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Review

Complete re-utilization of waste concretes–Valorisation pathways and research needs

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ABSTRACT

Global demand for buildings and infrastructure is extremely high as provision of shelter, sanitation and healthcare are paramount to safeguard the world's growing population. Concrete is a preferred construction material to meet this demand, but its production is leading to overexploitation of natural gravel and sand, causing an environmental crisis in regions where these materials are extracted unsustainably. Waste concrete is available globally, particularly in regions with fast growth of the built environment, and those struck by coordinated attacks, earthquakes or severe weather events. Waste concrete has mainly been used for producing recycled aggregates; however, its full recycling is still not practiced. Alternative uses include applications as fine recycled aggregates, supplementary cementitious materials, filler, and feedstocks for clinker production. These technologies still face challenges concerning their adoption and eco-efficiency. Restricted knowledge and operational barriers have also prevented implementation of beneficiation technologies for complete re-recycling of waste concretes, particularly the fine fractions produced during crushing. Despite these issues, it is recognised that the complete utilization of waste concrete offers unique opportunities for supply chain security, reducing natural resources consumption and enabling to move towards a Circular Economy. Harmonizing current practices for the treatment of waste concrete and the by-products generated during their processing, is a first step toward policy and standards development to enable their widespread use. This critical discussion addresses challenges and opportunities, as well as facilitation strategies needed to progress the complete re-utilization of waste concrete as a valuable resource for creating sustainable future infrastructure.

1. Introduction

Concrete has been indispensable to the development of societies during the 20th century, and the world will continue to rely on concrete for infrastructure throughout the 21st century. Whilst its benefits are well-established, the environmental impacts of concrete are coming under increasing scrutiny - the most prominent impacts of the concrete life cycle are embodied carbon emissions, consumption of natural resources during its production (e.g. aggregates (Gavriletea, 2017) and water (Miller et al., 2018)) and end-of-life waste generation. These issues are the subject of policies at the national and international levels (Di Filippo et al., 2019), and in many cases are also being proactively addressed by industry itself (Schneider, 2019). As a promising strategy to improve the lifecycle performance of concrete in both carbon emissions and waste, the recycling of concrete has arguably never been more important.

Recycling of concrete is understood as its processing to generate material to be used in the manufacture of other products. Recycling is considered distinctly from reuse of concrete - defined as the wholesale removal and reuse of concrete components in new structures - which has its own set of distinct opportunities and barriers (Iacovidou and Purnell, 2016). Recycling of concrete plays a key role in sustainability roadmaps, both for improving sustainability of the construction sector, and reducing the impacts associated with the unprecedented exploitation of

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natural resources, such as gravel and sand, amongst other minerals (Favier et al., 2018). Aggregate extraction can pose a range of issues for different regions, depending on both geology and societal factors. In Europe, the particular geologies of The Netherlands and Austria deprive them from resources for production of crushed rock and gravel, respectively (Langer, 2016); whilst in India, growing construction demand has led to sand extraction being responsible for the most extraction-related conflicts amongst all non-fuel minerals (Bisht and Gerber, 2017). Marine extraction poses particular environmental risks – besides the direct destruction of habitat and loss of species abundance and biodiversity in the dredged area (Newell et al., 1998), sediment plumes can be released during the process which have the potential to affect environments many kilometres from the extraction site (Kaikkonen et al., 2018). Recycling concrete to provide a resource stream of recycled materials, and hence reduce the demand for primary extraction of construction minerals, is identified as a way to ameliorate these issues.

Alongside the development of concrete recycling technologies, new conceptions of the concrete lifecycle have emerged: there is a movement away from the conventional 'cradle to grave' linear lifecycle and towards a 'cradle to cradle' circular lifecycle. Thus, concrete recycling is highly relevant both to the end-of-life management of structures and the design of new structures (De Schepper, 2014). This evolution in thinking can be considered within the umbrella of the Circular Economy. The Circular Economy has emerged partly as a response to the increasing environmental (and visual) impacts of waste, and is gaining widespread traction across the world both in national policy and industrial strategy (Kylili and Fokaides, 2017; Nußholz et al., 2019). The Life Cycle Assessment (LCA) of recycled concrete is not addressed specifically in the present paper. It is a much-needed discussion that deserves a separate treatment. As short comment, it should be mentioned that LCA, as quantitative technique, highly relies on appropriate inventories (Y. Zhang et al., 2019). Local conditions and lack of primary data tend to reduce the accuracy of these assessments, and these are aspects on which significant efforts are needed. In general terms, it can be said that whilst the impacts per unit mass of waste concrete are low, the vast volumes involved cause issues around the areas required for landfill (Gálvez-Martos et al., 2018). As a result, concrete recycling is promoted alongside several other Circular Economy strategies as a way to reduce the volumes and impacts of concrete waste (Ghisellini et al., 2018).

The waste streams generated from concrete demolition are diverse in both particle size and composition. For concretes made with blended cements (with supplementary cementitious materials such as fly ash, blast furnace slag) and/or fillers (e.g. limestone), some examples of properties that influence their recyclability are the potential compatibility issues of their fines (e.g. with chemical admixtures (Tahar et al., 2020)), possible high chloride (Debieb et al., 2009), sulfate contents (Tovar-Rodriguez et al., 2013), or leaching of other compounds (Galvin et al., 2014). Another factor determining the physical nature of concrete waste (and subsequent issues) is the stage of lifecycle when it is generated. Contamination of fragmented materials is more likely than for structural elements; it entails a threat for the valorisation of concrete rubble. In order to maximise the value of recycled concrete materials and their applications, there is a need for further exploration of selective demolition, and segregation techniques after crushing. The diversity both within and between different concrete waste streams offers challenges, but also opportunities for varied valorisation pathways and product applications.

Despite extensive reviews on the subject of RCA available in the literature (Behera et al., 2014; de Brito and Saikia, 2013; Kisku et al., 2017; Li, 2008; McNeil and Kang, 2013; Nedeljkovic et al., 2021; Pellegrino and Faleschini, 2016; Pepe, 2015; Purnell and Dunster, 2010; Rao et al., 2007; Safiuddin et al., 2013; Shi et al., 2016; Silva et al., 2014; Tam et al., 2018; Tam et al., 2021; de Brito and Agrela, 2019; Xiao, 2018; Xiao et al., 2012(Pacheco-Torgal and Ding, 2013; Rao et al., 2019)), integrated approaches for full recyclability of waste concrete are still missing. Major research and practice have been conducted on recycled concrete aggregate (RCA) made from Portland-cement based concretes; as a result, many of the technical challenges have been resolved in recent years (Kisku et al., 2017; Purnell and Dunster, 2010; Silva et al., 2014). However, most of this literature is limited exclusively to technical aspects, often from a singular perspective with an isolated focus on local RCA sources or on a specific waste stream. The development of a circular economy still misses joint comprehensive analyses of the simultaneous recyclability of different waste streams, integrating universal recycling principles, technical feasibility, consideration of local conditions, economic viability, and a full LCA of the overall process. Some disconnections in the literature can also be identified (e.g. reduction of recycling ratio of waste concrete by focusing on improving quality of coarse fractions only, costly enhancement treatments, disregarding of variability of sources and others). Such disconnections are discussed in detail in the following sections.

Overall, there seems to be still a biased focus on the coarse fractions, even when these only represent about 50–60% of the crushed waste concrete. As a result, the current state-of-the-art cannot yet avoid the fact that the adoption of recycling technologies varies widely between countries, even within the European Union (Gálvez-Martos et al., 2018) (Fig. 1). Consequently, there is increasing investigation of the non-technical aspects influencing adoption which are common across Circular Economy practices in general – policy (Hartley et al., 2020; Nußholz et al., 2019), business models (Manninen et al., 2018) and cultural factors (Kirchherr et al., 2018). RCA production and use are now a well-established practice, but much progress must be made to increase recycling rates of concrete as a whole, and utilize the other waste streams and concrete types which can pose different technical challenges. This is the focus of the current paper.

The aim of this paper is to discuss the pathways for integral valorisation for all fractions produced after waste concrete processing. For this, different alternatives are evaluated, focussing on a specific waste fraction or product application. The aimed contribution to the state-of-the-art is on having a better integration between technical and non-technical aspects. A singular integrated literature review is presented, where unexplored opportunities and barriers for achieving complete utilization of waste concretes are discussed. The goal of this literature review is therefore to identify drivers and challenges for waste concrete valorisation, taking into account the evaluation of the technical issues with consideration of the wider environmental and economic factors that will shape the extent to which these opportunities will be exploited by industry. Consideration of how demographic context shapes the supply of concrete waste and demand for recycled concrete products, is also amongst the objective of the analysis.

2. Opportunities for reducing the consumption of non-renewable resources

Sources of aggregates of all size ranges are a major need in the concrete industry. Initially recycling of waste concrete has focused on producing quality coarse recycled concrete aggregate (CRCA). Now, fine fractions are becoming of major concern. The global building boom has seen the demand for sand rise threefold in the last 20 years, and sand extraction is causing ecological harm in many regions (UNEP, 2019). New emerging technologies based on recycled construction demolition waste (CDW) open the opportunity to reduce primary sand extraction, and hence prevent damage to many natural habitats. In comparison, coarse aggregates, clays (for clinker production) and limestone (for clinker production and as filler), are typically more abundant and their extraction much less damaging compared to construction quality sand. Thus, there are environmental benefits for reducing primary extraction of these resources too, from preventing habitat disruption and reducing waste volumes.

The valorisation of the finest fraction produced during crushing waste concrete is an emerging practice. Nowadays, fine recycled

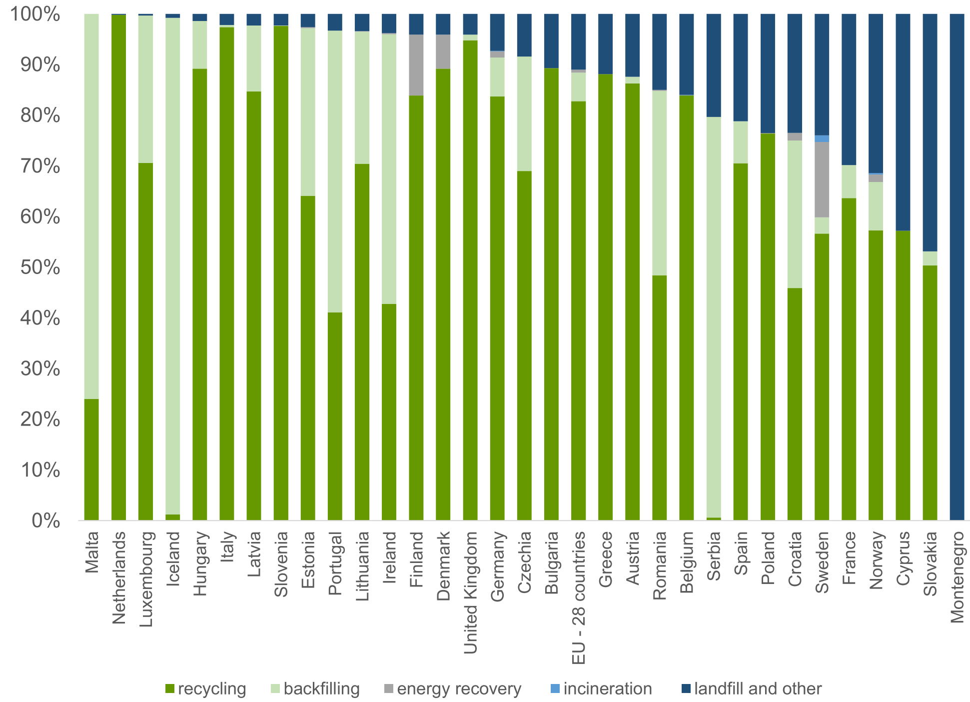

Fig. 1. Recycling rates of the mineral fraction of construction and demolition waste amongst the EU member states in 2020. (EEA, 2020).

concrete aggregate (FRCA) and recycled powder (RP) are mostly used in landfilling or downcycling. Without valorisation alternatives, the whole environmental impact of waste concrete processing is assigned to CRCA as the main recycling process product. By adding value to the fine fractions, the environmental impact of the CRCA would be indirectly decreased. About 5–10 wt.% of very fine dust and up to 50 wt.% of FRCA are generated during waste concrete processing (Fig. 2) to obtain CRCA (Chen et al., 2019). Additional fines are produced when mechanical treatments are applied to reduce the porosity of CRCA (Tam et al., 2007). The valorisation of all waste streams must be implemented not only for preventing downcycling of FRCA or RP but also for increasing the competitivity of CRCA.

Cost effectiveness is a major concern for progressing towards full recyclability of waste concrete. In many cases the costs of such processes remain confidential, and the material flow poorly documented which impedes to accurately conduct reliable quantifications beyond a specific case study. Overall, it has been identified that transport costs dominate the competition between natural aggregates and recycled aggregates

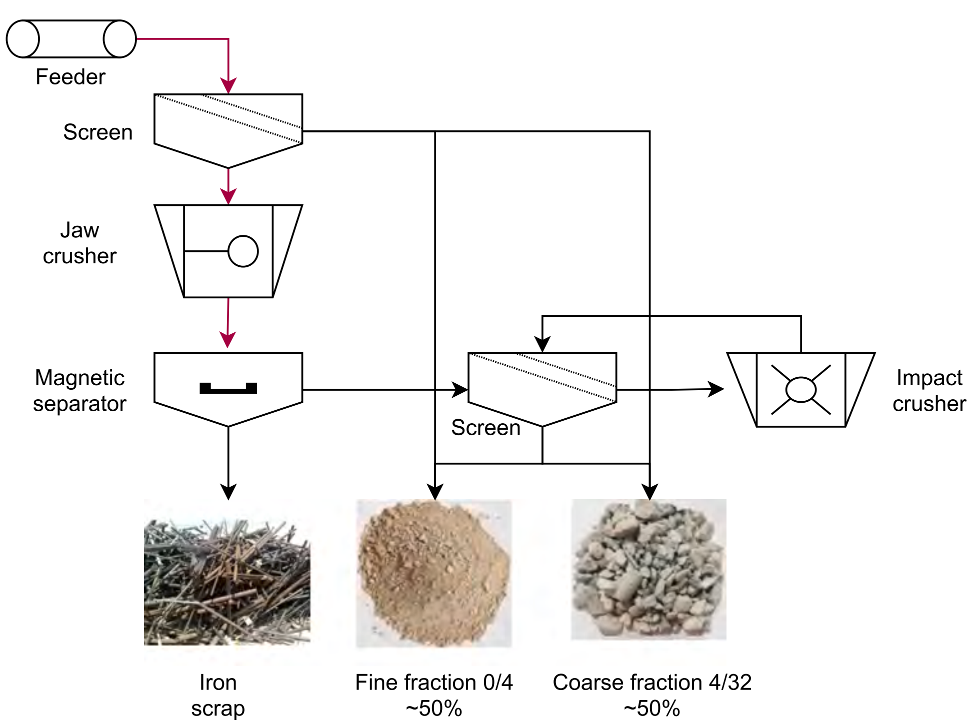

Fig. 2. Simplified flow of the concrete recycling process.

(Martinez-Lage et al., 2020). When analysing the data in Fig. 1, it is notorious that those countries with higher recycling rates and the most advanced policies for recycling of waste concrete, are also the countries with insufficient local sources of coarse or fine natural aggregates (e.g. The Netherlands, Slovenia, Italy, The United Kingdom, Bulgaria, Denmark). Cost for landfilling space and policies that introduce additional landfilling charges or taxes are also very efficient in promoting the reuse of waste concrete, but not so effective for preventing downcycling (Di Maria et al., 2018). Therefore, limitations of the valorisation of waste concrete are many times due to the lack of standard specification to encourage the implementation of recycled materials for non-structural and structural applications, rather than uncompetitive cost of recycled constituents (Tam, 2008).

In addition to technical and economic barriers, policies can also represent an obstacle in some cases. In recent years, several studies have assessed national and regional policies, including China (Aslam et al., 2020) USA (Jin and Chen, 2019), Europe (Tangtinthai et al., 2019), UK (Tangtinthai et al., 2019) amongst others. The choice of policy levers in a given country is influenced by its resources, demographics and construction industry, amongst other factors (Aslam et al., 2020).

2.1. Current potential and limitations for use of CRCA

The CRCA is the fraction for which valorisation pathways are the most resolved. The use of up to 30 wt.% CRCA is permitted in structural concrete for general applications by standards and codes in countries with advanced eco-friendly policies (CPdH, 2008; IRAM, 2016; Limbachiya et al., 2000). In 2018, mineral CDW in EU28 was 369 Mt (Eurostat, 2021) corresponding to only 12.7% of total production (and demand) of aggregate (2894 Mt (EAA, 2021)). Thus, in Europe alone, zero waste concrete could be achieved now if the produced CDW is transformed into suitable aggregates (and similarly for the fine fractions if they were utilized for concrete manufacturing at the currently permitted replacement levels).

Currently, the main interest of usage of CRCA at levels above 30 wt.% lies in associated environmental savings linked to transportation (Yazdanbakhsh et al., 2018). Broadening the application of CRCA requires ensuring and demonstrating proper performance of the concrete made with it. Deformability and transport properties of concrete are in general substantially modified as CRCA content increases (Thomas et al., 2018; Verian et al., 2018; Zega et al., 2014). The reduction in absorbent properties of CRCA would expand the range for its application (Sánchez de Juan and Gutiérrez, 2009). Beneficiation treatments (see Section 3) have shown variable degrees of success for improving the properties of RCA. The progress towards the industrial scale still requires studies on their efficiency and reliability.

The quality of CRAs is determined by the crushing process and the properties of the parent concrete (Khoury et al., 2018; Ulsen et al., 2013). The processing of waste concrete improves with further detaching of the different mineral phases. Some separation of aggregates and cement paste results from comminution that induces ruptures along the grain boundaries to release both components. The efficiency of this segregation depends on the interfacial transition zone that the natural aggregate forms with the original mortar. The primary crushing process is far from perfect for this aim. Crushers of different types such as jaw, impact, cone, or a combination of these are commonly used. Impact and cone crushers have been identified as more efficient than jaw crushers for detaching mortar from the natural aggregates (Figueiredo et al., 2018). Separating phases requires additional efforts to those of the simple reduction in size of particles. Only secondary processes can secure significant and consistent separation of aggregates from mortar fractions.

2.2. Fine recycled concrete aggregate (FRCA)

There is a significant number of publications discussing different technical aspects of processing and utilization of FRCA, for example the comprehensive technical state of the art paper by Nedeljkovic et al. (Nedeljkovic et al., 2021). In this section a general critical discussion of the utilization of FRCA, as well as opportunities and challenges for its widespread adoption is presented.

Whilst the majority of attention has been on the utilization of CRCA, FRCA also generated during the recycling process is usually downcycled in other current applications such as geotechnics (Azam and Cameron, 2013; Kawalec et al., 2017) or sent to landfill (Kaliyavaradhan et al., 2020). Regarding the environmental impact of FRCA, a reduction in the life cycle impacts compared to landfill disposal (in terms of person equivalent) of about 36% can be achieved by downcycling, and it can be increased to a 59% reduction by advanced recycling (Di Maria et al., 2018). Current policies do not encourage the use of FRCA in cementitious mixes (at least with ratios above 20–30% of the total content of the fine aggregates), mainly due to lack of consensus on its effect on the performance of mixes. There is a need to reach consensus to advance into more sustainable practices.

Despite the availability of experimental data, the use of FRCA as sand replacement in concrete production is controversial. In practice, the use of FRCA has been historically disadvised (Hansen, 1986), mostly in connection with its rough surface texture and high water absorption (Hansen, 1986; Zega and Di Maio, 2011) and concentration of weak cement paste particles and contaminants (Sosa et al., 2016). In addition, properties are usually more variable for FRCA than for CRCA (Evangelista and de Brito, 2014). There seems to be a consensus in the literature on a reduced performance in the fresh state of concrete with FRCA addition, but neither in the mechanical nor durability performance. While several studies conclude that the use of FRCA is detrimental (Cartuxo et al., 2015; Evangelista and de Brito, 2019; Puente de Andrade et al., 2020; Valencia et al., 2015), even with contents as low as 20 wt.% relative to the total fine aggregate (Evangelista and de Brito, 2010), other studies conclude that there is no significant influence, or that FRCA can even improve concrete performance in the hardened state (Kirthika and Singh, 2020; Leite et al., 2013; Yu et al., 2019). Overall, most of the studies recommend the use of FRCA only in non-structural applications.

The use of FRCA in concrete frequently leads to additional Portland cement consumption in cases where specific strength levels are targeted. In cases of alternative applications the focus is on workability, the main limitation being the water uptake from the mix and shape of the FRCA. Such effect can always be mitigated with low usage ratios (< 20 wt.% FRCA in concrete mixes (Zega and Di Maio, 2011)), but additional research is needed to neutralize the potentially detrimental effect of FRCA in concrete performance. The disregard for FRCA contrasts with the more widespread acceptance of CRCA (Zega et al., 2020). Both size fractions show similarities in connection with a higher relative porosity than respective fractions of virgin aggregate (Gonzalez-Fonteboa et al., 2018; Sosa et al., 2018). They also seem to equally depend on the features of the parent concrete (mainly compression strength and type of natural aggregate) and the processing used (Khoury et al., 2018; Ulsen et al., 2013). In contrast, the content of residual cement paste is higher in the fine fraction as its reduced hardness favors detaching as small particles. The mortar content in CRCA shows great variability (25 to 70% (Sánchez de Juan and Gutiérrez, 2009)) depending on the determination method. The range for the paste content of FRCA is likewise wide (18 to 70% (Engelsen et al., 2009; Hansen, 1986; Sosa et al., 2018; Zega, 2010)). However, the paste contents in FRCA correspond to higher equivalent mortar contents than those usually reported for CRCA. Due to its connection to porosity, the high cement paste content seems the main factor responsible for the increased detrimental influence of FRCA over CRCA on concrete performance.

Water absorption capacity (WA), as indicative of FRCA porosity, is another unresolved issue. The wide range of WA values in literature (2.4 to 19.3% (Courard et al., 2018; Delobel et al., 2016; Evangelista et al., 2015; Kou and Poon, 2009; Leite et al., 2013; Pereira et al., 2012;

Ravindrarajah and Tam, 1987; Z. Li et al., 2018; Zega and Di Maio, 2011)) is explained by higher contents of cement paste attached to the particles (Zhao et al., 2013), but some differences could be due to the specific testing method applied. The most used method for FRCA is the truncated cone method (ASTM, 2015; CEN/TC, 2013; IRAM, 2002). However, studies have shown that this method is very subjective and generally results in an underestimation of the WA (Sosa et al., 2018; Zhao et al., 2013). Moreover, variations of up to 60% have been reported when different operators carry out the determination on the same sample (Sosa et al., 2018). More than five new methods have been proposed to determine the FRCA WA, including dynamic gravimetry (Evangelista and de Brito, 2010), electrical conductivity (Sosa et al., 2018), absorbent paper (IFSTTAR, 2011), centrifugation (Z. Li et al., 2018), extrapolation from coarse fraction (Zhao et al., 2013), and others. The outcome of these different methods compared with those from the truncated cone method shows variations between 5 and 200% (Delobel et al., 2016; J. Kim et al., 2017; Le et al., 2016; Sosa et al., 2018; Yacoub et al., 2018; Zhao et al., 2013) mostly depending on the method considered (Fig. 3). This highlights the urgent need to identify suitable testing methodologies for evaluating WA of FRCA so confident concrete mix designs using these materials can be developed.

In connection with the previous, the impact of the FRCA on the effective water to cement (w/c) ratio of concrete mixes is an unresolved issue. Several studies have focused on determining the effective w/c ratio of RCA concrete (Bouarroudj et al., 2019; Maimouni et al., 2018; Velay-Lizancos et al., 2015; Z. Li et al., 2018) with dissimilar variables and methodologies. All these studies concluded that FRCA's water uptake within the mix is only a portion of the full WA determined by immersion in water. The reported ratios for FRCA range from 49 to 89%, which is far from an acceptable variation considering the potential impact of the effective w/c ratio on concrete performance.

The effect of FRCA on workability is less important for dry mixes, for which the fresh state depends less on water content. The use of 100% FRCA is feasible in roller-compacted concrete for pavements, especially as an opportunity to valorise aggregates contaminated with chloride or sulfate (Debieb et al., 2009). Such solutions add interest as transportation is reduced. The demolition of concrete pavements generates significant amounts of waste concrete with relatively homogeneous properties. The opportunity of processing and recycling the waste on-site in the new paving work requires some prevention of contamination with soil during demolition, but it can allow full recycling of the complete range of particle size in roller-compacted solutions.

2.3. Utilization of recycled powder (RP)

The limited amount of RP that can be obtained after primary comminution (about 10% in mass) may restrain extensive RP applications. Secondary RP can be produced by grinding in ball mills the FRCA resulting from the primary comminution. Given the difficulties that FRCA poses to be used in concrete production due to the reduction in concrete performance, its processing could be a convenient alternative. Differences in properties and performance may be anticipated for secondary and primary RPs on the basis of the lower paste content of the former, but this lower cement paste content might be an advantage for some applications. The main barrier for producing RP from FRCA is the energy required by the secondary processing, compared to the production of softer fillers. The rather simple situation for homogeneous materials becomes more complex for heterogeneous materials such as FRCA. Tailored production must address the relative hardness and contents of the type of natural aggregate and attached cement paste to be co-processed. Very variable efficiency can be expected depending on these features of the FRCA. A third source of RP is the particle liberation treatments to improve the properties of the CRCA, which leads to higher amounts of fines (particles < 63 μm) from the whole processing (Schoon et al., 2015). Using this detached RP is important to prevent reductions in the recycling ratio of waste concrete.

The properties of the parent concrete dominate the properties of the RP. Oksri-Nelfia et al. (Oksri-Nelfia et al., 2016) studied RP that was obtained by fully milling RCA to a maximum size of 300 μm and then sieving it to use the material under 80 μm. The ratio under 80 μm was 60 wt.% of the parent concrete and finer than the Portland cement used in the same study. In contrast, Laurente et al. (R.D. Laurente et al., 2016) applied limited grinding after trying inefficient long periods, obtaining RP with a lower specific surface area and a larger particle size

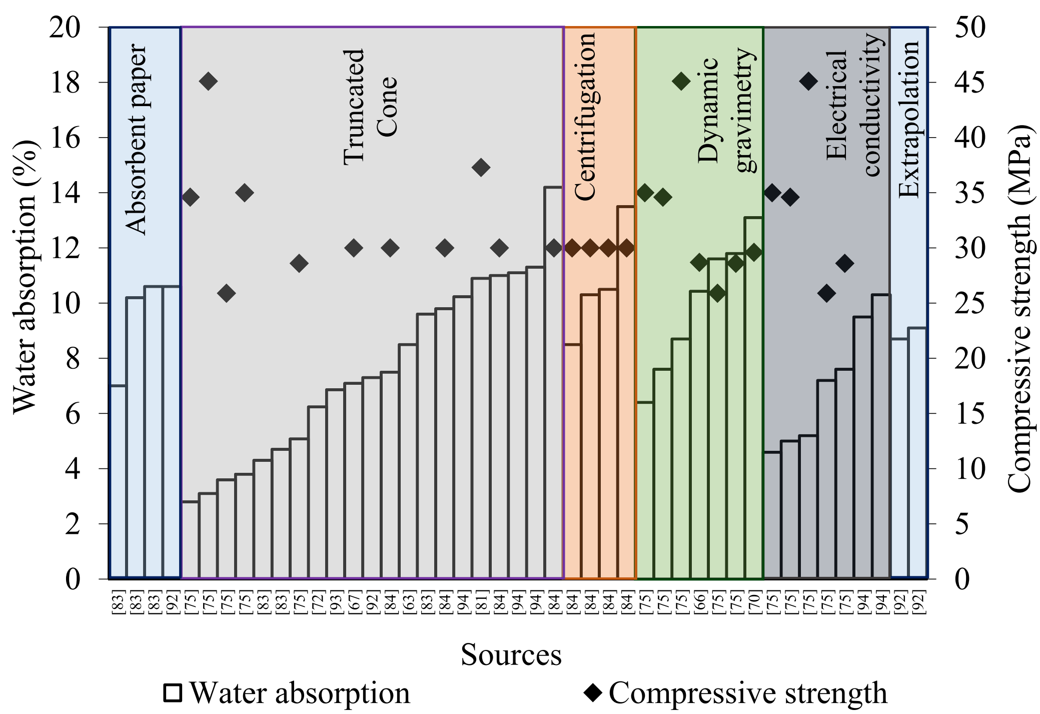

Fig. 3. Water absorption of FRA in the literature, compared to the determination method applied and the compressive strength of the parent concrete. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distribution than Portland cement. The main difference between the two studies is the hardness of aggregate in the waste concrete (limestone aggregates, and siliceous sand and crushed granite, respectively). As the hardness of natural rock increases, the adherent cement paste detaches more easily. This detached powder cushions the natural rock and reduces the efficiency of subsequent grinding. The effect of the natural aggregate hardness in the parent concrete on the cement paste content can be seen as analogous to the other RCA fractions (C. Zega et al., 2010; C.J. Zega et al., 2010).

In comparison to producing secondary RP from FRCA, the use of FRCA as a replacement for sand is less energy intensive. Depending on the geographical location and the energy source, the production of secondary RP would need to be well justified by added value to the concrete industry.

Research into the potential use of RP in new concretes and mortars has considered two opportunities as cement replacement: either as supplementary cementitious materials (SCMs), or as an inert material (filler) (Evangelista and de Brito, 2014). Regulation for both applications is generally based on performance, so this is the key point to focus on to check the suitability of these valorisation strategies. Whilst the use of RP as an SCM would have higher value as higher cement replacements can be attained, numerous studies suggest that its low reactivity makes RP suitable as a filler instead. It has been reported that anhydrous cement particles are present in the smallest fraction of FRCA which could potentially hydrate (Katz, 2003; Khatib, 2005; Khoshkenari et al., 2014). Poon et al. (Poon et al., 2006) identified belite (C_2S phase) in the finest fractions of FRCA (< 150 μm), and also Oksri-Nelfia et al. (Oksri-Nelfia et al., 2016) identified anhydrous cement in RP particles (< 80 μm), in contents below 4 wt.%. This is consistent with some cementing capacity of RP observed when using crushed concrete (Arm, 2001; Poon et al., 2006). Conversely, Sosa et al. (Sosa, 2015) observed negligible contents of anhydrous cement particles in two different RPs. Nonetheless, they still reported some slow cementation activity of RP. The suggested reaction of anhydrous cement particles present in RP can enhance the performance of concrete produced with RCA (Silva et al., 2014), but always with very small contribution to strength development. As a result of its very limited reactivity, use of RP as a filler is arguably the most pragmatic valorisation pathway.

The use of RP in the production of self-compacting concrete (SCC) offers a wide range of possibilities. For this application a very fine powder is not required as the role of the filler is supplementing the granular skeleton to improve workability, rather than as a cement replacement per se. Preliminary results (R.D. Laurente et al., 2016) show increased flow times but decreased cohesiveness of mixes when RP was used as limestone filler replacement. This was more notorious at higher replacement levels. Other studies show a consistent increase in superplasticiser demand as RP content increases (Kim, 2017; Xiao et al., 2018). This effect can be related to the higher water demand of RP due to its high porosity in connection with cement paste content (Sosa et al., 2016). In the hardened state, whereas Laurente et al. (R.D. Laurente et al., 2016) found that SCC's mechanical and transport properties are only slightly affected by the inclusion of RP as replacement of limestone filler, (Kim, 2017) indicated that SCC's mechanical and deformability performances are reduced when RP is used to partially replace Portland cement. With the replacement of Portland cement by RP, the dilution effect is the main reason for such reductions, which do not necessarily mean reduced eco-efficiency.

Another valorisation pathway as a filler is the potential use of RP in asphalt mixtures. The recycling in related industries demands minimal additional processing to the concrete waste and brings added value. For example, Chen et al. (Chen et al., 2011) found that the improved performance of asphalt mixture concerning water sensitivity and fatigue life is attributed to the greater surface roughness of RP compared to limestone filler. Besides some mechanical processing, only mild thermal treatment may be required in some cases. The reduction in landfilling and emission of greenhouse gases due to construction (Oksri-Nelfia et al., 2016) is presented as the main advantage of the use as inert filler.

Different strategies have been adopted to increase reactivity of RP, particularly the attached cement paste (Bogas et al., 2019; Carrizo, 2018; Florea and Brouwers, 2014; Letelier et al., 2017; Shui et al., 2008); for example thermal treatment between 500 °C and 900 °C which can result in the formation of new reactive phases, including glassy type phases with varying compositions depending on the type of SCM present in the parent concrete. Optimal replacement percentages of cement by thermally activated RP were found to be between 5 wt.% and 20 wt.%, which are comparable to the level of replacements achieved with conventional SCMs. Given the wide variety of concrete mix designs that can be found in demolition sites there is an urgent need to develop the scientific understanding of the existing composition-treatment-performance relationships for valorising RP as a potential cement replacement. Thermal treatments for reactivation of RP are not well justified from a sustainability perspective given the high energy demand and CO_2 emissions associated with increasing their reactivity. Nevertheless, there is great value in reducing exploitation of natural resources when RP is used as limestone replacement, and the required temperatures for the treatment of RP are much lower than those for clinker production, so it can be used as an SCM. Other advantages from the perspective of waste management (e.g. landfilling) need to be taken into consideration to determine the best solution for valorisation of RP from both economic and ecological perspectives.

2.4. Clinker production using waste concrete

Alternative feedstocks for clinker (main component of Portland cement) production are being increasingly adopted to reduce virgin clay and limestone consumption, and to decrease the CO_2 emission associated with decomposition of calcium carbonate during clinkerisation, by using alternative sources of calcium. Cement kiln dust, slags, fly ash, bottom ash, and other waste or industrial by products, have been tested and proven to improve the feedstock's burnability without significantly affecting the clinker properties (Galbenis and Tsimas, 2006). The composition of RP makes it suitable as alternative feedstock for clinker production. Fines from waste concrete typically have a CaO content between 8 and 30% (R.D. Laurente et al., 2016). The opportunity to utilize this as a resource for producing novel concretes has inspired different research approaches, such as optimisation of concrete mix design for its utilization at its end-of-life as an alternative raw material for clinker production (De Schepper et al., 2010; M. De Schepper et al., 2011). The life cycle assessment of this completely recyclable concrete showed savings of up to 7–35% of its global warming potential if all its components were used for producing normal strength concrete (De Schepper et al., 2014; M. De Schepper et al., 2011); and up to 36–60% (De Schepper et al., 2014) or 66–70% (M. De Schepper et al., 2011) if used for road construction or high strength concrete production respectively.

The carbon savings when using RP in clinker production depend on the content of residual natural aggregate in it. High CaO contents are desirable to favour larger level of replacement of limestone during clinkerisation. Reduction of 53% CO_2(eq) emissions can be reached when limestone is replaced by RP as an alternative raw material in clinker manufacturing (Kwon et al., 2015; Snellings et al., 2012). The CaO content in waste concrete increases if limestone aggregates were used in the manufacturing of the original concrete. Concerning energy savings, it seems to be advantageous if the RP is uncarbonated, since portlandite decomposes at a lower temperature than calcite. However, preventing carbonation of RP may be difficult to achieve. An improved burnability during clinkerisation is observed with addition of RP due to its cement paste content, associated with larger amounts of melt-forming phases. Galbenis and Tsimas (Galbenis and Tsimas, 2006) analysed the burnability of clinker feedstocks blended with variable contents of secondary RP. Inclusion of the RP, even at low ratios, resulted in a reduction of clinkerisation temperatures required to achieve formation of targeted phases, and also decreased the free lime content after clinkerisation. This suggests that any inclusion of RP as a clinkerisation feedstock has the potential to contribute to energy saving in the kiln.

3. Processing for maximising valorisation through emerging enhancement treatments

RCA finds limitations (not only technical but also lack of acceptance) for their application in concrete. Structural concrete resents the inclusion of a large volume of highly porous RCAs. Additional treatments can improve the properties of RCA and broaden its application. Extended liberation of particles removes attached cement paste and reduces the porosity of the aggregate. A successful application at industrial scale demands appropriate valorisation of the secondary products obtained from the removal of the attached cement paste. Aggregates are constituents with relatively low specific value, so optimised processing must always remain simple and economical.

Treatments can be grouped in two types: removal of attached mortar (i.e. liberation of particles) and improvement of RCA properties. The techniques detailed below have been applied mostly to CRCA in search of new pathways to valorisation achieved with additional liberation of particles. A few studies on FRCA are also available. It is important to note that evaluating the eco-efficiency of different concrete recycling processes is still an emerging topic (C.B. Zhang et al., 2019), and so no comprehensive comparison of each method's eco-efficiency is yet available in the literature.

The methods to remove attached mortar/cement paste are described in Table 1. Waste generation and virtual carbon of each one are variable. Moreover, additional research on eco-efficiency (e.g. LCA) of each is still pending.

The quality of the RCA can also be improved by subjecting it to densification or clogging treatments. These generate an outer layer that clogs the pores of the attached mortar in the RCA and consequently reduces its porosity. Amongst the different methodologies that have been proposed there is the biodeposition of calcium carbonate (Feng et al., 2020; Wu et al., 2020; Zhu et al., 2019) through the use of bacteria. With the aid of bacteria, this treatment immobilizes additional amounts of carbon in concrete rubble. This treatment is generally used in CRCA, but it has also shown its effectiveness for FRCA (Feng et al., 2020). The bacterial calcium carbonate precipitates on the surface and in the pores of the RCA and acts a barrier across its pore structure. A connection between the effectiveness and the pore size distribution can be established. In relative terms, the bio-deposition treatment is more

Table 1
Methods to remove attached mortar/paste in RCA.

Type	Background	Presumed specific waste generation	Presumed specific virtual carbon
Acid treatment	Procedure: RCAs are exposed to an acid solution that dissolves cement hydrates, and the quality of RCA increases with the reduction in cement paste content. Options: Varying concentrations and treatment durations have been tested using hydrochloric (H.S. Kim et al., 2017; Katkhuda and Shatarat, 2017; Tam et al., 2007), sulfuric (H.S. Kim et al., 2017; Tam et al., 2007), phosphoric (Tam et al., 2007), acetic (Al-Bayati et al., 2016), and salicylic (Zhao et al., 2013) acids. Difficulties: (a) Explicit efficiencies of each method (i.e., the relative amount of mortar or paste removed after treatment) are not reported in literature. (b) The key decision-making factors for choosing one method or another depending on the type of aggregate remain unclear. (c) Some acids present great challenges for acid waste management. (d) The eco-efficiency of these methods remains unknown.	High	High
Mechanical treatment	Procedure: The mechanical separation is achieved by the comminution of the attached mortar that is more easily segregated from the harder natural aggregate. The application focuses on CRCA, for which an improved aspect ratio can be obtained by reducing sharp edges. Options: Ball or jar milling are often utilized for this purpose (Figueiredo et al., 2018; Gjorv and Sakai, 1999), as well as use of eccentric shaft rotors (Shaban et al., 2019). Variable ball loading, durations, and rotation speed can be applied (Dimitriou et al., 2018). When no additional load is added in the process, the treatment is known as autogenous cleaning (Pepe et al., 2014). Durations between 30 min and 5 h have been recommended depending on the properties of the RCAs. In general, a low rotation speed is preferred (10–50 rpm). Abrasion comminution generates high quality CRCA with acceptable energy consumption. Difficulties: (a) Secondary waste or products are also produced during mechanical treatment. (b) The proportion of fines of the whole process is increased (Quattrone et al., 2014), and proper integration with a market for the RP produced is still necessary. Otherwise, the environmental impact of the process must be fully attributed to the improved CRCA. (c) A comprehensive approach to these beneficiation methods that simultaneously considers technical feasibility, efficiency, and the economic and environmental impacts is missing for a full definition of a competitive recycled product.	Moderate	Moderate
Thermal treatment	Procedure: When the RCA is exposed to high temperature, the tension generated due to differential expansion of the different components leads to separation of fractured mortar. Options: Temperatures between 300 °C and 600 °C, and exposure periods between 2 and 3 h have been used for this purpose (Ohemeng and Ekolu, 2020; Shaban et al., 2019). Pre-wetting of the aggregate and immersion in cold water after temperature exposure have been suggested as maximization strategies to remove larger amounts of attached mortar. Difficulties: Energy demand is an important constraint. The fuel-fed thermomechanical processes are very energy intensive, between 36 and 62 times more demanding than the conventional recycling process (Ohemeng and Ekolu, 2020; Shaban et al., 2019). Such costs make it difficult to implement them on an industrial scale without having a very valuable application for the by-product.	Low to Moderate	High
Microwave treatment	Procedure: Microwave heating induces tension at the paste-aggregate interfacial transition zone (ITZ) due to differences in porosity and electromagnetic properties of the phases. This method appears to have a high efficiency in separating the natural aggregate and the cementitious phase, even higher for CRCA than for FRCA (Akbarnezhad et al., 2011).	Low to Moderate	Low
High-performance sonic impulses	Procedure: Stresses are generated between the adhered mortar and the natural aggregate by applying sonic impulses to the RCA under water. For CRCA, a separation ratio of 70% of the attached mortar has been reported, while for FRCA this ratio is 40% (Linß and Mueller, 2004). Options: If the RCA is subjected to presaturation or the treatment is repeated cyclically, the efficiency of the method appears to increase (Katz, 2004).	Moderate	Low

efficient to treat materials with high porosity and large pores (Wang et al., 2017). Thus, the higher efficiency for finer fractions (García-González et al., 2017) is not surprising as they contain more attached cement paste. Moreover, the precipitated calcium carbonate is more compatible with cementitious materials, whereas ceramic particles show less affinity with the formation of more detachable precipitates (García-González et al., 2017). In all cases, a threshold amount of precipitated material is needed to secure notable enhancement. Weight increase due to precipitated calcium carbonate under 0.5% showed no practical impact on the properties of RCA (García-González et al., 2017). Moreover, both the quantity and the distribution of the biogenic calcium carbonate are equally important regarding the efficiency of the treatment.

The use of polymeric emulsions has also been effective in enhancing the properties of RCA. Different emulsions with different mechanisms were studied (Kou and Poon, 2010; Mandolia et al., 2020; Santos et al., 2017; Spaeth and Tegguer, 2013). Some of them cause water repellency, while others form a film on the surface of the RA which generates a clogging of its porosity. An additional effect of this treatment is a decrease of the surface roughness compared to untreated RCA. Some studies have demonstrated efficient improvement of RCA without significantly modifying concrete strength. The main advantage of such treatments is the peeling-off effect of treated aggregate that increases the aggregate recovery. In this case, it is a treatment more appropriate for natural aggregates and future recycling of conventional concrete (which would allow extensive particle liberation) rather than for RCA. Despite the promise of this treatment there are still some unresolved issues. The surface changes may reduce the compatibility of these treated aggregates with cementitious matrices. The particles show a weaker bond to the matrix, threatening strength performances (especially tensile strength) and a very weak interfacial transition zone. Furthermore, doubts on the eco-efficiency of the processing rise from the additional carbon footprint that the polymeric emulsions introduce in the final product.

A protective layer can also be achieved by applying a mineral admixture slurry. Different SCMs such as pozzolans, fly ash, silica fume, granulated blast furnace slag have been tested (Kisku et al., 2017; Sasanipour and Aslani, 2020; Shi et al., 2016; Yue et al., 2020). The improvement of RCA properties with this method is based, on the one hand, on the filling action that mineral additions have due to their great fineness and, on the other, on the pozzolanic action (Mistri et al., 2020).

Valorisation of CRCA in concrete mixes does not necessarily imply higher eco-efficiency. According to normal practice, the relative contribution of aggregates to the aggregated life cycle impacts of concrete approaches 6% (Dossche et al., 2016). This figure would vary depending on the transport distances, source and other variables, but it nonetheless gives an idea of the overall low relative environmental impact of aggregates. In reinforced concrete, this figure contrasts with the contribution of 27% from cement (also depending on the type of cement) and 29% of reinforcing steel (that can vary from one source company to the other). Thus, any incorporation of CRCA in concrete will hardly imply ecological benefits if it increases cement content in concrete to achieve the same performance. Such deduction can only derive from specific studies of LCA that consider all local conditions for the specific application.

4. Carbon capture capacity of concrete rubble

Increasing attention has been paid to quantifying and engineering the carbon capture capacity of cementitious materials. Given the scale of concrete use, a lot of carbon is at stake - an estimated 43% of the cumulative process emissions of cement manufactured between 1930 and 2013 has been reabsorbed by carbonation of cementitious materials (Xi et al., 2016). Due to the indispensable role and scale of use of concrete within buildings and infrastructure, concrete makes up an important part of carbon metabolisms, particularly in urban areas (Chen et al., 2020). Whilst the virtual carbon of concrete (i.e. the amount associated with its manufacture) is well-examined, the physical carbon of concrete (i.e. the carbon which is sequestered within it) is a frequently neglected aspect of carbon stocks and flows analysis. These arguments apply to concrete rubble as well as concrete in-service (Cao et al., 2020), with the main difference of a higher exposed surface area for concrete rubble. The importance of carbonation to the life cycle analysis of concrete is demonstrated in its inclusion in the recent rules on Environmental Product Declarations (EPD) for concrete products (CEN/TC, 2017). These rules provide guidance on calculating carbonation during both the use and end of life stages (Fig. 4), which are mandatory for a cradle-to-grave assessment (the recommended EPD scope for use on construction projects).

For most of concrete's modern history the focus has been on engineering concretes with a view to prevent or reduce carbonation. Recently, a range of drivers have stimulated growing interest in engineering concretes for fast carbonation. These twin aims (whilst being opposites) both call for a deeper understanding of concrete's carbon sequestration mechanisms and capacity in both primary use and after end-of-use. This quest is made more complicated by climate change, via a range of direct effects (i.e. changing atmospheric conditions) and indirect effects (i.e. a move to cements with lower embodied carbon with differing chemistries). New knowledge can effectively contribute to efficient prediction, accounting and engineering of these uses of waste concrete for carbon sequestration.

A range of different carbonation processes have been developed for waste concrete, which span a spectrum of process complexity and a range of carbonation achievable (Ho et al., 2021). The majority of these processes aim to produce a saleable product from the carbonation of concrete waste – for example, high purity $CaCO_3$ (Iizuka et al., 2017), or an SCM (Skocek et al., 2020). This is a logical approach, as it uses carbon capture and utilization as a way to help close resource loops. Nonetheless, there is arguably also value in exploring the use of concrete waste for carbon sequestration as a primary function (i.e. beyond those processes which can also supply a saleable product). This broadens the range of environments relevant to carbonation processes, particularly in saturated conditions. Deposits of alkaline industrial materials (e.g. ferrous slags) have been investigated with a view to enhancing the carbon sequestration rate of legacy waste sites (Mayes et al., 2018), and also promoted for restoring local environments suffering from specific problems (e.g. acidic waters) (Piatak, 2018). Emerging thinking around the use of enhanced mineral weathering for carbon sequestration is exploring how the process could be adapted for use in marine environments (Renforth and Henderson, 2017). Since the majority of concrete structures are used on land, the study of carbonation has focussed primarily on atmospheric conditions. There is therefore value in understanding how to control (and enhance) rates of carbonation of waste concrete in a range of saturated environments (Ho et al., 2021), in order to determine their wider potential for use as carbon sequestration sinks.

The ability to estimate and engineer the carbonation of concrete rubble is crucial for both recycling and sequestration options, for different reasons. Carbonation has been identified as a pathway that can potentially densify the RCAs. The precipitation of calcium carbonate in the pores contributes to clog them and reduce the connectivity of the pore structure. Artificial carbonation has effectively proven to enhance the quality of RCA (Shi et al., 2018; Zhan et al., 2019). Different concentrations of CO_2, pressure and time have been evaluated (Shi et al., 2018; Zhan et al., 2019; Zhang et al., 2015). The artificial carbonation enables a higher degree of carbonation and hence enlarged carbon capture capacity. The treatments based on carbonation improve not only the attached mortar but also the ITZ between natural aggregate and mortar (Shi et al., 2018) and they are suitable for CRCA and FRCA.

For RCA, it is then essential to be able to predict the effect of carbonation levels on the potential performance of recycled concrete. Depending on their degree of carbonation their properties might be compromised rather than enhanced. This does not function on a simple 'quality in equals quality out' basis - the initial mix design (e.g. targeted 28d strength) cannot be used as a guideline of the potential performance of the RCA. For sequestration, accurate prediction (within reason) of the carbonation extent is essential to undertake proper accounting of its contribution to carbon capture, and hence make an accurate assessment of carbon flows over the whole life cycle (Cao et al., 2020). The net benefits of carbonation must also consider the carbon cost (which is heavily dependant on fuel source) of the crushing operation itself (Dodoo et al., 2009).

Most research still focusses on carbon sequestration of concrete after end-of-use as either recycled material or landfill, rather than subsequent processing and use as a dedicated carbon sequestration sink. In some future scenarios, the latter may be a better option, such as in the case of shrinking cities where the transport distance to the nearest site with demand for RCA might result in prohibitive carbon cost. In this case, it is worth investigating how the waste can be optimally processed for carbon sequestration as a primary function (Ashraf, 2016), whilst integrating it into a natural environment. At the most basic level of processing, increasing the surface area has the potential to accelerate the carbonation rate (Xi et al., 2016). In the context of the current and future need to drastically stabilise atmospheric CO_2 levels, this could be a useful option to implement in some scenarios.

A key difference between different functions of concrete as a carbon sink is the effective surface area (Fig. 5), and the consequent effect on carbonation rate (Fig. 6). These concepts have been explored in great detail for other alkaline waste streams, namely ferrous metallurgical wastes and natural minerals (Renforth, 2019) – there is arguably value in exploring how these approaches might be applied to concrete waste. Whilst this would be considered as 'downcycling', there are likely to be situations where recycling as a carbon sequestration source yields higher overall benefits than recycling into a high value product.

The accurate determination of the most influential parameters that affect the carbon sequestration capacity of concrete is still missing. Both the carbonation depth and degree of carbonation are required to define the carbon sequestration capacity over time. Both of them are independent parameters (Andrade, 2020). Hydration products can form an external layer of carbonated material that impedes (or significantly delays) the carbonation of the underlying material. Then, carbonation depth can progress with variable carbon sequestration levels. Several parameters can affect this limitation of the carbonation degree (such as porosity, hydration degree, CO_2 concentration, relative humidity) (Galan et al., 2010). Thus, significant progress is still needed for the design of procedures that optimise carbon sequestration.

The aggregated effects of climate change include a rise in atmospheric CO_2 concentration and surface temperatures within a varying range of uncertainties. The IPCC (Intergovernmental Panel on Climate Change) have modelled different 'representative concentration pathways' (RCPs) representing different scenarios of climate action over the 21st century (Table 2) (IPCC, 2014; Moss et al., 2010). The most severe (RCP8.5) would result in >1370 ppm CO_2(eq.) by 2100 – over three times the current levels (410 ppm).

Regardless of the exact magnitude, rising trends in both atmospheric CO_2 concentration and surface temperatures will (in general) increase carbonation rates (Talukdar and Banthia, 2016). From the perspective of concrete as a carbon sink, this can boost the contribution of concrete regarding carbon capture which will therefore help to prevent catastrophic 'runaway' scenarios. However, taking into account the life cycle of concrete structures, this is not good news at all. Any gains from faster carbon sequestration will likely be more than outweighed by the reduction of structures' lifetimes (Saha and Eckelman, 2014), leading to their premature replacement and associated production impacts. Longevity – rather than simply embodied emissions alone - is increasingly recognised as an important factor in the overall life cycle impacts of concrete structures (Miller, 2020).

5. Demographic contexts affecting concrete recycling

Complementary to the material aspects previously discussed are wider societal factors. Amongst these, the literature has arguably underexplored how different demographic contexts can influence the demand for concrete and the supply of waste concrete.

In terms of macro-scale contexts, consideration has implicitly focussed on two scenarios: the 'steady state' of developed nations, and the 'rapid growth' of developing nations. Respectively, these scenarios describe a continual replacement/renewal of existing structures and small overall growth rate, and a large net growth rate. These two scenarios do broadly describe the current situations in much of the world, but they do not capture other scenarios which are highly relevant in both the present and future. Two additional scenarios will briefly be evaluated here – the first of which arguably presents more opportunities, and the second of which arguably presents more barriers (and so is considered in the following sub-section).

The first additional scenario concerns the future urban shrinkage in developed countries over the coming decades (Großmann et al., 2013),

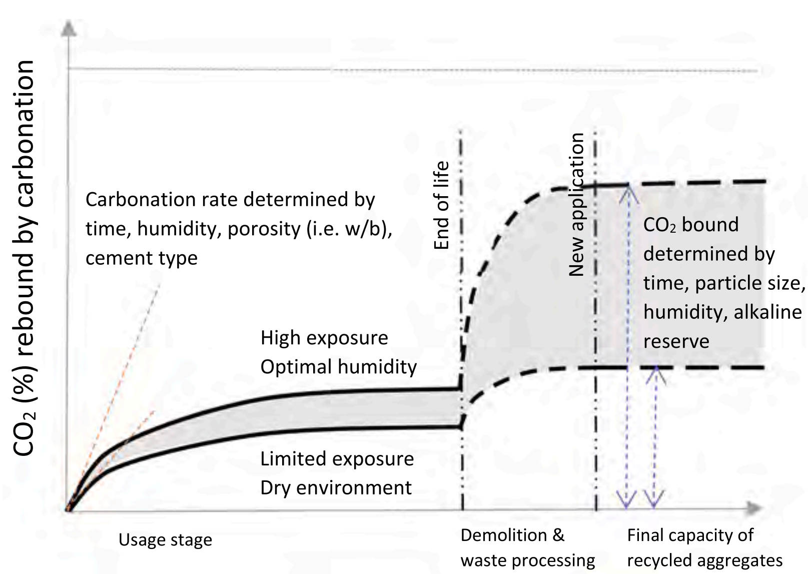

Fig. 4. A schematic representation of cumulative carbonation for variable exposure conditions and carbonation rates. Adapted from (CEN/TC, 2017).

and is speculative to some degree. Whilst the overall global population will continue to increase, several countries' populations are projected to decrease. Over the period of 2020–2050, Japan (−20.7 m), Russia (−10.1 m), Italy (−6.1 m) and even China (−36.9 m) are predicted to undergo population shrinkage (UN DESA, 2019). It is usually an unstated assumption that the demand for recycled concrete materials will far outstrip supply, and in most scenarios so far, that is correct – for example in the EU, the entire supply of CDW is estimated to only fulfil 2% of overall demand for aggregates (Gálvez-Martos et al., 2018). However, whilst this assumption may remain broadly true when considered over a national or regional scale, it is within the realms of possibility that at a local level (depending on urban governance), shrinking urban areas may produce a net supply of concrete waste that cannot be fulfilled by local demand. If the nearest viable market for the recycling of concrete waste for construction is significantly further away than an alternative source of natural or recycled aggregate (i.e. a distance greater than the critical distance, D_{cri}), then it would be disadvantageous to transport the concrete waste for reuse in construction (Fig. 7). In such cases, the purposeful use (and processing) of the concrete locally as a carbon sequestration source may be the most viable option.

The second additional scenario is that of post-disaster waste management and reconstruction. This presents several similarities and differences compared to 'peacetime' scenarios, as well as specific challenges and arguably a greater range of challenges and threats. Whilst relatively neglected as a specific scenario in the materials-based literature, it is a significant and tangibly different scenario for three main reasons. Firstly, disaster-generated waste represents a statistical 'fat tail' of waste generation – these events are rare, but the waste volumes they generate are often several times larger than the annual peacetime waste generation in the affected area (Fig. 8) (Reinhart and McCreanor, 1999). The same also applies for the quantities of material required for reconstruction.

Secondly, the exact nature of the post-disaster waste concrete depends partly on the nature of the disaster. This includes the mix of waste materials, as well as changes/additions to the waste as a result of the disaster itself (F. Zhang et al., 2019). Unlike in peacetime, the demolition or deconstruction of structures is not controlled. Therefore the waste stream consists of a broader range of materials, is more variable, and thus is of a lower quality than that typically obtained through selective demolition - for example, contamination with asbestos (Brown and Milke, 2016). Specific issues can also arise depending on the exact nature of the disaster. For tsunamis, salt inundation into materials from seawater can be an issue (Brown and Milke, 2016), and recycling treatment needs to ensure that harmful level of chlorides are not introduced into the concrete cycle. A knock-on effect of the Japan 2011 tsunami was the contamination of the concrete in the area around the Fukushima nuclear plant with radioactive isotopes of cesium (Arifi et al., 2014). A very common and general contamination source is the soil in contact with concrete structures. Although most of this soil contamination can be removed by appropriate sieving, it entails a cost and some particular clay types, even when in low quantities, can pose significant limitations for the valorisation of the waste. In the case of conflicts, the presence of unexploded ordnances is common and necessitates special care with processing waste (Brown and Milke, 2016).

'Negative selection bias' is also a factor influencing the material waste stream in disasters – buildings with lower quality concrete are more likely to be damaged or destroyed. There is a tragic pattern along the faultline of wealth – the impacts of disasters on the built environment are estimated as twenty times higher in developing countries compared to developed countries (Barakat, 2003). Much of this is attributable to poor structural design (e.g. lack of ring beams) (Ahmed, 2017), but often it is demonstrably caused by poor material quality too (Ambraseys and Bilham, 2011). In the 2010 Haiti earthquake, 220,000 people were killed and 100,000 buildings were destroyed, with a further 200,000 badly damaged. The informal housing which withstood the Haiti earthquake so poorly was typically made from concrete block masonry with a reinforced frame – however, despite the large volumes of waste, the materials themselves were very poor quality and so were typically not recycled (Ahmed, 2017). In several countries with seismic zones, it has been a common (and unlawful) practice to use poor quality aggregates, including unwashed sea sand which exacerbates corrosion (Çağatay, 2005; Doğangün, 2004). Caution needs to be exercised with using post-disaster concrete waste so that the tragedies of the past are not perpetuated, and construction with RAC (which might face increased variability) seems more difficult with reduced reliability across the construction sector.

Thirdly, the restrictions on the time-scale of processing puts severe limitations on both the time available for processing the waste and the time available for decision-making (Brown and Milke, 2016). The need to clear waste quickly puts limits on the type of processing which can be done on-site – and also the desire to rebuild quickly (Ahmed, 2017). Rapid decision-making, informed by disaster management plans, is at the heart of post-disaster management and reconstruction. In this context, environmental concerns are still of high importance – but are tempered by other practical constraints. Ways in which recycling can be maximised under these constrained conditions mark a distinction with peacetime scenarios. The recyclability of mixed waste in post-disaster scenarios is still an overlooked topic of research.

In much of the literature, construction and demolition waste is grouped together and specifics of the different waste streams are not considered. Whilst this grouping is often convenient, these different scenarios can be characterised by differences in the availability of waste concrete and the demand for new concrete for construction (Fig. 9). These four scenarios are not intended to comprehensively describe the variability found in all situations. Instead, they provide a framework

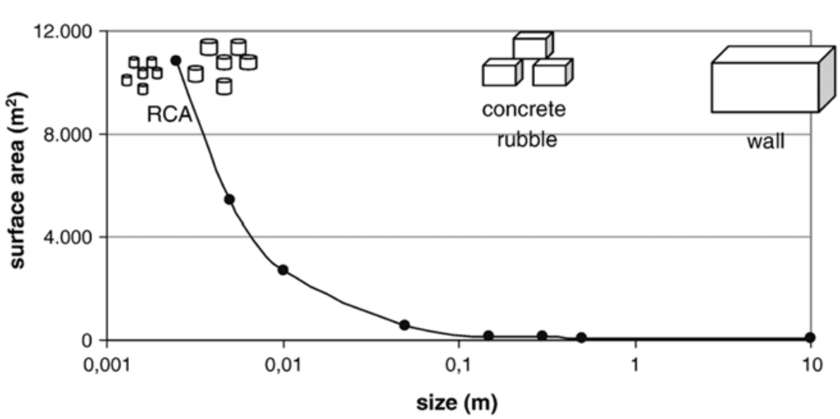

Fig. 5. The difference in surface area between concrete rubble, RCA and concrete walling. Reprinted from (Pade and Guimaraes, 2007).

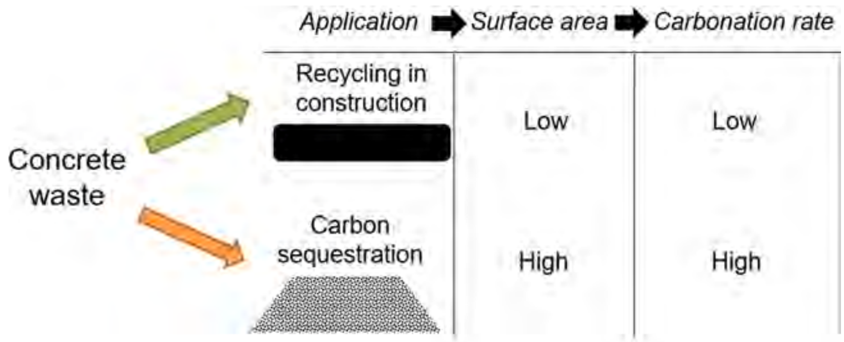

Fig. 6. One of the fundamental differences in the processing of concrete waste for recycling in construction and for potential carbon sequestration (as primary purpose) is the difference in surface area, and resulting difference in carbonation rate.

Table 2
Predictions of atmospheric CO_2(eq.) concentration and mean average surface temperature rises in 2100, for the different representative concentration pathways. Data from (IPCC, 2014; Moss et al., 2010).

Name	Pathway description	CO_2(eq.) concentration in 2100	Mean average surface temperature rise in 2100
RCP8.5	Rising	>1370 ppm	3.7 °C
RCP6.0	Stabilization without overshoot	~850 ppm	2.2 °C
RCP4.5	Stabilization without overshoot	~650 ppm	1.8 °C
RCP2.6	Peak and decline	~490 ppm	1.0 °C

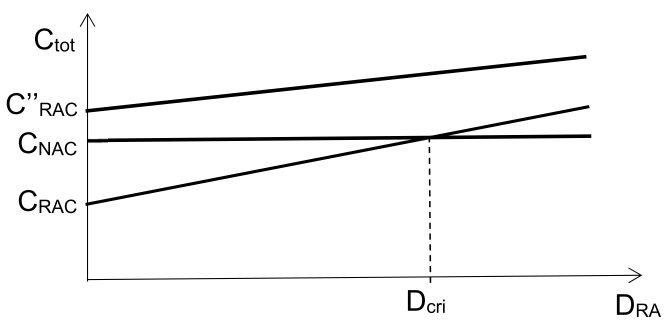

Fig. 7. At a critical distance between the site and the source of RCA (D_{cri}), the total carbon emissions of RAC (C'_{RAC} and C''_{RAC} for RAC with lower and higher emissions than NAC when transportation is not accounted for) exceeds that associated with a natural aggregates (C_{NAC}). Reprinted from (Y. Zhang et al., 2019).

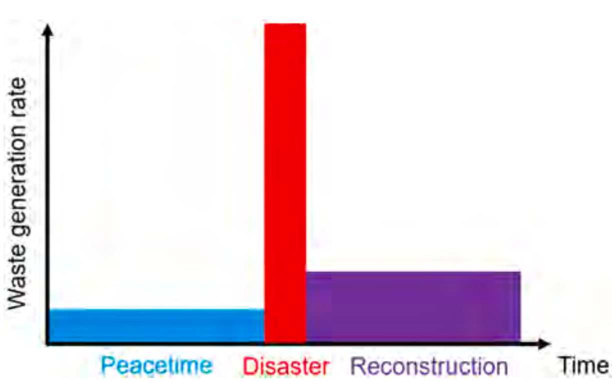

Fig. 8. A simplified schematic showing the changes in waste generation rates due to a disaster and subsequent reconstruction.

with which to discuss how the combination of material level information and situational information is required to make optimal decisions about what to do with concrete waste. The main challenge remains the conversion of the full volume of waste concrete into compliant resources for new construction.

6. General remarks and conclusions

The literature analysis of practices and knowledge gaps enabled identification of the main drivers and challenges for waste concrete valorisation. Overall, full valorisation of waste concrete has proven to be technically feasible. Some additional efforts are necessary, mainly on determining eco-efficiency through Life Cycle Assessment of the use of fine fractions and advanced treatments, as well as improving commercialization channels and reducing variability of recycled products. Local conditions have a significant impact on reaching high recycling ratios, from a technical, economical and policy point of view. Environmental implications, in addition to increased circularity, are essential in the eco-efficiency equation, mainly including potential carbon capture capacities and the impact on societal development.

6.1. Drivers for waste concrete valorisation

The use of recycled cementitious materials as feedstocks for new construction contributes to the development of a Circular Economy through closing resource loops. Most of the recycling technologies for concrete have proven to be technically feasible. The commercial viability requires more development, especially concerning waste concrete management and selective demolition to improve the quality of the recycled products. While the previous statement is valid for standard scenarios, special cases remain less explored. Scenarios of disasters or the shrinkage of cities entail different conditions in terms of the quality of concrete rubble and the management urgency for such volume of waste. Management in these situations must facilitate fast valorisation alternatives for the debris.

The extent to which existing concrete recycling practices are adopted has been encouraged by an increasing societal pressure and government sustainability agendas, including landfill taxes on demolition waste. Despite this, levels of recycling are still highly variable between regions, and so it is vital to address the factors affecting recycling practices in different construction and demographic contexts. The complete re-utilization strongly relies on proper consideration of local conditions. Recycling of waste concrete has been more favoured in regions where natural aggregates are scarce. The high environmental costs or long transport distances of competing natural resources make recycled cementitious materials more appealing in these areas. In other cases, the low specific market value of aggregates remains as the main barrier for the recycling of concrete, and processing that adds value must be further explored.

6.2. Challenges valorising all particle fractions

High-value applications are not possible without strategic research on advanced processing of waste concrete. Concrete recycling is a well-established industry in many countries, albeit limited to the simple crushing of waste concrete and using only the coarse fraction as aggregate. The fine fractions generally remain undervalued, meaning an obstacle for full re-utilization and commercialisation of waste concrete. Low recovery rates also affect the competitiveness and eco-efficiency of CRCA. The processing of waste concrete should find simultaneous valorisation opportunities for each of the three produced fractions of particle sizes: CRCA, FRCA and RP. The outstanding challenges and research needs are summarised as follows:

- A significant number of strategies have been explored to maximise recyclability of all waste concrete fractions, and to counteract the limitations in concrete performance observed when > 30 wt.% CRCA is used. Most of these treatments consist of eliminating the attached mortar to enhance the properties of the granular material and the segregation of phases, but they produce larger volumes of recycled fines in consequence. An alternative is the densification of the attached mortar. Little information on the eco-efficiency of these procedures is available, therefore determination of energy consumption, economic cost and generation of new wastes during the treatment (particularly wastewater and dust contaminants) are vital issues on which more research is needed.
- The use of FRCA in new concrete mixes remains as an unsolved issue. The multiplicity of testing methodologies to determine water absorption capacity tremendously affects concrete mix designs and leads to contrasting results. The conventional methods to determine water absorption of sand are unsuitable for FRCA. Different approaches lead to variable performance of concretes containing FRCA. Some of the detrimental effects reported in the literature could be linked with an unintentional increase in the effective water-to-cement ratio by overcompensation of mixing water. Thus, there is an urgent need to identify suitable standard testing methodologies that provide realistic results of water absorption of FRCAs and its actual impact on concrete mixes.
- The RP is arguably the least explored fraction. Applications as feedstocks for production of clinker, SCMs, or filler have been proven feasible to different degrees. In some cases, it might be possible to reduce the number of fractions to two by milling FRCA to RP. The implementation of these technologies as part of the waste concrete management requires additional efforts to solve the issues related with the variability of properties. To tackle variability in properties, the use of RP in low quantities is a straightforward answer that dilutes any alteration in the performance. However, the modest use of RP brings the problem of making the management competitive and reasonable. In principle, the use of RP as an inert filler seems the most direct and easy to implement. The advantages of using RP instead of limestone powder also remain largely unclear regarding the associated environmental impact. Life cycle assessment could help resolve such uncertainties. The compatibility with superplasticisers is an unresolved aspect. An increased superplasticizer demand may restrict solutions of this type.

6.3. Environmental considerations

In terms of eco-efficiency, additional benefits are frequently disregarded for the assessment of the recycling of waste concrete. The carbon capture capacity of cementitious materials can partly compensate for the embodied carbon of these recycled products. Given the importance of carbon emissions over the lifecycle of buildings and infrastructure, it is crucial to consider the extent of carbonation in concrete wastes for two key reasons: its contribution to climate change mitigation, and its effect on the properties of the recycled materials. It is also vital to consider how both of these may be affected in the event of a changed climate over the next 30–80 years. The efficiency of carbonation treatments in densification of RCAs is highly dependant on the CO_2 concentration used for the treatment; natural carbonation has been shown to have limited ability to improve the properties of RCAs. The more effective treatments are at artificial high CO_2 concentrations, which require additional investment of resources and energy, and association with highly emitting industries. It is then needed to conduct studies that address all aspects of such treatment for RCAs. In this sense, the added value seems to be in the carbon capture technology rather than in densification of RCAs.

Overall, great progress in utilization of waste concrete has been made in recent decades but there remain many open questions for their widespread use in the years to come. Concrete is a highly diverse material in many aspects, including composition, service environment, functional requirements, and applications. Global strategies must adapt to local boundaries to secure appropriate eco-efficiency. The range of emerging technologies to enhance recyclability of concrete provides great opportunities, but a universal challenge will be to implement these in a way that best meets the needs of the construction sector and wider community in a given area. The hope is that such a diverse range of options for recycling will provide the best chance of maximizing sustainable outcomes for the variety of waste concretes in different locations.

The reduction in the consumption of non-renewable resources for producing new concrete leads in many cases to an increased carbon footprint. Raising the recycling ratio of waste concrete seems mostly technically possible. However, integral strategies should be adopted to balance all the indicators of environmental impact. A focus limited to a single size fraction of recycled aggregate, or to the improvement of its performance as concrete constituent, may (unintentionally) frustrate efforts to achieve complete eco-efficient solutions. Integral research must also cover associated processes and secondary wastes of concrete recycling.

6.4. Policy and standardisation needs

The analysis of concrete CDW recycling policy is a subject area in its

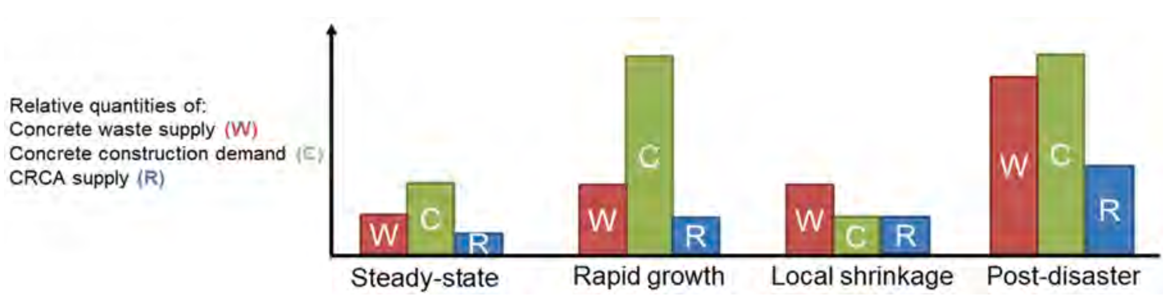

Fig. 9. A simplified schematic illustrating the relative amounts of concrete waste supply (W) and construction demand (C) for concrete for four different scenarios. The relative quantity of CRCA supply (R) is based on an estimated production ratio of 50% from waste concrete.

own right. For this article, a brief concluding comment can be made regarding specific issues for the novel concrete fractions considered here. From a waste management perspective, a multi-dimensional approach is needed to determine the existing regulations associated with waste concrete disposal (e.g. landfilling restriction and/or taxation) to identify strategies to incentivise its use by the construction sector. It is anticipated that in some regions the disposal of waste concrete might not be regulated, which calls for the creation of such regulations to enable their potential valorisation. The policy regulating the construction materials sector, and standardisation of such products need to enable full recycling of waste concrete considering the distinction of each fraction, and its intended application. Regarding FRCA, an advance into progressive standards (beyond 20–30% total fine aggregate content) for the valorisation of FRCA is limited by a lack of consensus in the literature. Development of new testing methods is required that is appropriate for this material. These are knowledge barriers which need to be resolved through further research, before standards and guidelines can be reappraised. Regarding RP, the appraisal of SCMs and fillers is generally based on performance and compliance with existing standards followed by the construction sector, so environmental regulations themselves do not provide a significant limitation to adoption. Nonetheless, given the often rapidly-evolving nature of both the scientific evidence base and national sustainability policies, close cooperation between all relevant parties will be required to minimize any time lags between commercial production of novel recycled concrete fractions and their safe commercial use.

CRediT authorship contribution statement

Yury A. Villagrán-Zaccardi: Conceptualization, Investigation, Writing – original draft, Funding acquisition. **Alastair T.M. Marsh:** Investigation, Writing – original draft. **María E. Sosa:** Investigation, Writing – review & editing. **Claudio J. Zega:** Investigation, Writing – review & editing, Funding acquisition. **Nele De Belie:** Investigation, Writing – review & editing, Supervision, Funding acquisition. **Susan A. Bernal:** Conceptualization, Investigation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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

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