energy required for grinding prior to reactivation was disregarded, as the estimates for the release stage are already highly conservative, based on an analogy with natural rock comminution, and this stage involves only the grinding of cement paste with residual amounts of aggregates.

2.2.2 Greenhouse gases emissions

The energy consumptions were converted into greenhouse gas (GHG) emissions, in particular CO_2 when data regarding other GHG emissions were unavailable, using the emission factors of the corresponding source of energy.

The electricity GHG emission factor in mainland Portugal declined from 0.526 $kgCO_2eq/kWh$, in 2005, to 0.092 $kgCO_2eq/kWh$, in 2023. Over the most recent 5 years with official data published and reviewed (2019 to 2023), it averaged 0.156 $kgCO_2eq/kWh$ (APA 2025). The large fraction of renewable sources in Portugal electricity power source mix combined with the Mediterranean climate, results in substantial seasonal variations of the electricity emission factor. Between January 2024 and December 2024, the minimum and maximum carbon intensities of electricity in Portugal were 0.011 $kgCO_2eq/kWh$ (25/02/2024) and 0.181 $kgCO_2eq/kWh$ (13/12/2024), respectively (Electricity Maps 2025). Different official sources present slightly distinct figures, with the EEA (2025) reporting a value of 0.115 $kgC0_2eq/kWh$ for Portugal in 2023.

The thermal energy is assumed to be supplied by natural gas, characterized by a lower heating value GHG emission factor of 0.0566 $kgCO_2eq/MJ$ and an oxidation factor of 0.995 (APA 2023). Different sources provide a relatively constant Lower Heating Value GHG emission factor (e.g., 0.0561 kg $C0_2eq/MJ$ in Krey et al. (2014); 0.0504 kg $C0_2eq/MJ$ in EPA (2025)). The carbon intensity of the fuel mix used for lime production is slightly lower, ranging from 0.063 $kgC0_2/MJ$ to 0.101 $kgC0_2/MJ$ when using PFRK technology (see **Error! Reference source not found.**), so this assumption is conservative.

The fuel used by combustion engines was considered to be diesel, since it is the most commonly used in commercial vehicles and machinery in Portugal. The energy content of diesel engine fuel varies from 38.3 MJ/l, reported by the Bureau of Transportation Statistics (BTS 2025), to 39.3 MJ/l, reported by the Department for Energy Security and Net Zero (2025). Following the ISO 16258 approach, Schmied and Knörr (2012) estimated a value of 35.9 MJ/l, so an average value of 37.6 MJ/l was adopted herein. Schmied and Knörr (2012) estimate a GHG emission factor of 2.67 kg CO_2eq/l for diesel, whereas a retail fuel supplier in Portugal reports a lower value of 2.30 kg CO_2eq/l (BP 2024). The difference between both sources is, at least partially, due to the incorporation of biodiesel in the latter, since 7% biodiesel decreases the GHG emissions factor to 2.48 kgCO2eq/l, which also affects the energy content, since biodiesel has a lower specific energy (32.8 MJ/l). The energy and emissions intensity

from direct use of the diesel in the combustion engine, but accounting for the energy consumed during the fuel production cycle increases the energy intensity to 51.3 MJ/l and the GHG emission intensity to 3.24 kg CO_2eq/l (Schmied and Knörr 2012).

The vehicle considered for transportation was a VECTO 5-RD, with (Mulholland et al. 2023): i) axle configuration of 4x2; ii) a gross vehicle weight rating (GVWR) above 16 t; and iii) a load capacity of about 10 t. A fuel consumption of 31.7 l/100 km and GHG emissions of 853.7 gCO_2eq/km is estimated assuming that 90% of the distance is done in regional delivery. In a 90% long haul regime, the fuel consumption decreases to 28.3 l/100 km and the GHG emissions to 773.5 gCO_2eq/km. ICCT (2018) estimate a fuel consumption ranging from 23 l/100 km (empty) to 36 l/100 km (loaded), averaging 33.1 l/100 km. These consistent estimates based on a distance base only fail when considering also the load since reference truck used in ICCT (2018), developed in ICCT (2017), is 40-tonne truck with a load capacity of 25.6 t. The specific fuel consumption of the VECTO 5RD is 0.0317 l/t.km, while the reference truck of ICCT (2017) is 0.01715 l/t.km. These values are slightly lower than reported by Schmied and Knörr (2012) for the corresponding load category, but within the same order of magnitude

3 RESULTS AND DISCUSSION

3.1 ENERGY CONSUMPTION

As source of raw material for the RC production, it is assumed concrete waste is available from the CDW plants in the form of recycled aggregates. Establishing the analogy with the lime production and considering a lime purity of 95%, the electricity consumption on the release stage ranges between 1.1 to 1.4 kWh/t (average 1.2 kWh/t) and the fuel consumption is between 21.5 to 87.9 MJ/t (average 54.7 MJ/t). Establishing the analogy with clinker production instead and using the environmental product declaration for Portuguese grey cement developed for the Portuguese Technical Cement Association (DAPHabitat 2023), the electricity consumption is 56 kWh/t and the fuel consumption 15.4 MJ/t. Overall, these estimates are similar, but with higher electricity consumption using the clinker analogy (Sousa et al. 2023a,b), whereas the lime analogy leads to higher fuel consumption estimates.

The estimate of the electricity consumed for comminution of the concrete waste during the release stage using the Bond's law is presented in Table A 2 (Appendix A). On average, it was assumed that concrete waste, in the form of recycled aggregates available at CDW plants, consists of 80% of particles smaller than 30 mm. The values estimated are aligned with the electrical energy reported by Hossain et al. (2016) for producing aggregates in industrial facilities: i) 3 kWh/t for fine and 4 kWh/t for coarse recycled aggregates; and ii) 6 kWh/t and 7.5 kWh/t for fine and coarse natural aggregates, respectively. These values are slightly lower than the 5 kWh/t reported by Figueiredo et al. (2024) for producing fine recycled aggregates under laboratory conditions.

Table A 3 in Appendix A presents average operational data from SECIL and SGR, evidencing: i) the differences between comminution of limestone and concrete waste; and ii) the relative importance of handling in comparison with crushing and griding. The data includes all activities and all types of aggregates produced in the facilities, so differences may exist over time and for the different types of aggregates produced. The operational data from SGR is consistent with Hossain et al. (2016) report that coarse recycled aggregates production requires 35 MJ/t of diesel for sorting plus 21MJ/t of diesel for processing (crushing, sieving, transport and handling).

Significant differences exist between the estimates from different approaches, with aggregate production data from real plants considerably higher than the other estimation alternatives presented. This indicates that the specific resistance of the material to process and the optimization of the plant plays a very significant role. For instance, in China the average electricity consumption for raw material

preparation in lime plants decreased from 30 kWh/t limestone, in 2014, to 16 kWh/t limestone, in 2019 (Meng et al. 2021a). The electricity consumption difference between the theoretical Bond's law electricity consumption and the lime production analogy might be of a coarser limestone particle size used as raw material for lime production.

Table 2 show the average energy consumption in the release stage for RC and HQRA under the various allocation scenarios.

Table 2 – Energy consumption in the release stage per unit of RC produced

Energy	Units	S1	S2 - ALT1	S2 - ALT2	S3
RECYCLED CEMENT					
Electricity					
Lime analogy	kWh/t	25.0	6.2	3.3	1.6
Bond's Law	kWh/t	77.1	19.2	10.3	4.9
Aggregates analogy					
SECIL	kWh/t	288.1	71.9	38.6	18.4
SGR	kWh/t	-	-	-	-
Fuel					
Lime analogy	MJ/t	1098.3	274.0	147.1	70.2
Bond's Law		-	-	-	-
Aggregates analogy					
SECIL	MJ/t	2635.4	657.4	352.8	168.5
SGR	MJ/t	825.8	206.0	110.6	52.8
HIGH QUALITY RECYCLED AGGREGATE					
Electricity					
Lime analogy	kWh/t	-	5.1	2.7	1.3
Bond's Law	kWh/t	-	15.8	8.5	4.0
Aggregates analogy					
SECIL	kWh/t	-	58.9	31.6	15.1
SGR	kWh/t	-	-	-	-
Fuel					
Lime analogy	MJ/t	-	224.7	120.6	57.6
Bond's Law		-	-	-	-
Aggregates analogy					
SECIL	MJ/t	-	539.1	289.3	138.2
SGR	MJ/t	-	168.9	90.7	43.3

The energy consumption on the release stage will also depend on the equipment used, has demonstrated by Lindqvist (2008) when comparing a cone crusher with a vertical shaft impact crusher. The equipment used also influences the size distribution of the final product, so an industrial setup will require an assessment of the equipment (or combination of equipment) that optimize the balance between energy consumption and amount of product obtained within the 0.15-0.5 mm range.

The separation stage does not exist in any industrial production, so the process was simulated extrapolating the laboratory data and manufacturer specifications. The energy for cleaning the concrete cement waste was estimated based on the specific energy consumption of air compressors reported by Mousavi et al. (2014) and considering an air demand of 10 m^3 per kg of raw material. The magnetic separator consumes 1.5 kWh/t of material processed, which considering two roles per production line corresponds to 3.0 kWh/t.

Table 3 present the results of the separation stage. In ALT2, the energy regarding the cleaning and separation of the coarser fraction was only allocated to the HQRA, therefore the values for the RC

remain constant between S1 and S2. No energy is allocated to NRA and NRF, so S3 is omitted from the tables since it is the same of S2.

Table 3 – Energy consumption in the separation stage per unit of RC produced

Energy	Units	S1	S2 - ALT1	S2 - ALT2
RECYCLED CEMENT				
Electricity				
Cleaning	kWh/t	8.4	2.1	2.1
Magnetic separation	kWh/t	20.5	5.1	5.1
HIGH QUALITY RECYCLED AGGREGATE				
Electricity				
Cleaning	kWh/t	-	1.7	3.7
Magnetic separation	kWh/t	-	4.2	9.1

The energy consumption of compressed air systems is highly variable, with typical industrial specific energy consumptions ranging from less than 0.1 kWh/m^3 to over 0.5 kWh/m^3. Several authors discuss the factors affecting the energy efficiency of compressed air systems (e.g., Uyan 2023; Nehler et al. 2018; Saidur et al. 2010), with some of the most relevant being: i) system design; ii) compressor type; iii) leakages; iv) pressure drop; and v) poor maintenance (e.g., dirty filters).

The permanent rare earth magnetic separators, on the other hand, tend to have a more consistent energy performance. However, the separation performance is sensible to the characteristics (e.g., particle size distribution; nature of the aggregates) and condition (e.g., humidity; presence of dust) of the material processed. As a result, an industrial setup may have more magnets or recirculation of the material to enhance the separation.

During the reactivation stage, only the hydrated cement paste is processed and RC is obtained, so scenarios S2 and S3 are not applicable. The energy consumption in this stage is exclusively linked with the RC production. The calcium hydroxide in the cement paste matrix will naturally carbonate when exposed to carbon dioxide. The carbonation depth will depend on various aspects, both related with the concrete properties (e.g., porosity, composition) and the environment characteristics (e.g., humidity, temperature, pollution). The carbonation reaction converts the calcium hydroxide into calcium carbonate and releases water, reducing the amount of calcium hydroxide in the cement paste. Since the dehydration of the calcium hydroxide is the reaction with the highest enthalpy, almost 4 times the energy required the C-H-S gel, and that requires the highest temperature (400°C to 600°C) (Bentz and Prasad 2007), conservatively the estimates presented herein assume that the concrete waste is made of fully hydrated non-carbonated cement paste. This assumption is conservative since it corresponds to the maximum hydration water content, which implies: i) the maximum mass loss; and ii) the maximum energy consumption.

Based on Sisomphon and Franke (2011) and Zhang et al. (2016), the calcium hydroxide was assumed to represent 18% of the cement paste by mass. Considering the water content in calcium hydroxide, 24 % of the cement paste mass loss was attributed to its dehydration, with the remaining 76 % due to C–S–H gel dehydration. The energy required for the reactivation amounts to nearly 1.4 GJ/t of RC, being roughly two thirds of the energy required for lime or clinker production (Table 4).

Table 4 – Energy consumption in the reactivation stage per unit of RC produced

Reaction	Units	Energy
Heating to 650ºC	MJ/t	792.7
Dehydration		
C-H-S gel	MJ/t	239.3
Calcium hydroxide	MJ/t	301.8
Total		

Theoretical	MJ/t	1333.8
Industrial	MJ/t	1422.8

The energy balance developed does not consider heat losses. However, this performance may be achievable in practice or even improved, particularly with energy recovery from the exhaust gas. Recovering energy from water vapor condensation in the kiln is not feasible because the reactivated cement would rehydrate. However, latent heat recovery outside the kiln is possible and could generate part of the electricity that is used in the process. Part of the sensible heat can also be recovered by injecting the RC cooling air into the kiln (Chen et al. 2022). The hypothetical scenario of full sensible and latent heat recovery would result in an energy consumption for reactivation of less than 600 kJ/t. This value is purely theoretical, but considering the thermal energy efficiency achieved nowadays for producing lime and clinker, it is not possible that an optimized energy efficient system may only require between 1000 kJ/t and 1500 kJ/t.

The reactivity of the lime decreases with the calcination temperature and depends on the limestone used (Moropoulou et al. 2001). The range of specific energy consumptions may be associated partially with the need to ensure both a high decarbonisation degree and a good residence time. Typical calcination temperatures range from 900ºC to 1200ºC (Schorcht et al. 2013). By establishing an analogy with lime production using the most energy-efficient kilns (PFRK) and assuming a linear relationship between temperature and energy, a thermal energy consumption of 1.6 GJ/t is obtained, consistent with the theoretical estimate including the energy performance of the production process.

For comparison purposes, the most efficient technology for producing Portland cement (dry process with six stage cyclone preheaters and precalcining kilns) only requires 3.0 GJ/t of clinker (Schorcht et al. 2013). This value is lower than what is required for lime production despite the higher temperature needed for the sintering reaction and the need for calcinating the calcium carbonates in the clinker raw material. This is explained by: i) the mass loss differences (for each tonne of clinker, approximately 1.55 tonnes of raw material are consumed, whereas producing 1 tonne of lime requires about 1.78 tonnes of raw material); ii) the efficient use of the exhaust heat from the rotary kiln to calcinate most of the raw material in the cyclone preheaters and precalcining kilns; and iii) the nature of the reactions varies, with some sintering reactions being exothermic, while calcination is highly endothermic .

In addition to the thermal energy, the reactivation also requires electricity to operate the kiln. Using an analogy with lime production and adjusting for the temperature and thermal energy required, the estimated values are 8.9 kWh/t and 11.6 kWh/t, respectively. Table 5 resumes the estimates, adopting the lime analogy estimates as reference, except for the thermal energy required for reactivation and electrical energy for separation.

Table 5 – Total energy consumption per unit of RC produced

Energy	Units	S1	S2 - ALT1	S2 - ALT2	S3
RECYCLED CEMENT					
Thermal					
Reactivation	MJ/t	1422.8			
Electricity					
Release	kWh/t	25.0	6.2	3.3	1.6
Separation	kWh/t	28.9	7.2	7.2	7.2
Reactivation	kWh/t	8.9	8.9	8.9	8.9
Fuel					
Release	MJ/t	1098.3	274.0	147.1	70.2
Transportation	MJ/t	158.2			
TOTAL	**MJ/t**	**2742.1**	**1877.3**	**1747.5**	**1668.9**
HIGH QUALITY RECYCLED AGGREGATE					
Electricity					

Release	kWh/t	-	5.1	2.7	1.3
Separation	kWh/t	-	5.9	12.8	-
Fuel					
Release	MJ/t	-	224.7	120.6	57.6
TOTAL	**MJ/t**	**-**	**136.1**	**58.9**	**136.1**

In practice, RC production will produce a variety of products with practical use and market value, which includes the HQRA, NRA and NRF. In fact, NRA and NRF are already produced at CDW plants and this technology will allow obtaining these products with a higher value. So, the most plausible scenario is S3, which requires 1968.3MJ/t of thermal energy, 17.7 kWh/t of electricity and 70.2 MJ/t of fuel for producing RC.

3.2 GREENHOUSE GASES EMISSIONS

GHG emissions from the thermal energy in RC production were estimated assuming 100% natural gas as fuel and a kiln efficiency of 94%. This results in a GHG emission intensity of 0.0626 kgCO2eq/MJ, which is in the lower end of the thermal energy carbon emissions intensity of the lime production and slightly lower than that of the clinker production. The average of the yearly mean GHG intensity of the Portuguese electricity between 2019 to 2023 (0.156 $kgCO_2eq/kWh$) is used for estimating the emissions from electricity consumption. A GHG emission factor of 2.485 $kgCO_2eq/l$ was adopted for diesel fuel, corresponding to 0.0657 kg CO_2eq/MJ. This value entails that most diesel for road transportation incorporates some additives (e.g., biodiesel) lowering both the energy and emissions.

Table 6 detail the GHG emissions from RC and HQRA production, respectively, by stage and energy source for clarity and reproducibility.

Table 6 – GHG emission per unit of RC produced

Energy	Units	S1	S2 - ALT1	S2 - ALT2	S3
RECYCLED CEMENT					
Thermal					
Reactivation	kgCO2eq/t	80.13			
Electricity					
Release	kgCO2eq/t	3.90	0.97	0.51	0.25
Separation	kgCO2eq/t	4.51	1.12	1.12	1.12
Reactivation	kgCO2eq/t	1.39	1.39	1.39	1.39
Fuel					
Release	kgCO2eq/t	72.2	18.0	9.7	4.6
Transportation	kgCO2eq/t	10.4			
TOTAL	**kgCO2eq/t**	**172.5**	**112.0**	**103.2**	**97.9**
HIGH QUALITY RECYCLED AGGREGATE					
Electricity					
Release	kgCO2eq/t	-	0.80	0.43	0.20
Separation	kgCO2eq/t	-	0.92	1.99	-
Fuel					
Release	kgCO2eq/t	-	14.77	7.93	3.79
TOTAL	**kgCO2eq/t**		**16.49**	**10.35**	**3.99**

3.3 DISCUSSION

The different estimation approaches underline the variability in energy consumption and the corresponding GHG emissions associated with the industrial deployment of the RC technology investigated in this study. Previous studies estimated the total energy consumption of RC production in Portugal to be of 2215.0 MJ/t, un-adjusted, 2704.1 MJ/t, (Sousa et al. 2023a,b), an estimate lower

than the 2905.3 MJ/t of the present study. However, the energy consumption estimates entail significant differences in terms of the sources of energy used. The present study reveals that the energy from fuel consumption is much higher (1256.5 MJ/t against 163.9 MJ/t), while the electricity is much lower (64.8 kWh/t against 212.8 kWh/t). Regardless, the shift leads to similar estimated total GHG emissions of 172.5 $kgCO_2eq/t$ compared to 171.1 $kgCO_2eq/t$, un-adjusted, 208.9 $kgCO_2eq/t$, adjusted. This result is mostly explained by the substantial decrease of the GHG emissions associated with electricity (from 0.215 $kgCO_2eq/t$ to 0.156 $kgCO_2eq/t$) and road transportation (from 0.140 kgCO2eq/t.km to 0.055 kgCO2eq/t.km). Regarding the latter, the difference is mostly due to considering a larger capacity truck for the transportation, which better represents reality considering that the European Union 2021 fleet average specific GHG emissions are 0.052 kgCO2eq/t.km (Musa et al. 2024). More importantly, the GHG emissions in this more refined estimate are still a small fraction of the 750 $kgCO_2eq/t$ for Portland cement produced in Portugal depicted in the Portuguese grey cement environmental product declaration (DAPHabitat 2023).

Based on the analogy with the lime production, the thermoactivation was assumed to resort to natural gas for generating the necessary thermal energy. However, the lower temperature required for the dehydration reaction to occur allows the use of electrical kilns. Projects such as the DE|CARBONATE (Katajisto 2020) have already demonstrated the feasibility of electrifying calcination both in the lime and cement industry. Parra and Romano (2023) estimate a 30 % increase in energy consumption for a fully electrified cement plant, but with the growing share of renewable energy this presents an opportunity to reduce GHG emissions.

In Portugal, the average yearly electricity GHG emission factor is still slightly higher than the natural gas used for the lime or cement production due to the losses in the distribution network. However, GHG emissions from electricity production in Portugal has been decreasing steadily over the last decades and it is expected to decrease further in the future has more renewable energy plants are built. Also, some of the electrical energy could be generated onsite (e.g., wind or solar in addition to the latent energy recovery), decreasing the GHG emissions of the process even further because the transmission losses would be minimal. One of the major practical challenges with latent heat recovery is the presence of combustion compounds (e.g., sulfuric oxides, nitric oxides or hydrochloric oxides) that condensate along with water and are potentially corrosive (Zheng et al. 2022). In an electric kiln, the exhaust would consist of air with high water vapor content, thus overcoming this issue.

Concerning the HQRA, despite the additional separation stage, the energy consumption is lower than the value reported by SECIL for producing natural coarse crushed aggregates. In terms of GHG emissions, Braga et al. (2017) estimate emissions of 27.9 $kgCO_2eq/t$ for crushed fine aggregate produced in Portugal, a value roughly 70% higher than the emissions of the HQRA in the most unfavourable scenario. Even the river fine aggregate GHG emissions, estimated to be 9.87 $kgCO_2eq/t$ by Braga et al. (2023), are similar to HQRA estimates in scenario S2-ALT2 and exceed largely scenario S3. The implementation of the patented technology used in the present research might boost the industrialization of the CDW plants. The substantially lower specific energy consumption from processing the raw material in the cement and lime industries indicate that more energy efficient CDW plants are possible, along with a shift to greener energy sources.

4 CONCLUSIONS

The assessment conducted in this study demonstrates that producing RC and HQRA from concrete waste using a patented magnetic separation-based technology has a lower burden than their traditional counterparts. The RC is not equal to PC, but it is similar and can be used as a partial substitute with hydraulic properties, in the most demanding applications (e.g., structural concrete), or as a replacement, in less demanding applications (e.g., mortar). Emitting between only between 13%

and 23% of the GHG of Portland cement, depending on the scenario considered, the potential environmental benefits are substantial. As a by-product of the RC production, HQRA would have no environmental impact in scenario S1. Assuming tha HQRA are another product that can be obtained with the technology (scenarios S2 and S3), the energy consumption and GHG emissions are between 41% and 86% lower than the equivalent crushed fine aggregates and only slightly higher than normal recycled aggregates in S2 since the magnetic separations has a very energy consumption.

The environmental benefits associated with RC and HQRA are not restricted to the GHG emissions reduction. The use of concrete waste as the raw material source effectively contributes to a circular economy, reducing simultaneously the amount of waste deposited in landfill or applied in low value uses (e.g., backfilling) and the consumption of natural virgin raw material.

ACKNOWLEDGMENTS

The authors acknowledge the Portuguese Foundation for Science and Technology (FCT, https://ror.org/00snfqn58) for funding this research through project PTDC/ECI-CON/0704/2021, and through the project UIDB/06438/2025 (https://doi.org/10.54499/UID/06438/2025) of the research unit CERIS. The authors also acknowledge the support of SECIL, Vimajas, Portuguese Air Force, and Cobert for supplying the materials used during the experimental campaign, and Oficinas do Convento, Montemor-o-Novo, for supporting the production of the CEB.

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820 APPENDIX A

821 Table A 1 - Reference data for lime production (Schorcht et al. 2013; Stork et al 2014)

	Units	Min	Max	Reference
Thermal Energy				
Kiln				
Vertical				
Parallel flow regenerative kilns (PFRK)	GJ/t CaO	3.2	4.2	
Annular shaft Kilns (ASK)	GJ/t CaO	3.3	4.9	
Mixed Feed Shaft Kilns (MFSK)	GJ/t CaO	3.4	4.7	
Horizontal				
Long Rotary Kilns (LRK)	GJ/t CaO	6.0	9.2	
Rotary Kilns with preheater (PRK)	GJ/t CaO	5.1	7.8	
Electrical Energy				
Total	kWh/t CaO	15.0	60.0	
Crushing and screening	kWh/t CaO	1.9	2.4	Gutiérrez et al. (2012)
Kiln	kWh/t CaO	26.2	49.3	Gutiérrez et al. (2012)
Vertical				
Parallel flow regenerative kilns (PFRK)	kWh/t CaO	20.0	40.0	
Annular shaft Kilns (ASK)	kWh/t CaO	18.0	35.0	
Mixed Feed Shaft Kilns (MFSK)	kWh/t CaO	5.0	15.0	
Horizontal				
Long Rotary Kilns (LRK)	kWh/t CaO	18.0	25.0	
Rotary Kilns with preheater (PRK)	kWh/t CaO	17.0	45.0	
Grinding	kWh/t CaO	4.0	40.0	
Fuel				
Quarry	MJ/t CaO	37.0	151.0	Gutiérrez et al. (2012)
Combustion emissions				
Vertical				
Parallel flow regenerative kilns (PFRK)	t CO2/t CaO	0.202	0.425	
Annular shaft Kilns (ASK)	t CO2/t CaO	0.224	0.465	
Mixed Feed Shaft Kilns (MFSK)	t CO2/t CaO	0.224	0.708	
Horizontal				
Long Rotary Kilns (LRK)	t CO2/t CaO	0.365	1.062	
Rotary Kilns with preheater (PRK)	t CO2/t CaO	0.269	0.617	

822 Table A 2 - Bond's law estimates of the specific electrical energy consumption in the release stage

Parameter	Units	Min	Max	Mean
Work Index	kWh/t	9	14	12
Passing size feed	mm	20	40	30
Passing size product	mm	0.8	0.5	0.7
Specific energy	**kWh/t**	**2.55**	**5.56**	**3.84**

823 Table A 3 - Operational data from crushed (SECIL) and recycled (SGR) plants

Parameter	Units	SECIL	SGR
Fuel			
Handling	MJ/t	131.3	36.8
Crushing/Griding	MJ/t		4.4
Electricity			
Handling	kWh/t		
Crushing/Griding	kWh/t	14.4	
Total	**MJ/t**	**182.9**	**41.1**
	kWh/t	**50.8**	**11.4**

824