Resources, Conservation & Recycling 225 (2026) 108580

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Full length article

# Recovered cement paste for recycling and production of cement in different countries

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ARTICLE INFO

*Keywords:*
Concrete recycling
Cement production
Recovered cement paste
Construction and demolition waste

ABSTRACT

Using waste concrete as recycled aggregates is a down-cycling practice because cement paste, responsible for 80–90 % emissions and 40–60 % cost in concrete, is not extracted. A better approach is to separate cement paste from aggregates, which can produce better quality recycled aggregates and recovered cement paste (RCP) with high calcium content. This paper compares processing techniques for producing RCP and proposes a new classification currently absent from reports and standards. We evaluate potential RCP applications in cement production, as raw meal for clinker production and for cement replacement after forced carbonation. Further, we evaluate potential of quality-adjusted substitution of RCP for cement production across a panel of countries, with a range of different economic status, to outline optimal practices for cement recycling. Finally, this paper aims to change the perception of concrete waste, showing that when processed efficiently, it can be recycled into cement with minimal loss at each cycle.

## 1. Introduction

Construction activities around the world generate over 3 billion tons of construction and demolition waste (CDW) every year (Akhtar and Sarmah, 2018). After buildings are demolished, the waste can be sorted into various streams; some materials, like steel scrap and reusable elements, have high commercial value, while others, primarily bulk materials such as concrete, are considered of much lower value. Some high-income countries, for example in Europe, are able to process and reuse >90 % of this waste (Zhang et al., 2019) whereas emerging countries landfill most of it due to the lack of recycling facilities, technology and awareness (Rao et al., 2007). However, the latter are starting to realise the need for recycling due to shortages of raw materials for construction (Ram et al., 2019), and shorter transportation distances if the virgin aggregate quarries are far away. Further, the vast quantities of this waste pose a challenge for landfills, driving efforts to divert as much of it as possible. This waste could be avoided to some extent by promoting better building design options for reducing the overall embodied carbon of buildings (Dunant, 2024). Concrete, although considered less valuable, represents a large investment of $CO_2$ and energy which is lost when used in low-value applications such as sub-base or filler.

The construction sector aims to transition from a linear to a circular economy (Iacovidou et al., 2017). This is part of a broad push towards net zero emissions. Indeed, this transition can only be achieved by maximizing the value derived from waste materials. However, increasing the investments focused on material production and research could help in meeting the net-zero targets (Dunant and Allwood, 2024). In the context of high income countries, waste concrete typically constitutes approximately 60–70 % of total CDW (U.S. Environmental Protection Agency, 2018; Monier et al. 2011). It is commonly crushed to produce recycled concrete aggregate (RCA), which can be used as a partial substitute for virgin aggregates in new concrete. The use of RCA is limited due to its lower density, high water absorption and the cracks developed as a result of crushing the waste concrete, which can negatively affect the mechanical and durability properties of concrete made with it (Etxeberria et al., 2007; Xiao et al., 2013). Consequently, excess RCA is used as filler or for sub-base applications. This process is a downcycling one, as the aggregates and cement are not recovered to their initial quality.

A way to retain the value of using waste concrete is to separate the cement paste from the aggregates. Fig. 1 shows three scenarios of waste concrete recycling based on the separation of aggregate, sand and cement paste. The current practice is to crush the waste concrete which can only cycle aggregate in limited quantity, and the rest of the crushed

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https://doi.org/10.1016/j.resconrec.2025.108580
Received 10 February 2025; Received in revised form 4 September 2025; Accepted 6 September 2025
Available online 11 September 2025

concrete will be used as sub-base or filler (see Fig. 1a). However, when cement paste is separated, more aggregates can be cycled back to the production of concrete and separated recovered cement paste (RCP) may be used as supplementary cementitious materials (SCM) (see Fig. 1b). Further, effective separation of cement paste also enables cement cycling as well as the production of cleaner recycled aggregates and sand, which can replace virgin materials. More importantly, the high purity RCP can potentially replace limestone in cement raw meal (see Fig. 1c).

Cement and aggregate separation is an emerging area of research aiming to use RCP in high-value applications to leverage the calcium content in the cement paste (Diliberto et al., 2017). Cement paste is a source of decarbonised lime and has the potential to substitute limestone in applications that can tolerate some silica content. The technology for this recovery process is improving rapidly, with some initiatives trying for large-scale implementation (Heidelberg Materials, 2024). The terminology in literature is not consistent, different terms such as 'concrete fines', 'recycled concrete fines', 'recovered concrete fines', 'recovered cement', 'recycled cement paste', are used for this fine fraction of waste concrete. Therefore, we would like to propose defining it as "recovered cement paste" (RCP). We believe it is important to maintain the term "RCP" to emphasis that the primary goal of concrete recycling should be the recovery of cement paste rather than silica, which does not yield significant environmental benefits. Therefore, this paper uses RCP for this fine fraction as it is intentionally produced and not as a consequence of the conventional recycling process. However, the fine powder produced during the CDW crushing could be termed as 'recycled concrete fines (RCF)' as it may contain a high amount of silica.

This paper integrates a review of the processing technologies for cement paste separation complemented by extensive experiments and the evaluation of its overall potential for use in cement production. A new, refined, definition of RCP is proposed, which includes recommendations on particle size and a classification based on chemical composition. We provide a comprehensive analysis of RCP availability and its application in cement production for a representative panel of countries. This analysis links the circularity potential for countries based on CDW generation, cement demand, and country-level development. Finally, we propose an assessment system to maximise the value of recycled concrete, transforming it from a low-quality aggregate into a valuable carbon sink and decarbonized calcium source. Through this technological and economic analysis, we aim to change perceptions and demonstrate that cement is a truly recyclable material.

## 2. Current interest and uses of RCP in literature

The current state-of-the-art on recycling concrete waste is not focused on the recovery of cement paste because there is no established demand for RCP in high volumes. Further, many studies on this topic used artificial RCP, produced by hydrating pure cement paste (Fang and Chang, 2015; Lu et al., 2018; Mao et al., 2024) – this is termed as hydrated cement paste (HCP) in this paper. However, HCP is not representative of the RCP produced from concrete waste which commonly has a high silica content from sand and aggregate crushing. Kim (2017); Li et al. (2021); Ma et al. (2020); Mao et al. (2020) and Ren et al. (2020) produced RCP from the CDW sourced from recycling plants, but the reported yields were very low. Typically, the fine RCA has high water absorption, and RCF has less value. Therefore, CDW recycling plants are optimised to minimise the fine fraction, and it is considered a by-product in current operations, resulting in a low yield of RCF. Consequently, the calcium content in that RCP is very low (Kim, 2017) and sometimes also has a relatively high alumina content due to the presence of bricks in waste concrete (Li et al., 2021; Liu et al., 2025; Mao et al., 2020).

A new standard, EN 197-6:2023, has recently been introduced, permitting the use of recycled building materials, particularly RCP as main constituent for cement production. This standard allows RCP to be used in cement for applications such as structural concrete, as well as in mortar and grout applications. However, the standard specifies that RCP does not contribute to the reactivity of the cement. The use of RCP is permitted in composite cements (CEM-II and CEM-VI) as the main constituent of cement, ranging between 6 % and 35 % by mass. Appendix Table A1 shows the technical requirements specified for the source material as well as for the produced RCP.

The use of RCP as a partial cement replacement helps prevent, to some extent, the downcycling of the fine fraction of waste concrete, which had previously been landfilled. However, this definition of RCP lacks clarity regarding particle size and chemical composition, particularly calcium content. Improving these definitions and quality classification could facilitate better use of good quality RCP with higher calcium content, allowing for more substitution and improvement in cement properties.

Fang and Chang, 2015; Gastaldi et al., 2015; Kwon et al., 2015; Lu et al., 2018; Mao et al., 2024; Serpell and Lopez, 2013; Shui et al., 2009 and Zhu et al., 2018 used HCP to substitute cement, which had high calcium since it was produced by hydrating pure cement. Appendix Table A2 shows the source, processing method and characteristics of RCP produced from concrete waste; all these studies in the literature were focused on RCP production from waste concrete, here we have excluded studies which used hydrated cement paste as a model for RCP. Appendix Table A2 shows that three types of processing/beneficiation techniques can be used for the production of RCP at scale: crushing, milling and heating or a combination of these. The waste concrete sources encompass concrete ranging from 28 days old to over a century old.

The main oxide chemical components of RCP are silica, calcium, alumina, iron, sulphur, magnesium and alkalis including sodium and potassium. Appendix Fig. A1 shows the chemical composition of RCP from the literature studies mentioned in Appendix Table A2. To chart the RCP composition, apart from calcium and silica, a combination (or sum) of alumina and sulphur is considered (see Appendix Fig. A1). While silica and calcium oxide together contribute >80 % of the RCP mass, the alumina content varies between 5 and 7 %. The $SO_3$ is important as there

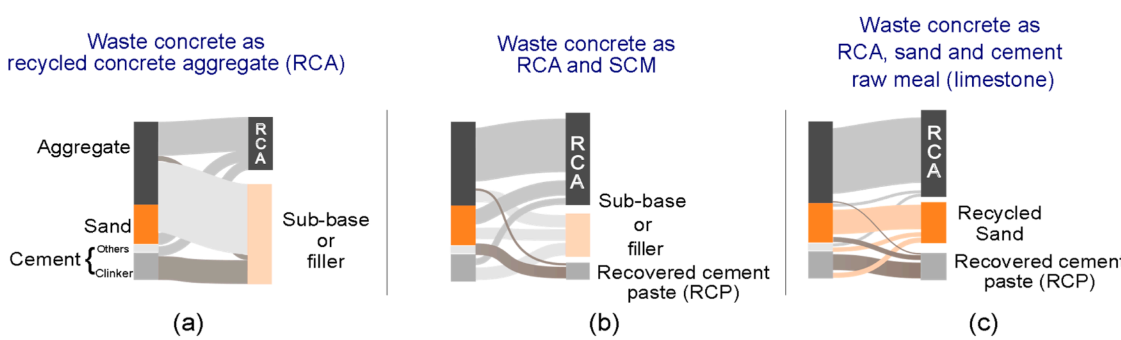



**Fig. 1.** Concrete recycling practices.

is a risk of contamination from other construction waste containing high sulphur, such as gypsum and plasterboards. If these are mixed in waste concrete, the RCP will show an increase in both calcium and $SO_3$. However, the high $SO_3$ is not desirable for RCP nor recycled aggregate as this could increase the water absorption and decrease the quality of aggregates. Similarly, the separation of wood, plastic, bitumen, glass, and contaminants poses challenges and requires manual sorting, which is largely done by deploying manpower on conveyor belts in CDW recycling plants. Therefore, the mixing of these materials with concrete needs to be avoided at the source to achieve maximum material recovery.

Many studies do not mention the yield of RCP production. The yield is a critical factor that can help in determining whether it is feasible to use a beneficiation process to produce RCP. If the yield is very low, it would not be worthwhile for recyclers to invest time and capital, and it would also fail to establish a viable business model.

In summary, the recycling of concrete waste currently does not prioritise the recovery of cement paste due to low demand. Research studies often use pure hydrated cement, which tends to overestimate the benefits of using RCP due to higher calcium content and absence of silica contamination, which is typically found in waste concrete. Additionally, the chemical composition and specifications of RCP are not established, resulting in low-application such as soil stabilisation. However, the benefits of using it for cement production are greater (Shima et al., 2003); as cement and limestone replacement can abate higher $CO_2$ emissions. A number of uses for RCP have been proposed and the current trend is to use RCP for mineral carbonation (Haripan et al., 2024; Ho et al., 2024) and cement production as the main constituent of cement (EN 197-6:2023); also as part of raw-meal (Holcim Geocycle, 2022). Currently, there are some industrial-scale solutions under development (Heidelberg Materials, 2024), which are promoting the high value recycling and triggering the market to develop new supply chains. The popular uses of RCP are explained briefly.

### 2.1. RCP for $CO_2$ mineralisation

The use of RCP for $CO_2$ mineralisation relies on hydrated cement phases (Portlandite, C-S-H Ettringite etc.) to react with $CO_2$ to form calcium carbonate ($CaCO_3$) (Zhan et al., 2014). Especially fine particles tend to have higher carbonation potential (Jiang et al., 2022) and faster rate of $CO_2$ uptake than coarse particles (Algourdin et al., 2023), which could be further increased if aqueous carbonation is performed (Jiang et al., 2023). Given the high availability of waste concrete, the overall potential for $CO_2$ mineralisation has been estimated to be significant (Ho et al., 2023). This paper focuses on the carbonation of RCP in its powdered form and there are limited studies specifically addressing this topic. While there are several studies address RCP carbonation within concrete (e.g. Ashraf, 2016; Šavija and Luković, 2016, for an overview), those have been intentionally excluded from our review. Also, most studies on this approach have used HCP (Skocek et al., 2020) and laboratory grade high-purity $CO_2$ gas (Shi et al., 2018), both of which overestimate the carbonation potential: HCP has more uncarbonated calcium phases than RCP produced from waste concrete. Similarly, the use of high-purity $CO_2$ gas in a closed chamber cannot be compared with carbonation for high volumes of RCP, which would require a source with a huge amount of pure $CO_2$ and large volume chambers; both require a lot of energy and could be very challenging with the current state of development in this area. However, carbonation of fresh concrete at industrial scale has been experimented with portland blended cements (Zajac et al., 2025).

For example, Fang and Chang (2015) achieved 20 % $CO_2$ uptake by carbonating the HCP and Zajac et al. (2020) and Lu et al. (2018) were able to replace 20 to 40 % of carbonated HCP without significant loss of performance in cement. While these studies indicate ultimate technical limits of replacement, the use of HCP will overestimate the performance compared to RCP produced from concrete waste. The carbonated RCP has been used to produce bricks (Ouyang et al., 2024), which have demonstrated better performance compared to uncarbonated RCP bricks. Gholizadeh-vayghan and Snellings (2022) used lab-prepared RCP (< 3 mm) for carbonation and applied 0.5 bar pressure at 80 °C for 30 h and achieved high $CO_2$ uptake of about 32.5 g/100 g cement used in waste concrete. However, this study used RCP to replace aggregates, and resulted in a decrease in strength and flowability compared to natural aggregates despite an improvement over uncarbonated recycled aggregates. Also, the yield of RCP and calcium content were not reported in this study. Nedunuri et al. (2021) collected waste concrete samples of different ages (up to 60 years) and achieved 4 to 8 % $CO_2$ uptake by using forced carbonation with the help of sonication, which is probably more representative of RCP produced from the crushing method.

### 2.2. RCP for cement substitution (as main constituent of cement)

The chemical composition of RCP is dominated by silica and calcium phases. When used as a main constituent of cement, it has the effect of a filler and has some reactivity from the calcium, which can be beneficial for blended cement. Li et al. (2021) substituted 30 % of cement with RCP, with 18 % calcium content which resulted in a strength reduction of 30 % compared to the reference mix. Another study used 0–4 mm RCA, which was finely ground and used to replace 25 % of the cement (Diliberto et al., 2021), resulting in a loss of 25 % of the strength of the reference cement. The reference cement used was CEM-I, and the resulting mix was found to be comparable to CEM II/B. This is similar to the recommendations provided in the new standard, EN 197-6:2023. Apart from direct use, the carbonated RCP can be used as main constituent of cement, which is being experimented at industrial scale (Heidelberg Materials, 2024).

### 2.3. RCP as constituent of cement raw-meal

An active area of research is to add RCP in the raw meal of cement kiln feed (Krour et al., 2020; Snellings et al., 2012; Villagrán-Zaccardi et al., 2022). We have excluded studies (such as Gastaldi et al., 2015) which used HCP to substitute cement raw meal because they do not accurately represent the real quality of RCP which could be produced using waste concrete. However, HCP produced cement with 50 % Alite ($C_3S$), claiming $CO_2$ reduction of 33 % from decarbonisation, which shows that fundamentally it is possible to reclinker hydrated cement. Schoon et al. (2015) tested three types of RCP with calcium content of 15 to 25 % from different processing techniques to evaluate the replacement of reference raw-meal material. They claimed that the silica fraction is the only limiting factor for raw-meal substitution. They could only substitute 15 % of RCP in cement raw-meal due to the high silica content. Using limestone aggregates in concrete would increase the calcium content in the RCP (De Schepper et al., 2013); however, this is not typically observed in practice. In most of the studies, RCP is used as a source of silica and only to a lesser extent as a source of calcium.

Instead of RCP, Izoret et al. (2019) used four types of recycled sand fraction (or RCF) (0–4 mm) for cement raw meal substitution, with a calcium content between 15 and 20 %. In these studies, RCP substituted foundry sand and the burnability of recycled sand with high amount of quartz (typical of RCF) was found suitable for clinkering in cement kiln. The grinding of clinker was also found to be very similar to that of conventional clinkers. A maximum replacement of 25 % was achieved, and a reactive clinker was produced with ~ 60 % of Alite ($C_3S$) content.

These studies indicate that RCP can be utilised in raw meal, as it does not affect the burnability and grindability of the produced clinker. However, the level of substitution will be limited by the silica content, which also limits the substitution of limestone. If RCP is only considered as an alternative to silica sand or clay, the environmental benefits are limited, and the related transportation efforts might not be justified. Therefore, RCP should aim to substitute limestone in the raw meal. Since the separation processes are not perfect, when RCP is used, some amount of silica is inevitably replaced, as sometimes silica constitutes a significant portion of RCP.

### 2.4. RCP as part of flux materials for electric arc furnace (EAF)

There is an emerging area of recycling cement in which RCP is used as a part of flux materials for steel scrap recycling in EAFs. The chemistry of slag in EAF is controlled in such a way that the slag has properties similar to Portland clinker. RCP is used as a source of decarbonised lime to substitute conventional flux (lime), and the heat required to produce cementitious phases is provided by the molten steel in the furnace—saving $CO_2$ emissions for limestone calcination and fossil fuel burning. Further details of this technology can be found in Dunant et al. (2024).

A few companies have started exploring business opportunities for using RCP, and the technology for RCP production is now being developed at an industrial scale (Gebremariam et al., 2020; Heidelberg Materials, 2024). Previous studies have not looked at the production of RCP with high calcium content, and most research on its uses is done on pure hydrated cement, which cannot be produced from waste concrete. Further, there is no agreed definition of RCP that specifies limits on chemical composition and particle size. This paper addresses these gaps by:

- evaluating scalable processing techniques to recycle waste concrete to maximise resource efficiency and to achieve complete (or high levels) material circularity.
- defining the quality parameters and yield for RCP scaled production using different processing techniques.
- assessing the use of RCP for cement replacement, carbonation and substituting limestone in cement raw-meal.

The manuscript is organised into two main sections: Section 3 covers the technical potential of processing routes, while Section 5 discusses the limitations of material flow in utilising the produced resources. Given the inherent complexity of the subject, Section 4 bridges these two sections and highlights the critical parameter, the methodology used for materials flow analysis, as well as explains how one use could be prioritised based on the $CO_2$ emission. Further, Section 6 proposes a new definition and classification of RCP. Also, integrates processing techniques and materials flow in a new index to explain the circularity potential of waste concrete in different countries.

## 3. Experimental program and results of waste concrete processing

The first part of this section explains the materials and processing routes, in particular waste concrete crushing sequences and beneficiation methods that describe how this crushed concrete can be used as feed to extract RCP by separating it from sand and aggregates. Further using the design of experiments and results of yield and chemical composition are explained.

### 3.1. Materials and processing (crushing and beneficiation) methods

The waste concrete samples used in this research were sourced from CDW recycling plants in London. The samples were collected each month from different CDW plants, over a year to get a representative sample of concretes being processed. The waste concrete itself was collected from different sites, and it is expected to be a mix of different grades concrete and different ages. Overall, this could cover all possible variations of waste concrete in the field. It is to be noted that this study only considers the waste concrete arising from demolition activities since the volume of this waste is significantly higher than that from new construction activities. Using the same source material, we used a range of processing and beneficiation techniques to estimate the potential of each for the scaled processing of concrete waste.

#### 3.1.1. Crushing sequence for waste concrete

Many process combinations can be used to crush waste concrete (Rajan and Singh, 2020), the steps used in this study are shown in Appendix Fig. A2a. It shows the process flow diagram used for crushing and processing the waste concrete into different sizes of RCA. The sorting of pure concrete elements, primary crushing, removal of steel rebars and separation of unwanted materials (plastic, wood, bitumen, etc.) are the common steps in the crushing process (Ram et al., 2019). The three crushing routes used in this study are explained below:

- Two-stage crushing

It is the most common type of process using Jaw and/or Impact crushers, which is used by many CDW recycling plants. This process aims to produce coarse RCA while minimising the fine aggregates and powder fraction. These RCA are mainly used to substitute virgin aggregate for filling or non-structural concrete applications.

- Three-stage crushing

This process is primarily focused on producing fine RCA. The feed from two-stage crushing is used to feed a tertiary crusher (horizontal/vertical impact, or cone or roll crushers), which further reduces the RCA to usually particles below 5 mm or 12 mm in size. This process is used for producing a high volume of fine RCA. However, three times crushing generates higher powder fraction in RCA, which is not suitable for many aggregate applications but has a higher yield of RCF.

To reduce the powder content (<75 µm particles or clay/silt), some recycling plant washes these aggregates. The fine particles are transported with water and sedimented to separate the powder fraction. These wet processes are not included in this study because they are focused on removing slit and clay from CDW which is not suitable for cement production. Currently, there is no use for this fine fraction, and it is disposed of in landfills.

- Selective crushing

This method uses the feed from primary crushing to produce concrete chunks of 40–50 mm. This size is specifically selected to minimise the production of powder by avoiding the crushing of coarse aggregates.

#### 3.1.2. Beneficiation of crushed waste concrete

The crushed waste concrete is further processed using three beneficiation techniques to produce RCP and RCA of different qualities as shown in Appendix Fig. A2b. In this study, particles below 150 µm size is considered RCP, the particles between 150 µm to 5 mm are recycled sand and the remaining particles between 5 and 20 mm are coarse RCA.

- *Route 1: Crushing*

This route uses the feed material from two-stage crushing. The fine particles (<150 µm) are sieved to produce RCP. This route is based on the current scenario of concrete recycling where no additional processing is done.

- *Route 2: Milling*

In this beneficiation technique crushed waste concrete is milled for the separation of cement paste and aggregates. Typically, large size particles have less cement paste adhered to their surface and the finer fraction is rich in cement paste. Therefore, the feed from three-stage crushing with particles below 5 mm is used for beneficiation and milling large particle (such as from two-stage crushing) is avoided as it will not be effective for cement paste separation. To evaluate this production route, we used batches of two kilograms of crushed waste concrete (<5 mm) milled in steel drums with four kilograms of steel balls of 5 to 20 mm size. The milling was done for 15 min at 25 RPM. This method helps in scrubbing the soft cement phases which are adhered to sand and aggregate particles. In this method, the milling aims at generating attrition and abrasion forces and avoid the crushing of aggregates. Excessive milling consequently increases the aggregate fraction (silica) (Shi et al., 2019), which could reduce the recovery of cement paste fraction.

This process also generates clean sand, which is superior to conventional recycled sand that has a high water demand due to the presence of porous cement paste. The clean sand exhibits low water absorption (Ogawa and Nawa, 2012) because most fine particles are removed during the sieving process, and the sand particles are cleaned through milling and scrubbing.

- *Route 3: Heating and milling*

This method is focused on recovering all three constituents (cement, sand and aggregate) of concrete as intact as possible. The crushing is done in such a way to get 40–50 mm size concrete chunks, avoiding the crushing of coarse aggregates. Then these chunks are heated at 500 °C for 1 h in an electric furnace to weaken the concrete by the combination of dehydration and differential thermal expansion. The details on optimisation of heating temperature and time can be found in Prajapati et al. (2021). After 24 h of ambient cooling, the samples were milled in a ball mill using steel balls. A batch of 2 kg of heated chunks was mixed with 8 kg of steel balls with varying diameters of 5 to 40 mm and milled for 15 min at 25 RPM. The first round of milling for 5 min was done using bigger size steel balls (40 mm) to break the concrete chunks, and the remaining 10 min using <20 mm balls for scrubbing action. Similar to the previous process of milling, the crushing of aggregates should be avoided to minimise the increase in the amount of silica in a finer fraction. This process produces sand and aggregate of high-quality as the separation of cement paste is very effective. These recycled aggregates can substitute virgin sand and aggregate without affecting concrete properties (Prajapati et al., 2023).

### 3.2. Design of experiments

The experiments were designed to compare the production of RCP using three different beneficiation techniques which are explained in the previous section. The feed waste concrete was sourced from CDW plants and brought to the laboratory. A representative sample of 100 kg of waste concrete was collected from each of the three crushing methods. Further, samples of 2 kg from each crushing method (two-stage, three-stage, and selective crushing) were selected for beneficiation. For the two-stage crushing method, the feed concrete was used for sieving RCP, while the feed from three-stage crushing was used for milling. In the case of thermal beneficiation, chunks of concrete 40–50 mm in size were manually selected for feed material, as the crushers at the CDW plant were not optimised to produce this size of particles. The waste concrete received at the CDW recycling plant is representative of the broad range of concrete that can realistically be processed and reflects the potential outcomes that could be achieved when such processes are implemented at a larger scale. We believe these results are useful because they are within the range reported in the literature and extend even further. Nevertheless, the RCP quality primarily depends on processing techniques and contaminant-free waste concrete feed. Additionally, the crushing and beneficiation methods presented in our study propose several viable options that can be implemented using industrial-scale equipment in different countries, depending on the available technology. After the beneficiation, the processed waste concrete was sieved into different size fractions: as RCP (< 150 μm), sand (Fine RCA), and aggregate (Coarse RCA). The yield of each fraction was recorded, and RCP samples were analysed for chemical composition using X-ray fluorescence (XRF) technique.

### 3.3. Results of waste concrete processing

This section explains the yield of different size fraction and their chemical composition to compare different processing techniques.

- **Yield of recycled products:** Fig. 2a shows the yield of each size fraction after concrete waste processing using different combination of crushing sequences and mechanical/thermal beneficiation. The crushing route produces a very low amount of RCP, while the other two routes yield a considerable quantity (8–15 %). From a yield perspective, the milling and heating routes would be preferable as these volumes could incentivise the producers as well as users. Moreover, clean sand and aggregates have better economic value, as their quality is superior to conventional RCA (Prajapati et al., 2021).
- **Chemical composition of RCP**: Fig. 2b shows the chemical composition of the produced RCP from this study (refer to Table SI 1.1 in supplementary information for complete detail on chemical composition). It is compared with RCP produced from other processes in the literature (see transparent light grey colour area). In this study, the highest CaO was produced with the heating method. There are few literature reports found with high calcium yield, however some are due to the impurities coming from gypsum as indicated by the high $SO_3$ in chemical analysis (Letelier et al., 2017). The other two methods (crushing and milling) in this study show lower calcium content (20 to 30 %) that can vary depending on the type/stages of crushing and method of milling. The high silica in RCP is mainly a consequence of fine powder generated by crushing or excessive milling of sand and aggregates. The finer fraction (<75 μm) from heating route can have the highest calcium content and is very close to the pure cement. It shows that the heating route is very effective in cement paste aggregate separation and shows a practical limit of calcium recovery that can be achieved with current technology.

One potential source of high-calcium content RCP is in the sedimented washout water from ready-mix concrete plants. While this is sometimes considered in the same waste category as CDW, depending on the guidelines of different countries, it could be treated separately. Nevertheless, this RCP is readily available without any processing, apart from drying the free water (moisture). Unlike demolished concrete, the carbonation level could be lower if not exposed for a longer duration, which can be beneficial for $CO_2$ mineralisation as well as cement raw-meal. Currently, a substantial amount of concrete washout is being dumped, but it could be an opportunity for new businesses to explore its uses.

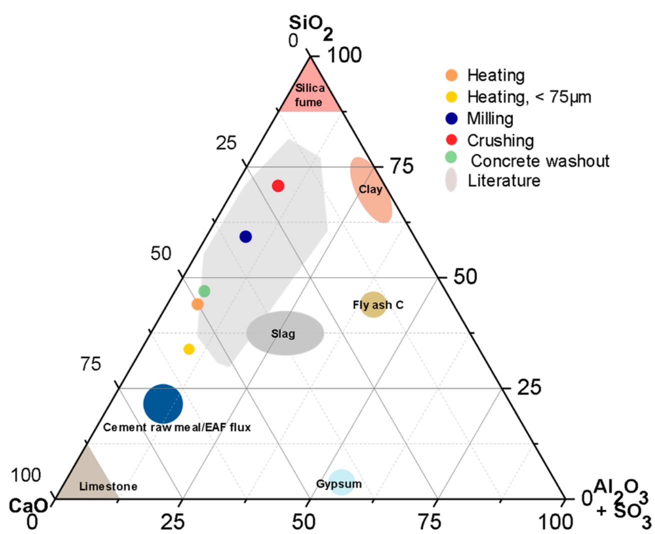
The results of our experimental program show that RCP could be produced from different crushing processes and beneficiation techniques. Most of the cement particles, irrespective of the beneficiation techniques, are found in fine particles (such as <75 or 100 μm). The coarse particles (typically >150 μm) are low in cement paste, and their chemical composition is dominated by silica-bearing phases. Based on Fig. 2b, the RCP could have a broad range of chemical composition. However, the emphasis on RCP production techniques should be given to the gain in calcium and should be classified based on the quality.

## 4. Methodology and critical parameters of RCP for use in cement production

In this section, the RCP is considered to be use for cement production. Therefore, the quality of RCP from each processing method is compared with the technical requirements for different cases of cement production. The technical requirements and substitution limits for RCP use in cement production are formulated based on literature, as well as results of the experiments of this study while considering the EN

| Processing route | RCP (0.15 mm) | Fine RAC (0.15 to 5 mm) | Coarse RAC (5 to 20 mm) |
|---|---|---|---|
| Crushing | 3-5 | 45-48 | 50-55 |
| Milling | 8-12 | 88-92 | - |
| Heating | 10-15 | 30-35 | 45-50 |

(a)

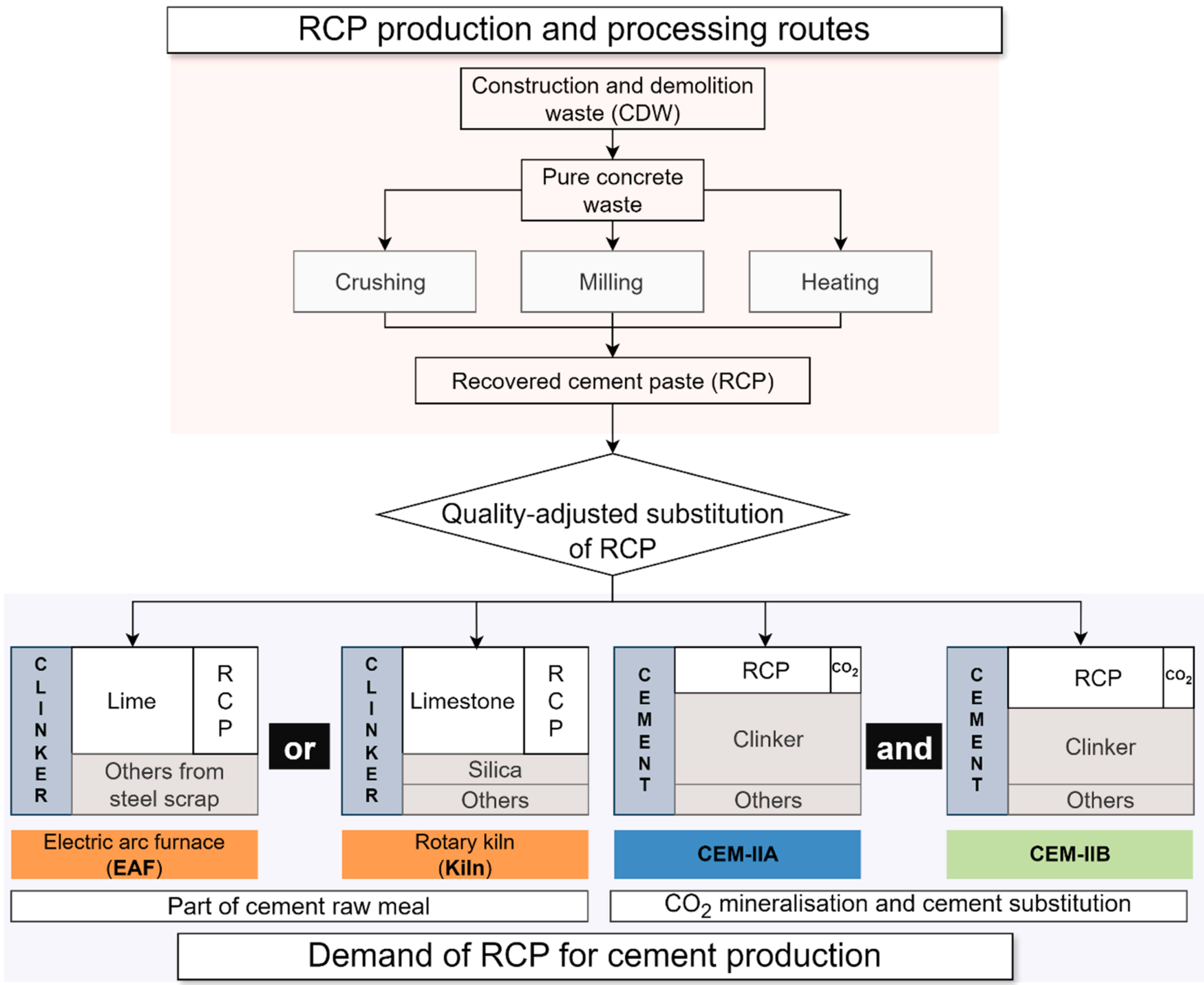



(b)

**Fig. 2.** (a) Yield ( % of feed) and size fraction of recycled concrete products (b) Analysis of the indicative quality of RCP produced by different processing routes from experimental program of this paper. The light grey outlines the range of literature results plus 5 %. The routes cover the complete range of reported data in the literature with respect to lime enrichment.

standards. Once the main parameters are identified, each production method of RCP is evaluated for different cement uses. Finally, we calculate $CO_2$ emissions for different processing techniques and cement substitutions to define the preferred options for RCP use to achieve maximum environmental benefits.

Based on literature and current interest in the application of RCP, two main uses (raw-meal for clinker and direct cement substitution) of RCP for cement production are considered. These two uses cover a total of four options—two for using RCP for cement raw meal, and one of them could be considered based on the available technology. Similarly, two options for cement substitution, both of which can be used together. Further details on these uses are given below:




(a)

| Production routes of RCP | Cement raw meal (EAF/Kiln) | $CO_2$ mineralisation and substitution# | | |
|---|---|---|---|---|
| | | CEM-IIA (20% replacement) | CEM-IIB (15% replacement) | $CO_2$ capture capacity (by mass) |
| **Crushing** | 6.6 | 18.2 | 13.7 | 9% |
| **Milling** | 12.8 | 17.0 | 12.8 | 15% |
| **Heating** | 28 | 15.6 | 11.7 | 22% |
| **Remarks** | Substitution of limestone* | As per EN 197-6:2023 | | Mass of $CO_2$ uptake is ~50% of the mass of calcium in RCP |

(b)

**Fig. 3.** (a) Methodology for the use of RCP in cement production (b) quality-adjusted substitution limits of RCP for cement production,*Details of cement raw meal and the chemical composition of constituents can be found in the supplementary document, #Maximum replacement for CEM-IIA is 20 % as per EN 197-6:2023, CEM-IIB replacement is restricted to 15 % as the maximum replacement of cement in this study is assumed to be below 35 % of total cement demand.

- **Part of cement raw meal in EAF or kiln (EAF or Kiln):** This use considers RCP as a source of decarbonised calcium. Therefore it is targeted to substitute only the limestone used in the cement raw meal in a conventional kiln or as part of flux material used for clinker production using an EAF as described in our previous publication (Dunant et al., 2024).
- **Main constituent of cement after carbonation (CEM-IIA and CEM-IIB):** For this application, RCP is used as a 'main constituent' for cement, such as for the production of blended cement, which is also described in EN 197-6:2023. To take advantage of uncarbonated phases in RCP, it is carbonated to mineralisation $CO_2$ in cement paste, and then used as the main constituent of cement for CEM-IIA and CEM-IIB, up to 20 % and 35 % substitution by mass, respectively.

In previous studies, researchers either used one type of RCP for various purposes or different qualities of RCP for just one specific use. However, in this study, three types of RCP have been produced, and three cement substitution scenarios are considered. The critical parameters are shown in Appendix Table A3 and some of them are briefly discussed:

### 4.1. Critical parameters of RCP for cement production

This section presents new criteria that should be considered when using RCP for cement production. The critical parameters for each cement production scenario are based on the chemical composition of source concrete material, processing technique and the technical requirements. It is important to highlight these here, to emphasise and explain their relevance for 'quality-adjusted' and 'quantity-adjusted' substitution of RCP for different uses and $CO_2$ emission calculations respectively. Here, 'quality-adjusted' is referred to the limit of RCP substitution which is imposed by chemical composition of RCP (such as amount of silica or calcium phases). Whereas 'quantity-adjusted' is referred to the cases where limits are applied based on availability of RCP for a particular case of cement production. Overall, this section summaries the findings of the literature as well as experimental results discussed in the previous sections of this study.

- ***Yield of RCP***: The yield of RCP is expressed in mass ( %) of feed material. The ratio of the other two products (sand and aggregate) also helps in analysing the effect of processing and the produced volumes that can be used for replacing sand and aggregates. However, the focus in this paper is on RCP as this contains high quantity of calcium. The yield is particularly very important in the process as material volumes define whether a treatment/processing route will be commercially viable. It is difficult to suggest a fixed value but yield of at least 10 % could be considered suitable for both economic and environmental benefits.
- ***Calcium content***: For all uses, the amount of calcium in RCP plays an important role however, the new standard EN 197–6:2023 does not specify any limit for the calcium content. Generally, the calcium content varies between 20 % and 50 % by mass, depending on the processing techniques.
- ***Particle size***: The particle size is more important if the surface area of RCP is essential such as for the reaction in cement and for the absorption for $CO_2$ gas. Therefore, it is mainly important when RCP is used to substitute the cement, however it can be further ground to achieve the desired particle size. In general, the particle size <150 μm is desirable to avoid high contamination of silica. The particle size of RCP for raw-meal use is less critical as it has to be ground with the other constituents to be used in the rotary kiln. For RCP use in the EAF, the particle size does not matter since it cannot be directly used in powder form and must be used along (or pelletised) with other flux materials. However, for both raw-meal applications, RCP should be stored carefully to prevent it from carbonisation and avoid heat losses for decarbonisation.
- ***Silica content:*** Higher silica content is generally undesirable because silica does not participate actively in any chemical reactions, especially for $CO_2$ mineralisation and as main constituent of cement. In different quality RCP, silica content can vary from 40 % to 80 % by mass. However, there is potential to provide more specific details regarding permissible silica limits for various applications. For instance, high silica content cannot effectively replace a large amount of limestone in raw meal. The burnability of quartz and feldspar in RCP can cause clinkering problems in cement kilns which need to be tested before using it in the kilns. Additionally, high free silica could attack the refractory lining of EAF.
- ***Sulphur:*** The sulphur content in cement is regulated by the standard (EN 197–1:2011). Therefore, if RCP is used as a substitute for cement, the sulphur content may restrict the substitution rate. Additionally, the overall sulphur content in cement (from other sources such as fossil fuels) may also limit the direct substitution of cement with RCP. When RCP is used for re-clinkering in cement kilns, high levels of $SO_3$ become particularly concerning, as they can accumulate in the cooler sections of the kiln and disrupt operations. Interestingly, the high sulphur may not limit the use of RCP in EAFs because the high temperature evaporates the sulphur, which is taken out from the fume extractors. In a gypsum-free waste concrete source, the sulphur content (as $SO_3$) in RCP typically ranges from 1 % to 2 %.
- ***Maximum substitution limit:*** The maximum amount of CaO in RCP is limited by processing. The maximum substitution of RCP is limited by the presence of impurity which is mostly silica and $SO_3$ content for cement raw-meal use. Higher silica content limits the limestone substitution and high $SO_3$ could hinder the kiln operations. For cement substitution, total organic and alkali content, as well as $SO_3$ content, could limit the uses if they exceed the permissible limits by cement standards. While the literature of different uses pushed the limits of substitution, the EN 197-6:2023 standard limits substitution in cement (as main constituent) between 6 and 35 % by mass.

### 4.2. Methodology for quality-adjusted substitution of RCP for cement production

The use of RCP is constrained by its chemical composition, presence of other materials in cement, the amount of available waste concrete and the limits imposed by the current standards. This section explains the method for determining the potential for absolute substitution of RCP, linking the chemical composition of RCP to its application for cement production for a country. The availability of concrete waste and the production of cement in a country are used to generate realistic estimation of cement replacement scenarios. The RCP substitution for cement production is adjusted based on the quality of RCP.

Fig. 3a illustrates the steps used in this paper for using RCP in cement production. It is divided into two parts, RCP production routes and it's uses for cement production. RCP production involves one of the techniques (crushing, milling and heating) explained previously in Section 3.1. The use of RCP for cement production can be further divided into two parts, as raw material for clinker (orange colour) and cement substitution after $CO_2$ mineralisation for CEM-II A (blue) and CEM-II A (green). Here, clinker raw materials (limestone, silica, and other minor materials) for cement kiln are shown, and limestone is substituted with RCP. The other way of producing clinker in an EAF involves the addition of lime and other elements (such as silica, alumina, and iron oxide) that come from steel scrap. In this case, lime is substituted with RCP as a source of decarbonised calcium and silica. On the other side, cement is made of clinker and other materials, where RCP (after carbonation) is added in different amounts to produce CEM-IIA and CEM-IIB cement classes.

The total quantity of CDW generated in a country is estimated, along with the amount of pure concrete waste available. Then, the total volume of RCP produced through different processing methods—such as crushing, milling, or heating, is calculated. We then consider the substitution of RCP based on its chemical composition. Once the chemical compatibility has been evaluated, the volume of RCP production is compared with the cement production to calculate the maximum absolute substitution for each country. Scenarios are then formulated evaluating the quality-adjusted substitution demand and limits.

For example, cement substitution of RCP after forced carbonation, the $CO_2$ mineralization capacity of RCP produced from crushing, milling and heating is considered to be 9, 15 and 22 % by mass, respectively (See Fig. 3b). It is assumed that mass of $CO_2$ uptake is ~50 % of the mass of calcium in the RCP (Gholizadeh-Vayghan and Snellings, 2022), however this could vary from 20–40 % depending on the source and processing technique (Haripan et al., 2024). The RCP from milling and heating process contains more amount of uncarbonated calcium phases and therefore can store more o3. The total cement substitution (including CEM-II A and B) is limited to 35 % of the cement demand.

RCP used for cement raw meal is considered only to replace limestone, not as a source of silica. Quality-adjusted substitution of RCP for cement production in the raw meal is calculated based on clinker production, whereas the direct substitution of cement is based on the total cement produced. Finally, the circularity potential of waste concrete is assessed based on examples of countries at various GDP and income levels, illustrating the potential use of waste concrete in cement production which is explained in the next section of this paper.

As mentioned in the previous section, the maximum substitution of RCP in cement is mainly dependent on chemical composition. There are several studies that recommend acceptable limits for substitution that do not significantly affect cement properties. For example, RCP of quality similar to that produced using the milling route as SCM can have maximum substitution of 25 to 30 % (Diliberto et al., 2021; Prošek et al., 2020). Carbonated RCP, from hydrated cement can substitute up to 40 % (Skocek et al., 2020; Zajac et al., 2020), these examples shows maximum potential substitution but practically cannot be produced from waste concrete. However, the current standard EN 197-6:2023 recommends lower values compared to those reported in the literature. Similarly, for cement raw meal (for cement kiln), up to 25 % RCP can be used (Izoret et al., 2019; Krour et al., 2020). Fig. 3b summarises the substitution limit of RCP in cement production, covering the constraints of standard, maximum limits of $CO_2$ sequestration using forced carbonation with pure $CO_2$, and lastly, the replacement of limestone in cement raw meal.

### *4.3. Definition of circularity potential index (CPI) of cement circularity*

To provide a better understanding of cement circularity, we have introduced a new metric: Circularity Potential Index (CPI). This index helps to visualise and compare which processing method for RCP has the highest potential for cement production. The CPI is the ratio of available RCP to the amount of clinker produced (see Table SI 2.1 in supplementary informations). CPI a dimensionless metric and its values can range from 0 to potentially over 100, particularly in scenarios where the amount of available waste concrete exceeds the requirements for cement production. Though cement can be used instead of clinker for CPI, which allows both uses (cement raw meal and direct cement substitution) of RCP, since each country has different clinker factors for cement production, we used clinker to simplify the CPI index. This index serves as a better indicator of cement circularity.

### *4.4. Prioritising RCP use for cement production based on $CO_2$ emission savings*

RCP is a valuable resource, particularly in the case of thermal processing which can be costly compared to other methods. Therefore, it is expected from the actors exploiting this resource to prioritise higher-value uses where maximum environmental/economic benefits can be achieved. This study presents the $CO_2$ emissions for processing both, a tonne of concrete as well as a tonne of cement, covering the perspectives of recyclers and users. For example, recyclers are likely to be more concerned with the $CO_2$ emissions for processing a tonne of waste concrete, while users are more focused on emission reductions by using the cement produced with RCP.

Fig. 4a shows the RCP production emission from one tonne of concrete waste using different beneficiation processes (refer to Table SI 1.2 in supplementary information for more details). These $CO_2$ emissions are based on the electricity consumption for processing waste concrete. Though depending on the size of the feed and the output material, crushing and milling processes could have slightly different energy consumption. Indeed, crushing and milling machines use electricity, and the heating process can also be electrified, as the temperature (500 °C) is within the range of current industrial equipment. The crushing process has the lowest emissions but the recycled products are of low quality and yield is minimal. The milling process has higher emissions but can have more yield than the crushing process. The heating method has the highest emissions, but the yield and recycled aggregate quality are much higher than the other two processes. For comparison, Fig. 4a also shows $CO_2$ emissions for one tonne of RCP production if all the concrete processing emissions are allocated to RCP and the emissions for producing aggregate are discounted. These are further compared with $CO_2$ emissions from a tonne of lime and cement production as a reference.

Fig. 4b indicates that the preferred use of RCP is as cement raw meal (refer to Tables SI 1.3, 1.4 and 1.5 in supplementary informations for more details). This approach avoids the direct chemical $CO_2$ emissions associated to the calcination of limestone during clinker production. Further, a superior quality/more valuable product (clinker) can be produced. This approach results in net emissions savings, demonstrating overall $CO_2$ savings across all three processing methods: crushing, milling, and heating. Notably, despite high emissions from heating route, the net emission saving is highest. After this, the use of RCP for $CO_2$ mineralisation and cement substitution could be done, to have the benefits of sequestering carbon as well as reduced cement usage.

Fig. 4c shows the emission from quantity-adjusted RCP production and savings from $CO_2$ capture and limestone fines (filler) avoided by using RCP. The net emission savings from cement substitution are minimal for the crushing and milling routes when compared to using RCP as raw meal. In fact, the heating route has less $CO_2$ emissions savings than the milling route since this method is energy intensive. A comparison of net $CO_2$ emissions from these applications indicates that RCP produced from the crushing and milling route is advantageous for $CO_2$ capture and cement substitution. While using RCP as cement raw meal (lime replacement) is beneficial across all types of RCP, the highest $CO_2$ emission savings are achieved by using RCP produced from the heating route, as it can replace a significant quantity of lime due to its higher calcium content. It is to be noted that the electricity grid emission factors of the UK are used in this analysis for Fig. 4a. However, the emission factors can vary significantly across different regions; therefore using local factors would provide a more accurate comparison. A visual summary of substitution and the avoided $CO_2$ emissions of using RCP in a cement kiln can be seen in Fig. 4d (refer to Tables SI 1.3 and SI 1.5 in supplementary information for more details).

To estimate the potential benefit of developing the different beneficiation routes, we have assumed that the most valuable uses of the RCP are exhausted first. Under this assumption, the potential supply of RCP would be used to produce the most benefits. As this reflects both environmental and economic benefits, we assume this would reflect the preferred order in industrial applications as well.

## 5. Country-level analysis of supply and demand of RCP for cement production

For the country-level analysis, a panel is selected that covers developed, emerging, and developing countries with varying cement production. Then, the availability of concrete waste, RCP production and quality-adjusted RCP demand for cement substitution are evaluated to

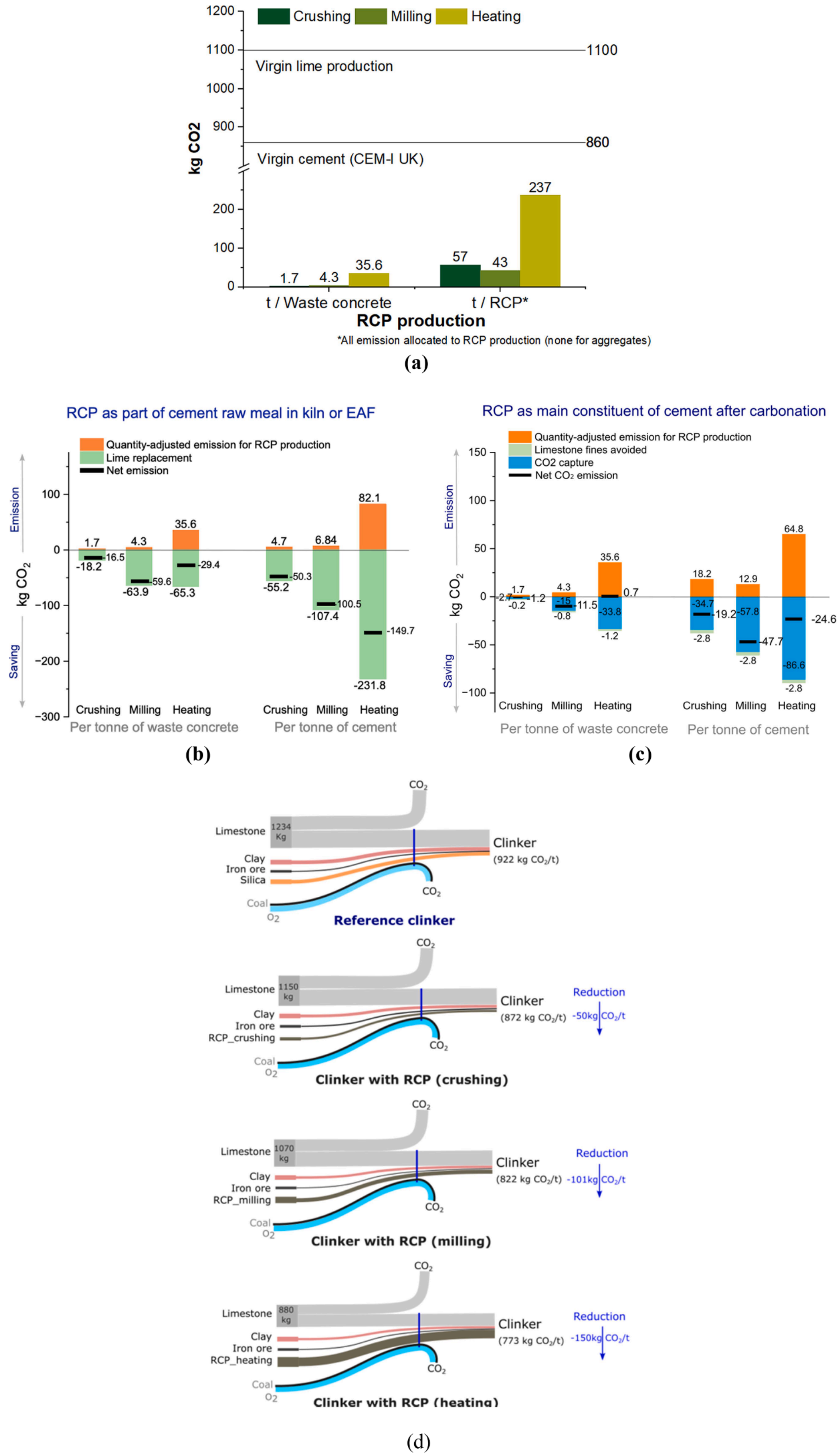



**Fig. 4.** (a) Emission from RCP production using different beneficiation processes, and $CO_2$ savings from using RCP as (b) cement raw meal and (c) cement main constituent after carbonation (d) visual summary example of RCP use for limestone substitution in cement kiln.

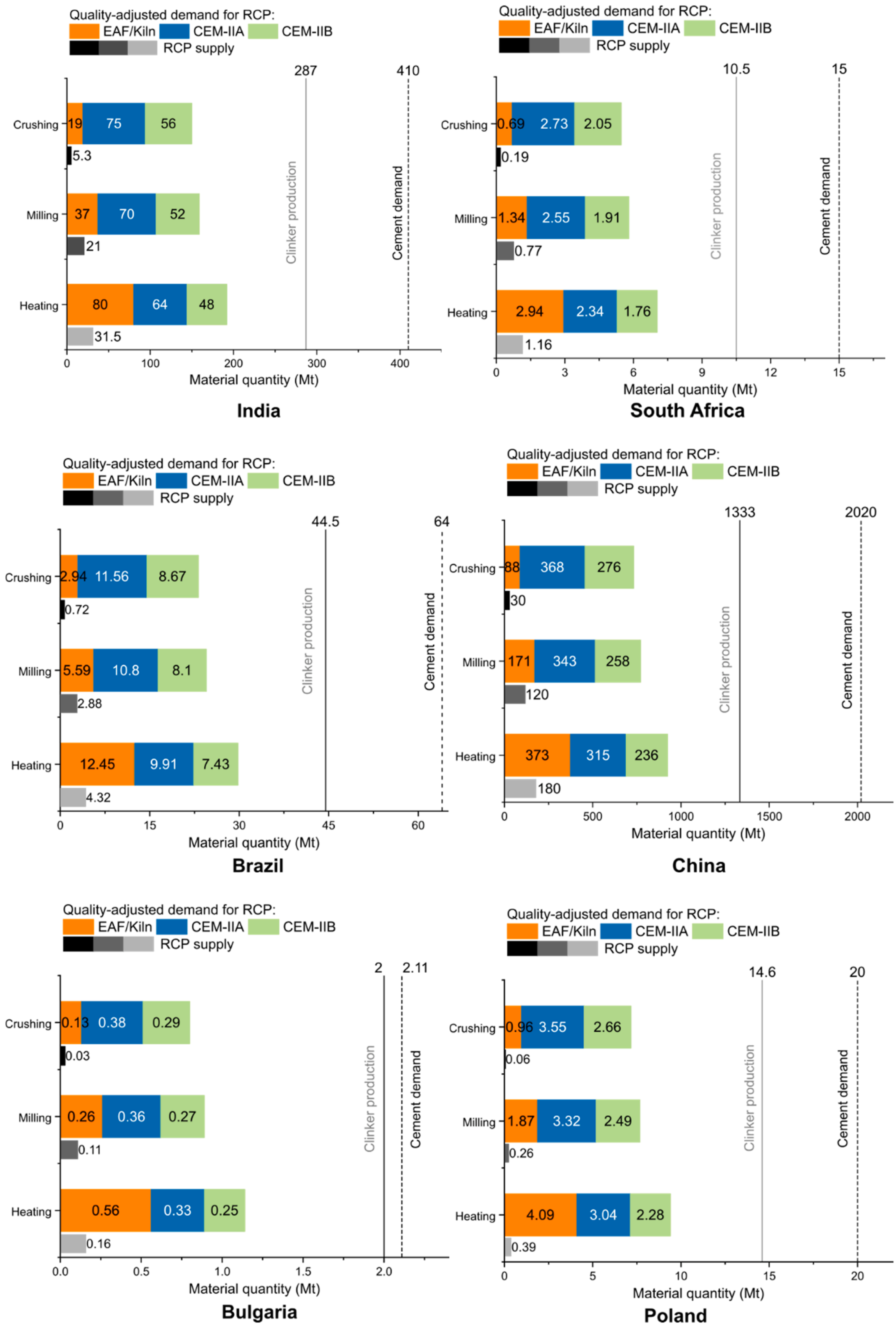



**Fig. 5.** Quality-adjusted demand and supply of RCP for cement production.

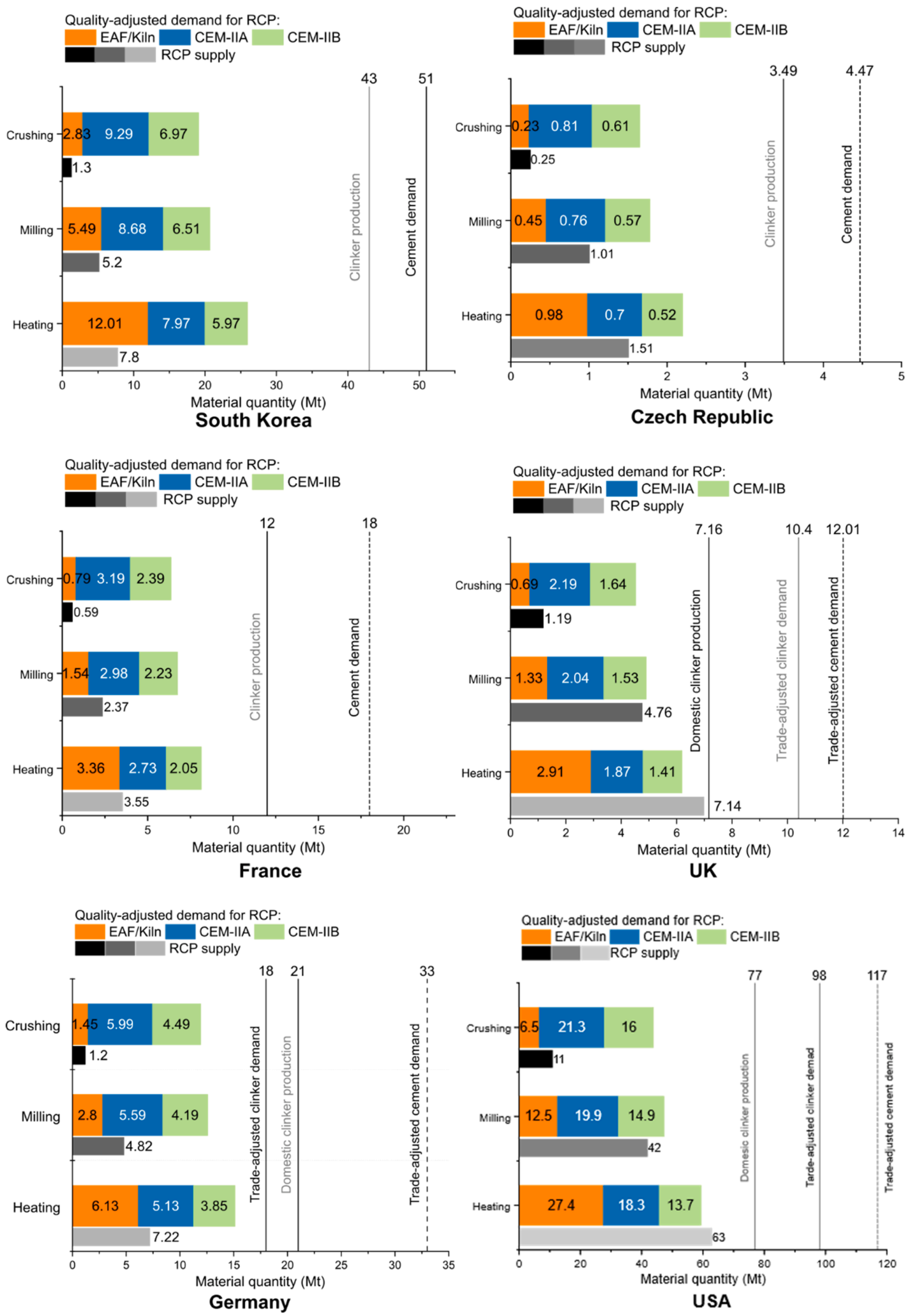



**Fig. 5.** (*continued*).

compare the supply and demand of RCP for cement production. Further, cement recycling is explained for different countries based on their wealth and current economic status.

### 5.1. Panel selection of countries evaluated for their circularity potential

Appendix Table A4 shows selected countries in order of increasing GDP per capita, adjusted for PPP (World Bank, 2022). These groups cover different scenarios of low and high CDW generation as well as cement production. These countries represent over 40 % of the total world population with >2.5 billion tons of cement production and generate around 4 billion ton of CDW every year. Some are major producers of cement, while others are expected to experience significant growth in construction over the next two decades. Conversely, some are facing a decline in cement production, and there are those that have reached a point where cement demand remains constant. With these examples, we can cover a range of different scenarios for CDW generation and cement production to understand the conditions to achieve higher circularity potential of cement.

### 5.2. Quality-adjusted demand for cement production and supply of RCP in different countries

Fig. 5 shows the available supply of RCP (in different colours) in the market by using crushing (black), milling (dark grey) and heating (light grey) routes. The RCP supply is compared with the quality-adjusted maximum demand of RCP as raw-meal for clinker (EAF/Kiln) and as main constituent of CEM-IIA and CEM-IIB (blended) cements after carbonation. The potential RCP demand for raw meal is based on the clinker, for some countries clinker factor is estimated based on cement production when actual data on clinker production is not available. Similarly, potential RCP demand for CEM-II A/B is based on cement production. When data on cement imports and exports are available and are in significant volumes, corrections have been made to align them with domestic consumption for more accurate accounting (refer to Table SI 2.1 and 2.2 in supplementary informations for more details).

For example, the UK produces 7 Mt of clinker, and the total demand for cement is 12 Mt, which is met by importing cement (UK Government Department for Business and Trade, 2024a). The quality-adjusted demand of RCP is much higher if the RCP is produced from the crushing route. However, the deployment of milling and heating routes for waste concrete processing could provide enough volume to meet the demand for cement production. This analysis shows how much cement can be cycled in different countries taking into account cement demand and the availability of waste concrete. It is important to note that in this analysis, all of the waste concrete is considered to be processed and used within the country as transporting recycled materials or waste concrete to other countries is unlikely.

### 5.3. Relation between cement cycling and country wealth

We identified three categories of countries with respect to CDW generation and construction demand (See appendix Table A4). The first category includes countries with increasing CDW generation and cement production, the second category includes the counties in transition, which are at the peak of cement production, and finally, those with steady CDW generation and cement production. These categories are explained in the following sections:

#### 5.3.1. Countries with increasing CDW and cement production

We focus on four countries: South Africa, India, Brazil, and China. Currently, South Africa generates approximately 15 Mt of CDW annually (Berge and von Blottnitz, 2022), while India generates around 700 Mt (Banerjee et al., 2016), and China generates about 2500 Mt (Duan et al., 2019), the highest in the world. The proportion of concrete in total CDW varies across these countries, influenced by the types of construction in the previous decades. Cement production is expected to increase rapidly in Africa, Brazil, and India, while it is on the decline in China. In South Africa and India, the proportion of waste concrete in CDW ranges from 30 % to 40 %. This is primarily due to the historical use of masonry structures, resulting in lower volumes of RCP. In contrast, Brazil and China have higher concrete fractions in CDW, which lie between 50 % and 60 %. It is anticipated that the proportion of waste concrete in total CDW in China will rise, given the substantial amount of concrete construction over the last two decades.

#### 5.3.2. Countries at peak of cement production and rapid infrastructure building

The second group of countries have a higher GDP per capita than the previous group and have reached or are close to reaching the peak of cement production. For instance, South Korea experienced a peak in 2017, producing a record 57 Mt of cement (National Waste Generation and Processing Status, Korea 2021). Despite being a small country, it generates 80 Mt of CDW annually due to a recent surge in construction activities. Similarly, Poland and Bulgaria are nearing their peak or may experience slow growth in cement production. Currently, CDW generation is relatively low in both countries. Therefore, the gap between RCP availability and cement demand is high (see Fig. 5). Especially, the ongoing infrastructure projects in Poland are contributing to the highest gap between cement production and the availability of RCP.

#### 5.3.3. Countries with steady CDW generation and cement demand

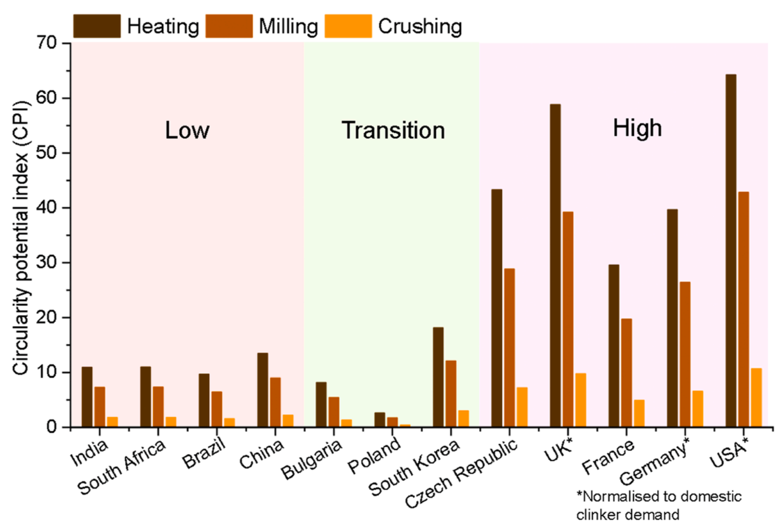
The UK, France, Germany and USA have higher GDP per capita than the last two groups of countries. The Czech Republic has reached this group recently, primarily due to a favourable PPP correction. These countries experience a stable cement demand for construction, as their GDP per capita shows low or constant growth, which also affects construction activities. Cement production in the UK and France peaked around 2005. In the last decade, cement production has been stable in the UK (8–9 Mt/year) as well as France (16–18 Mt/year) (British Geological Survey, 2024). Over that period, the population of this group has remained relatively stable, which is reflected in their cement consumption. The UK and USA import approximately 3.6 (UK Government Department for Business and Trade, 2024b) and 26 Mt (U.S. Geological Survey 2024) of cement respectively, while Germany exports about 6.9 Mt. As a result, clinker production in these countries was adjusted to meet domestic demand. Germany and the UK have nearly the same levels of per capita cement consumption. However, the UK generates 68 Mt of CDW every year (UK Government Department for Business and Trade, 2024b), with a higher proportion of concrete; this, along with lower clinker production, shrinks the gap with RCP availability. Similarly, the USA generates 400 Mt of CDW with almost 70 % of waste concrete (U.S. Environmental Protection Agency, 2018), which can potentially be used for RCP production to meet cement production demand. Although there are some similarities between these countries, such as high GDP per capita, each country is influenced by its unique local circumstances such as physical deterioration and socio-economic trends.

## 6. Discussion

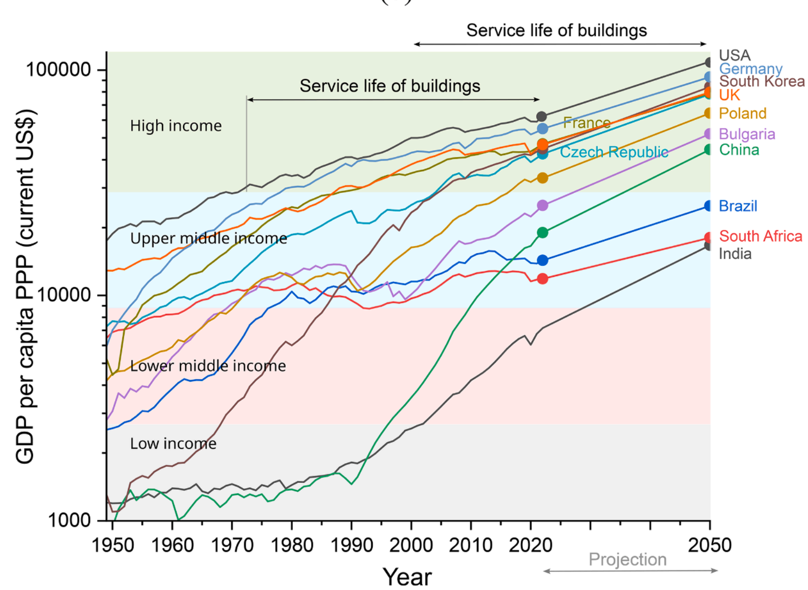
This section is divided into three sub-sections that include: the proposed definition and classification of RCP, circularity potential, and its dependency on time and country wealth. The RCP classification is based on critical analysis of the results of this study, literature as well as gaps in the standard. The cement cycling is explained using circularity potential index by analysing the country level data. Cement cycling is linked to a nation's wealth, which develops over time. This time dependence is demonstrated through an analysis of historical economic growth (as GDP per capita) in relation to the service life of buildings.

| Calcium content (as CaO) | RCP quality | Recommended uses |
|---|---|---|
| >45% | Very high (high limestone substitute) | Cement raw meal |
| 35-45% | High | Cement raw meal, Cement filler, $CO_2$ capture |
| 25-35% | Medium | Cement filler, $CO_2$ capture |
| <25% | Low | Cement filler |

(a)




(b)




(c)

**Fig. 6.** (a) Proposed classification of RCP quality and recommended uses (b) Circularity potential index (CPI) for RCP (c) Time dependency of cement cycling and GDP per capita PPP in US$.

### 6.1. Proposed definition and classification of RCP

There have been many studies and reports on RCP processing and uses, but the definition of RCP is still not established. As a result, there are no clear recommendations regarding particle size or chemical constituents beyond limits for sulphate and chloride which are addressed in cement standards. Our results show that the RCP properties are mostly dependent on the separation efficiency and cement used. Previously, one of the authors had used the same method in India and achieved similar results (Prajapati et al., 2021). Though the CDW in different countries could have different compositions based on the local practices, the RCP is a product of processing only 'waste concrete', provided that proper sorting is done to separate the other constituents of CDW. Additionally, as cement is a standardised product all over the globe, measures of RCP quality can also be generalised. Based on the results of this study, RCP could have any particle size below 300 μm but we recommend that RCP should have a particle size of <150 μm to avoid high silica contamination. The $SO_3$ content of RCP in most of samples were <2 %, which is in line with the EN 197-6:2023 limit. We find that RCP can be classified in four quality categories as shown in Fig. 6a depending on their intended final use.

This classification of RCP presents a clear guideline to maximise the benefits of using RCP. For example, RCP with high calcium content could be used to replace limestone in raw-meal, or if used as cement main constitute could replace more than what is mentioned in the standard which could lead to better cement properties. Similarly, the low calcium RCP could be simply used as cement filler as less or no reactivity is expected in this case. For $CO_2$ mineralisation, a detailed investigation to determine the uncarbonated calcium fraction in RCP is required. Otherwise, the carbonation potential could be overestimated, as sometimes concrete waste is already highly carbonated. However, it is difficult to estimate the carbonation of waste concrete as this comes from different parts of the structures and is mixed while processing in the CDW plants. This depends on many factors such as exposure area, processing techniques, storage conditions etc. Further, the use of limestone aggregates in concrete production (De Schepper et al., 2013) can show higher calcium in RCP, which can be beneficial for cement substitution, but for cement raw-meal uses, the calcination energy and emission need to be carefully accounted. The standard (EN 197-6:2023) may recommend additional requirements beyond those listed in Appendix Table A1. These requirements aim to encourage recyclers to achieve higher separation efficiency in extracting lime from waste concrete which would lead to a reduction in $CO_2$ emissions and savings of raw materials. However, it is important to evaluate the investment feasibility across countries, which can be done by considering economic conditions, market demand and manpower availability. This evaluation helps in understanding the balance between costs and profits for allocating resources.

### 6.2. Circularity potential index (CPI) of concrete waste for different countries

This study focuses on RCP production for use in cement while assuming that recycled aggregates are used as replacements of virgin aggregates and sand. Fig. 6b illustrates the CPI for three RCP production routes across different countries (refer to Table SI 2.1 supplementary information for details). Alongside, Appendix Fig. A3 shows the generalised trend for CPI with GDP/capita. Together, these indices help highlight trends in cement circularity. The CPI in the context of three group (as seen in appendix Table A4) of countries is briefly explained below:

In the first group of countries (India, South Africa, Brazil, and China), shows low CPI, ranging between 10 % and 15 %. This indicates that while RCP can be used to some extent in cement production, there remains a significant demand for primary raw materials like limestone. The second group, which includes Bulgaria and Poland, exhibits an even lower CPI due to the current increased level of cement production and limited RCP availability, which is a transition period from low to high CPI. South Korea has a slightly higher CPI in this group, owing to a higher CDW generation rate, which increases the availability of concrete waste (or RCP) for cement substitution.

The third group has the highest CPI between 40–60 %, indicating high potential for cement cycling. The Czech Republic has had stable cement demand and a slow increase in CDW generation in the last decades. The UK and USA presents an interesting case, with the highest CPI resulting from the availability of substantial concrete waste. Particularly, the UK generated waste from the demolition of buildings and ongoing redevelopment of transport infrastructure built in the 1970s. Notably, in 2020, cement production in the UK also decreased by 11 % due to economic and environmental constraints. Germany and France have a slightly lower CPI of around 40 % in this group, which is attributed to higher per capita cement demand in Germany and a lower proportion of concrete in total CDW generated in France. In general, it could be observed that when countries move from lower to higher GDP per capita, the CPI increases. However, there are stages in between (as seen for Bulgaria and Poland today) when the gap increases to its highest level due to the peak demand of cement.

This section discussed cement cycling in the context of current development. The next section connects the historical development of an economy to explain the time dependency of cement cycling.

### 6.3. Time dependency of the cement cycle

Apart from GDP per capita, the cement cycle has a time dependency which is linked to the long-term development of a country. Fig. 6c shows income groups with GDP per capita (PPP) for various countries (World Bank, 2024). The data have been systematically analysed since 1950 and projections for 2050 is made from extrapolating the last 20 years of growth forward. It reveals a good correlation between higher GDP per capita and elevated circularity potential (CPI). The UK, USA, Germany and France have been in the high-income group since the 1970s, almost 60 years, which is also about the same time as the service life of the building. Due to their long-standing position in the higher income group, the current demand for construction, notably infrastructure is low; therefore, the demand for cement is steady. Since the construction activity is steady in these high-income group countries, the waste concrete generation from demolition activities has been almost the same for the last decade, which presents the opportunity to recycle it efficiently to achieve material circularity.

There is a time lag when transitioning to a higher CPI, which can be seen in the example of South Korea, which has recently reached a higher income level but has not been there long enough to reach a high CPI but will reach a higher circularity potential in future. This indicates that the cement demand needs to be stable and the generation of waste concrete should be increased to have high RCP availability.

China and India have both been in the lower income group since 1990. However, China experienced significant growth in construction, leading to it becoming the largest producer of cement globally. Recently, cement production in China peaked and is now gradually declining. It is anticipated that CDW generation in China will continue to rise, which may elevate its CPI in the future. Meanwhile, India is rapidly advancing and expected to see substantial growth in cement production (IBEF, 2024). Historically, India has built more masonry structures, but concrete construction has been picking up recently, particularly in infrastructure projects like roads, bridges and high-rise buildings.

If current trends in cement and CDW generation continue, countries like South Korea are projected to achieve a higher CPI by 2050. China is expected to reach a high CPI by 2060, coinciding with a decrease in cement demand as many buildings constructed today and over the past decade, will be demolished, generating more waste concrete for RCP production. Meanwhile, India is experiencing a rapid increase in cement demand, with more concrete constructions replacing traditional brick and masonry structures. This trend could contribute to an increase in the fraction of concrete waste, and together with lower cement demand in future, a high CPI will be seen for India around 2070.

## 7. Conclusion

**RCP quality and uses for cement production**: Calcium content and yield are the most important quality parameters for RCP processing. RCP can be produced using crushing, milling and heating routes based on the market readiness, demand in the market and the existence or development of the supply chain. A high degree of separation can be achieved by adopting the heating route using the concrete waste sourced from CDW plants. Cement substitution can tolerate high silica content, as there is no restriction on the silica content in EN standard. Therefore, the RCP produced from crushing and milling routes can be used. However, the use of RCP with high calcium content (or lower silica content) for cement raw meal is preferable to minimise the addition of limestone; therefore, the RCP from the heating route should be preferred. The $SO_3$ content in RCP should be carefully monitored, and gypsum products should be separated and removed from waste concrete during demolition.

There is potential to further understand the separation efficiency of RCP using micro-analytical techniques and further improve the calcium content using powder beneficiation techniques. Also, a relatively pure source of RCP exists in the form of concrete washout from ready mix concrete production, which is currently discarded since the industry has not identified a practical use for it.

**RCP availability and circularity potential**: The Circular Potential Index currently stands at a low level for the newly emerging countries, primarily as a result of the rising demand for raw materials required for cement production. This rising demand poses challenges to achieving a more circular economy. The developed countries with stable cement demand have a higher CPI. When cement demand decreases, waste generation remains constant, indicating that construction activities continue at a steady pace. In this situation, the CPI could even increase if maximum waste recovery is achieved, and appropriate technology is employed to recover RCP. While the CPI is currently low in emerging countries, there exists an opportunity to develop the supply chain and motivate stakeholders to process waste concrete efficiently, fostering circularity. The efforts in this area need to start today to be ready in the coming years to reduce emissions.

This analysis highlights that in the context of an advanced economy, RCP has the potential to fulfil the limestone requirements essential for cement production, provided that suitable processing standards are implemented. For example, RCP from heated beneficiation route can replace as much as 28 % of limestone in cement kilns, which means the UK can produce 2.91 Mt clinker using raw-meal blended with RCP. Concrete can be a circular material, which can be sustainably managed throughout its entire lifecycle—from production to disposal. When handled properly, end-of-life concrete can be recycled into cement, with a minimal loss in each cycle.

## Glossary

**Concrete:** Mix of cement, sand, stone aggregate and water used for construction

**Waste concrete:** Concrete waste generated from demolition of old concrete structures

**CDW:** Construction and demolition waste, typically mix of concrete, masonry, brick, plastic, wood, ceramic, glass etc.

**HCP (hydrated cement paste):** fine powder produced by hydrating pure cement, with no other impurities

**RCF (recycled concrete fines):** fine powder produced as a by-product from crushing of waste concrete

**RCP (recovered cement paste):** fine powder extracted by processing concrete, using a combination of crushing and beneficiation techniques (milling, heating etc.) with the aim of extracting cement paste from concrete

**Concrete washout**: RCP extracted from returned ready-mix concrete (fresh state) by washing/reclaimers

**EAF:** Electric arc furnace, used for steel scrap recycling

**Mt:** Million tonnes

**GDP/capita:** Gross domestic product/total population

**PPP:** Purchasing power parity (price measure of specific goods in different countries)

**CPI:** Circularity potential index (a new dimensionless metric proposed as measure of cement circularity)

## CRediT authorship contribution statement

**Rohit Prajapati:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shiju Joseph:** Writing – review & editing, Methodology, Formal analysis. **Patricio A. Burdiles:** Writing – review & editing, Formal analysis. **Julian M. Allwood:** Writing – review & editing, Resources, Methodology, Funding acquisition. **Cyrille F. Dunant:** Writing – review & editing, Validation, Resources, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Rohit Prajapati reports a relationship with Reclinker Ltd. formerly Cambridge Electric Cement Ltd. that includes: consulting or advisory, employment, and equity or stocks. Shiju Joseph reports a relationship with Reclinker Ltd. formerly Cambridge Electric Cement Ltd. that includes: consulting or advisory, employment, and equity or stocks. Patricio Burdiles reports a relationship with Reclinker Ltd. formerly Cambridge Electric Cement Ltd. that includes: consulting or advisory, employment, and equity or stocks. Julian Allwood reports a relationship with Reclinker Ltd. formerly Cambridge Electric Cement Ltd. that includes: equity or stocks. Cyrille Dunant reports a relationship with Reclinker Ltd. formerly Cambridge Electric Cement Ltd. that includes: board membership, employment, and equity or stocks. Cyrille Dunant, Julian Allwood has patent ##US20240318271A1 pending to Cambridge Enterprise Ltd. 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.

## Acknowledgement

This research was funded by EPSRC 'Cambridge Electric Cement, Zero-emissions from old concrete paste replacing flux in electric-arc furnaces' (Project no.: EP/W026104/1) and Innovate UK (grant G116761, Cement2Zero). The authors acknowledge the support by Day Aggregate Ltd. for providing waste concrete samples.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108580.

## Appendix

Tables A1, A2, A3, A4 and Figs. A1, A2, A3

**Table A1**
Technical requirements for the source material and RCP in EN 197-6:2023.

| Material | Property | Limit |
|---|---|---|
| Waste concrete source (≥ 90 % by mass concrete) | Bitumen | ≤1 % by mass |
| | floating material | ≤2 $cm^3$/kg |
| | Glass | ≤1 % by mass |
| Concrete fines | Total organic content (TOC) | ≤0.8 % by mass |
| | Sulfate content ($SO_3$) | ≤2.0 % by mass |
| | Clay content | <1.20 g/100 g |

**Table A2**
Source, processing method and characteristics of RCP reported in literature.

| **Concrete source** | **Processing technique** | **Max. particle size (um)** | **CaO ( %)** | **$SiO_2$ ( %)** | **$Al_2O_3$ ( %)** | **$SO_3$ ( %)** | **Yield ( % of feed)** | **Reference** |
|---|---|---|---|---|---|---|---|---|
| C&D plant | Cone cavity ball mill | 75 | – | – | – | – | – | (Ma et al., 2020) |
| Lab prepared concrete | Jaw crusher | 3 mm | – | – | – | – | – | (Gholizadeh-Vayghan and Snellings, 2022) |
| – | – | ~300 | 12 | 59 | 10 | 0.5 | – | (Kim, 2017) |
| Concrete waste | – | 200 | 12 | 59 | 10 | 0.4 | – | (Kim and Choi, 2012) |
| 4 year old drainage channel | Crushing and grinding | ~100 | 14 | 42 | 14 | 0.7 | – | Prošek et al., 2020) |
| C&D plant | Advanced Dry Recovery (ADR) | 2 mm | 15 | 65 | 5 | 0.6 | – | (Schoon et al., 2015) |
| Concrete waste | Crushing and sieving | 63 | 17 | 60 | 10 | 0.7 | – | (Li et al., 2022) |
| C&D plant | Dust collector | 75 | 18 | 51 | 14 | 0.9 | – | (Li et al., 2021) |
| 20-year old RC building | – | 75 | 19 | 65 | 8 | – | – | (Ren et al., 2020) |
| C&D plant | – | ~75 | 19 | 47 | 12 | 1.5 | – | (Mao et al., 2020) |
| 50 year old railway sleeper | Crushing and grinding | ~150 | 21 | 40 | 12 | 1.2 | – | (Prošek et al., 2020) |
| Lab concrete | – | ~100 | 21 | 57 | 11 | 1.2 | – | (Xiao et al., 2022) |
| Concrete waste | Crushing and ball mill | 45 | 21 | 57 | 11 | 1.2 | – | (Singh et al., 2023) |
| C&D plant | Static separator (KDH) | 250 | 23 | 45 | 6 | 1.2 | 4.8 | (Schoon et al., 2015) |
| Concrete (Source A) | – | ~75 | 23 | 43 | 7 | 1.5 | – | (Zajac et al., 2023) |
| Concrete (Source B) | – | ~125 | 23 | 43 | 5 | 0.9 | – | (Zajac et al., 2023) |
| C&D plant | Crushing, sieving and ball mill | 150 & 75 | 23 | 52 | 14 | 0.8 | – | (Shi et al., 2019) |
| 50 MPa lab concrete | | | 23 | 55 | 3 | 1.0 | – | (Moon et al., 2005) |
| 62 MPa lab concrete | | | 23 | 52 | 3 | 1.0 | – | (Moon et al., 2005) |
| C&D plant | Ball mill with hot air stream (CTP) | 250 | 24 | 45 | 6 | 1.2 | 7 | (Schoon et al., 2015) |
| Lab prepared concrete | Crushing, sieving and ball mill (RC1) | ~150 | 24 | 39 | 8.0 | 1.1 | – | (Oliveira et al., 2020) |
| 107 year old column | Crushing, separation and grinding | ~75 | 24 | 36 | 8 | 1.6 | – | Prošek et al., 2020) |
| 29 MPa lab concrete | Crushing and sieving | 150 | 25 | 52 | 2 | 1.1 | – | (Moon et al., 2005)* |
| 60-year RC building | Jaw crushing | 150 | 28 | 51 | 8 | – | – | (Nedunuri et al., 2021) |
| Concrete (Source B) | – | ~400 | 29 | 25 | 4 | 1.9 | – | (Zajac et al., 2023) |
| C&D plant | Crushing | 106 | 29 | 28 | 7 | 2.3 | 5–10 | (Chen et al., 2019) |
| C&D plant | Crushing and sieving | 750 | 29 | 25 | 6 | 1.8 | – | (Vashistha et al., 2023) |
| Lab concrete | Crushing and ball mill | 100 | 29. | 28 | 7 | 1.1 | – | (Chen et al., 2022) |
| Concrete waste | Crushing, heating and sieving | 75 | 31 | 49 | 9 | 2.0 | – | (Liu et al., 2020) |
| Lab prepared concrete | Crushing and sieving | 150 | 33 | 45 | 2 | 1.0 | – | (Florea et al., 2014) |
| Concrete waste | Crushing and ball mill | 300 | 38 | 31 | 10 | 3.4 | – | (Letelier et al., 2017) |
| Concrete waste | Crushing and ball mill | 75 | 40 | 31 | 12 | 3.3 | – | (Letelier et al., 2017) |
| Concrete waste | Crushing and ball mill | 150 | 40 | 31 | 10 | 3.3 | – | (Letelier et al., 2017) |

* Insoluble is added to $SiO_2$ content.

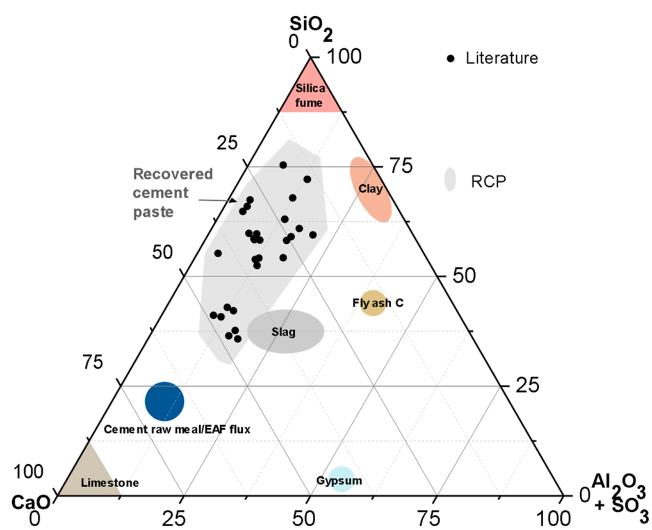
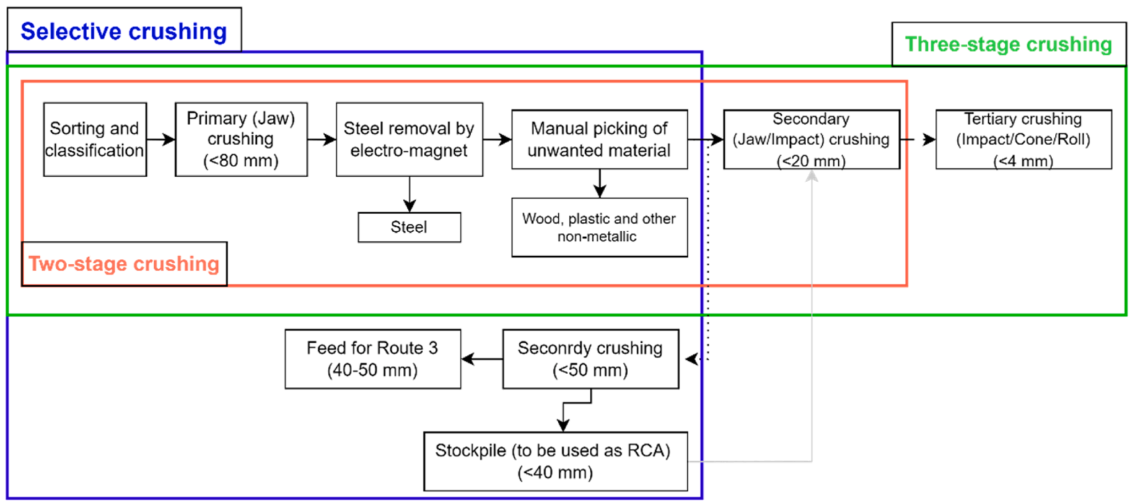
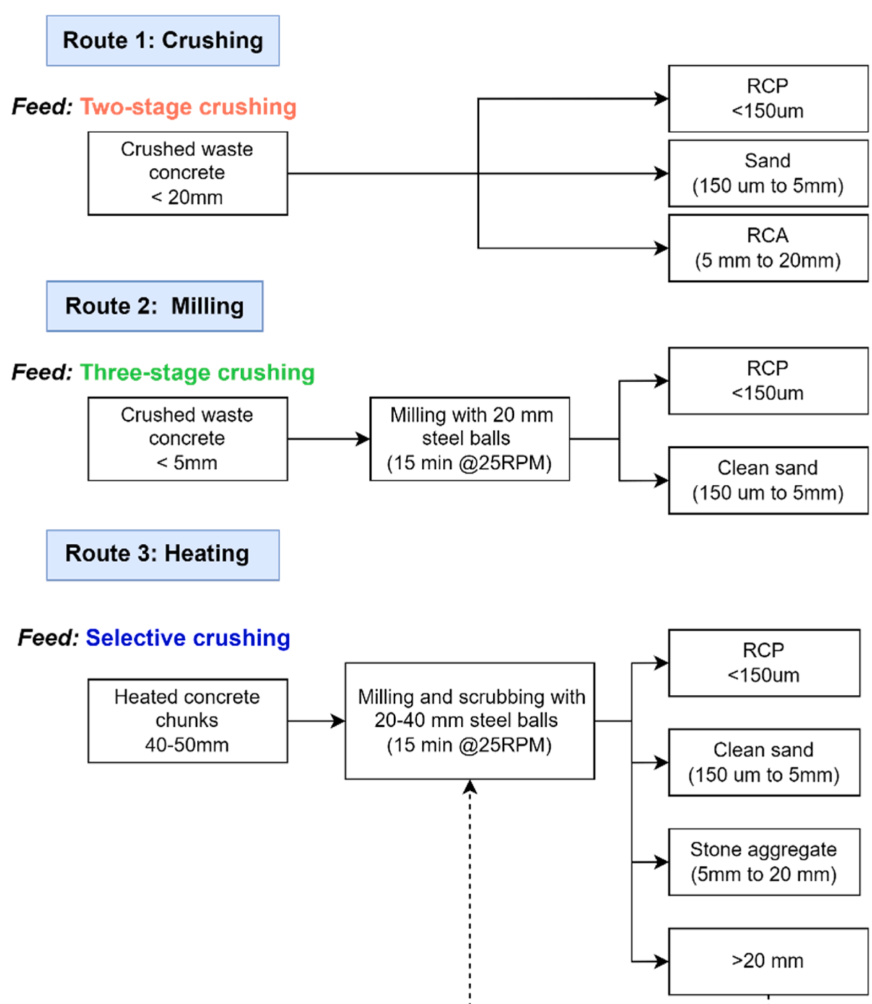



**Fig. A1.** Chemical composition of RCP obtained from waste concrete processing in literature. The light grey outlines the range of literature results plus 5 %.




(a)




(b)

**Fig. A2.** (a) Process flow used for crushing the waste concrete (b) Beneficiation techniques to produce RCP and RCA used in this study.

**Table A3**
Critical parameters of RCP for cement production.

| Uses | | Critical parameter | References |
|---|---|---|---|
| As part of cement raw meal | EAF/Kiln | • Calcium content<br>• High $SO_3$ content<br>• Burnability of quartz and feldspar content | (Dunant et al., 2024; Izoret et al., 2019; Krour et al., 2020) |
| As main constituent of cement | CEM-IIA and CEM-IIB (after carbonation) | • Calcium content, particle size<br>• Residual anhydrous clinker<br>• Aggregate type (silicious or calcareous)<br>• Fineness<br>• Non-carbonated alkali oxides | (Diliberto et al., 2021; Nedunuri et al., 2021; Prošek et al., 2020; Zajac et al., 2021) |

**Table A4**
GDP per capita, adjusted for PPP (World Bank, 2022).

| Country | GDP/capita PPP (US$, 2022) | Remarks |
|---|---|---|
| India | 9000 | Increasing CDW generation and cement production |
| South Africa | 15,000 | |
| Brazil | 20,000 | |
| China | 23,000 | |
| Bulgaria | 35,000 | Recently attained the peak of cement production and rapid infrastructure building |
| Poland | 47,000 | |
| South Korea | 51,600 | |
| Czech Republic | 51,700 | Steady cement demand and CDW generation |
| UK | 57,000 | |
| France | 58,000 | |
| Germany | 67,000 | |
| USA | 78,000 | |

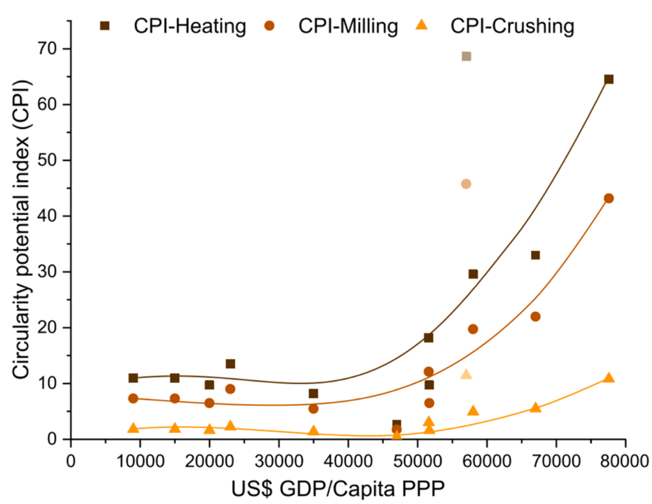



**Fig. A3.** Generalised trend of CPI with GDP/capita (UK as outliers).

## Data availability

No data was used for the research described in the article.

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