Chapter 4
The Circular Construction Industry

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Abstract This chapter defines circular construction, and how the construction industry should prepare and make interventions to promote the transition from a linear model to circular and sustainable ways of designing, constructing, maintaining and dealing with waste. Circular construction is an emerging business strategy that promotes the reuse and recycling of as many raw materials as possible in a bid to minimise CO_2 emissions and waste to landfill. The chapter focuses on construction and demolition waste (CDW) and how potential new technologies developed for other applications can be utilised to bring circularity to CDW management. CDW alarming impacts have caused increased public concerns. Aiming to boost resource exploitation efficiency, circular construction should improve CDW waste management practices. However, transition and implementation of circular construction practices are slowed down by technical, social and legislative barriers. Circular construction, as an important component of sustainability, is a new business model that promotes the maximum reuse and recycling of raw materials and products to reduce waste and CO_2 emissions. Reduce, reuse, recycle and recover are essential interventions for a circular construction, with a systemic shift in the culture and mindsets of stakeholders.

Keywords Circular construction · Circular economy · Demolition waste · Recycling · Recovery · HS2

1 Introduction

The construction industry is responsible for more than 30% of natural recourses extraction, as well as 25% of solid waste generated worldwide due to its linear

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economic model of "take, make, dispose" (Benachio et al., 2020). The built environment accounts for 39% of global energy-related CO_2 emissions (Orr et al., 2019). As a result of recent progress in reducing operational energy and implementing stringent standards for near-zero energy buildings, embodied energy is one of the most critical features of whole-life energy consumption in buildings. Adopting a circular construction model and utilising raw materials efficiently are a crucial step in reducing emissions. Buildings use structural material inefficiently, while generating nearly 50% of waste (Orr et al., 2019). This could be due to individual misconceptions among engineers or cultural phenomena in which engineers unquestioningly repeat previous techniques without examining their sustainability.

Worldwide policies indicate a recognition on rapid actions which are required to mitigate resource depletion, greenhouse gas emissions and climate change in the construction industry. These actions should be focused on implementing a circular economy approach, where construction materials are used in a sustainably (Ghaffar et al., 2020). Circular economy in Europe may generate a net benefit of EUR 1.8 trillion by 2030, while also solving rising resource-related concerns, creating jobs, fostering innovation and providing significant environmental advantages (Kirchherr et al., 2018).

The demand for using eco-friendly resources, coupled with advances in digital technologies and waste materials valorisation, is leading to unprecedented opportunities in the construction industry. With an eco-design concept, the construction industry must bring environmental aspects into consideration through eco-efficient design (minimising negative impacts) and eco-effective design (maximising positive effects, including profit). Waste has always been and continues to be a major issue for the construction industry. In 2019, the UK, approved legislation aimed at reducing its contribution to global warming by 2050. The G7 followed suit in June 2021, pledging to lay up a plan to achieve net-zero greenhouse gas emissions by 2050.

2 Principles of Circular Economy Concept

Circular economy (CE), a regenerative system, in which growth is gradually decoupled from the consumption of finite resources, offers a response to global challenges. EC is an economic system based on business models that substitute the paradigm of "end-of-life" with "reduce, reuse, recycle and recover" resources in production, distribution and consumption processes. The circular economy is founded on three principles: (1) waste and pollution should be designed out: today's products should be transformed into tomorrow's resources and the negative effects of economic activity on human health and environmental resources should be eliminated (e.g. the use of hazardous and toxic compounds, greenhouse gas emissions, air, land and water pollution). (2) The materials and products should be kept in use: prioritising operations that increase product utilisation and reuse to preserve the embedded energy, labour and materials. (3) Natural systems should be restored: adopting practises that not only avoids natural resources degradation but also enhances their availability over time. CE models are supported by concepts such as reverse logistics, cradle-to-cradle design, eco-efficiency and the hierarchy for waste management—reduce, reuse, recycle and recover (Ogunmakinde et al., 2021). CE enables economic growth without increasing resources' consumption and is a concept that implies the redesign of industrial systems, and deep transformations on production chains and consumption habits. Thus, CE strategies are clearly aligned with the United Nations Sustainable Development Goals.

Several countries, including the UK, China, Japan and all members of the European Union, have embraced CE concepts into their policies and legislation (Smol et al., 2017). However, the implementation of CE in different industrial sectors has followed diverse approaches, and the lack of common strategies and instruments has limited the desired widespread of CE (Singh & Sung, 2021). CE models are supported by concepts such as reverse logistics, cradle-to-cradle design, eco-efficiency and the hierarchy for waste management—reduce, reuse, recycle and recover (Ogunmakinde et al., 2021). Several countries, including the UK, China, Japan and all members of the European Union, have embraced CE concepts into their policies and legislation (Smol et al., 2017). However, the implementation of CE in different industrial sectors has followed diverse approaches, and the lack of common strategies and instruments has limited the desired widespread of CE (Singh & Sung, 2021).

At present, there are no available measurements or indications that can be employed to verify that a structure is circular. It is challenging to establish the magnitude at which circular transformation occurs in the construction industry without a robust mechanism to benchmark and monitor circularity efforts and interventions. Material lifespan, urban mining and circular design are examples of indicators that should be developed with specific user and data needs in mind. Analysing industrial design standards and tools is imperative in order to investigate the possibilities of establishing adapted or new indicators for monitoring circularity throughout the chain value. The Ellen MacArthur Foundation defines four important parameters for achieving a circular economy: (1) circular business models, (2) circular design, (3) reverse logistics and (4) enablers and favourable conditions (i.e. public policy). Without addressing circular business models and new engineering processing it will be impossible for the built environment to fully move towards a circular economy. Therefore, it is critical that commercial leaders from all tiers of the supply chain work towards new business models.

The goal of the circular construction industry is to promote sustainable development for present and future generations through economic success, environmental quality and social equality (Kirchherr et al., 2017). Despite the fact that CE has grown in relevance among policymakers, academics and entrepreneurs, the conceptual correlation between sustainability and CE remains unclear. This may have a negative impact on scientific advancement in terms of sustainability and the spread of CE-based practices. The CE and sustainability both need the integration of non-economic characteristics into development that requires the cooperation of different stakeholders where business model innovations are key for transformation of industry (Geissdoerfer et al., 2017). It is important to note that technological innovations are crucial for further developments of CE and sustainability but often pose implementation problems. On the other hand, differences between sustainability and the CE are in their respective main motivation; i.e. for the CE concept the goal is better use of resources, valorisation of waste (from linear to circular), whereas the sustainability concept is a balanced integration of economic, social and environmental performance (Geissdoerfer et al., 2017). Moreover, the responsibilities are shared, although not clearly defined in the concept of sustainability, while for the case of CE the responsibility of implementation lies with the private business and regulators/policymakers. Most of the research efforts focus on the environmental performance improvements of the CE rather than taking a holistic view on all three dimensions of sustainability.

The principles of circular construction could be summarised in the following major and generic categories:

(1) Constructing and developing in harmony with nature, considering the climate emergency;
(2) Using waste as a resource where construction materials and products should flow in a closed loop;
(3) Resilience through diversity where infrastructure development with multi-components are more resilient;
(4) Use energy from renewable resources such as solar, wind, hydro and tidal power;
(5) System approach and system implementation is key, e.g. considering multi-factors, multi-actors and multi-stakeholders.

Circular construction, in line with sustainable development, is a guiding principle for expansion and growth based on environmental quality, economic prosperity and social equity, which should be achieved without jeopardising future generations' potential. When it comes to circular construction, the focus on economic prosperity is predominantly noticeable among practising engineers while environmental aims are most important for the academics, without investigating the economic feasibilities of their lab-scale developed solutions. The circular construction can improve the competitiveness of stakeholders by protecting businesses against shortage of resources and unstable prices, and this will then create innovative business opportunities and efficient methods of production and consumption (Kirchherr et al., 2017). To achieve circular construction, two of the main bottlenecks are: (1) changing the mindset of industry stakeholders towards cleaner production of raw materials, (e.g. promoting secondary raw materials recovery from different waste streams), (2) overcoming the technical issues, where there could be a low market acceptance (e.g. prices, legal barriers and regulations) for recycled construction materials and products (Ghaffar et al., 2020).

3 Innovative Technologies for Circular Construction

Innovative technologies are the real game-changers for delivering circular construction, which promotes reactive decision-making, i.e. what happened in the past; and being proactive, i.e. what can be done better.

Digital networks, intelligent robotics, digital image analysis, robotics for waste separation, sensor-based infrastructures for waste collection, geographic information systems, global positioning systems to assist waste disposal and data sharing to support product lifecycle analysis are all examples of innovative technologies used to bring the circular construction vision to life (Kabirifar et al., 2020; Sarc et al., 2019). For example, smart interconnected assets can provide predictive maintenance to extend the life of the asset, blockchain can reduce waste by creating traceability and transparency in the supply chain and 3D printing makes the repairs of spare parts easier. As a new emerging technology, artificial intelligence (AI) has the potential to support and accelerate human innovation in product design, bring together elements of successful circular business models and optimise the infrastructure required to loop materials and products back into the economy. AI capabilities could assist in constructing an effective economic system that is regenerative by design, resulting in a step-change that goes beyond incremental efficiency increases. Design innovation is required in the circular economy to keep materials, products and components at their highest utility and value at all times, recognising the distinction between technical and biological cycles. ZenRobotics is an example of industry enterprises contributing to circular construction, they were one of the first companies to use AI and robots in a demanding waste processing environment. To extract recyclables from waste, the company uses combined AI and robotics technologies. ZenRobotics's technology enables increased waste sorting flexibility, which leads to enhancing the efficiency of secondary material recovery and purity. Cameras and sensors coupled with AI technology were employed to monitor the Waste. ZenBrain, an AI software, examines sensor data to produce a precise real-time analysis of the waste stream. The heavy-duty robots make autonomous decisions on which pieces to remove based on this analysis, which leads to a rapid and precise separation of waste and it enhances the secondary raw materials recovery efficiency.

The potential value unlocked by AI in helping design out waste for food will be up to USD 127 billion a year in 2030. This is achieved by opportunities in farming, processing, logistics and consumption phases (Artificial Intelligence and the Circular Economy, 2013). Using image recognition to detect when fruits are ready to pick, better matching food supply and demand, and increasing the value of food by-products are some of the specific applications. This is an example from different sectors to the construction; however fundamental similarities between the prospects imply that AI's potential to generate value in a circular construction is huge. Integrating the capabilities of AI in the construction sector creates a substantial and unexplored possibility to support efforts to fundamentally transform the construction industry into a resilient, regenerative and long-term solution for combating the global challenges.

To encourage applications that cover and go beyond the domains of circular design and circular business models, it is vital to raise awareness and understanding of how AI and other innovative technologies may be utilised to support the transition towards circular construction. AI could be used to redesign entire networks and systems in any industry, such as reorganising supply chains and enhancing global reverse logistics infrastructure (Chiaroni et al., 2021).

Recent advances in AI-based data analysis techniques, especially in smart sorting systems, provide a solution for automated on-site classification methods. On-site sorting has many advantages and developing mobile machines and plants that can operate on-site is one of the innovative developments that have potential in contributing to circular construction. Since on-site operations require less workforce and resources than sorting at recycling facilities, it can also improve the reusability and recyclability of CDW and therefore contributes to production of high-quality products (Bao & Lu, 2020). Wang et al. proposed simultaneous localisation and mapping (SLAM) technology and the instance segmentation method, which enable the robot to deal with complex site environments, resulting in enhanced on-site CDW sorting accuracy (Wang et al., 2020). Blue Phoenix Group, established in 2008 in the Netherlands, provides a patented solution called Advanced Dry Recovery (ADR) method, for recovering and upgrading fine non-ferrous metals from municipal waste-to-energy ash. In the ADR method, the wet mineral fraction is separated from the coarser ash fraction comprising the precious small metal particles. This fraction can then be separated from the mineral aggregates using conventional eddy current separators to extract non-ferrous metals. The ash fraction less than 12 mm includes the most valuable percentage of non-ferrous metals (Advanced Dry Recovery (ADR), 2008). The heating air and classification system (HAS) works in conjunction with the ADR system. The HAS technology uses a combination of ADR's air knife (1–4 mm) and rotor (0–1 mm) products as its input material. HAS is developed to expose the fine fraction aggregates to hot gas in order to dry them out and remove unwanted small CDW impurities, such as plastic shards and wood. The procedure consists of a particle–gas interaction in a fluidised-type reactor, wherein the air is employed to convey the heat while classifying fine aggregates depending on their particle size. Heating is used to dry the material and activate the ultrafine particles, mostly comprised of hydrated cement.

Figure 1 illustrates our developed concept diagram for an integrated innovative solution which could deliver circular construction. It starts with smart dismantling as opposed to complete demolition, where the chances of recovery of secondary raw materials and reuse of components are higher. Combining new technologies with advanced sensors and robotic sorting, recycling systems offer a unique upcycling approach that can be utilised for a selection of input materials whilst consistently maintaining the ability to produce high-quality outputs, i.e. circular products. Pre-demolition audits and mobile on-site operations can be critical to the success of circular construction, while remanufacturing process aligned with modern methods of construction, such as prefabrication and 3D printing can assist with the circular product developments (Chougan et al., 2021; Ghaffar & Mullett, 2018). Issues around

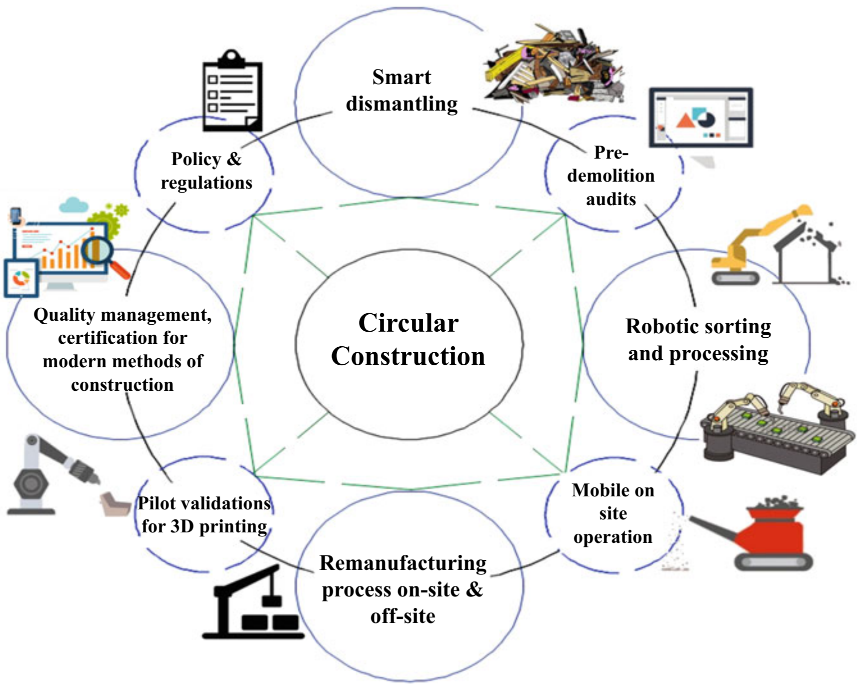

Fig. 1 Circular construction concept (author's original)

quality management and certifications require policymakers, scientists and practitioners to come together and make responsive policies and regulations that allow and enforce circularity within the construction industry.

More specifically, practitioners in the industry must be inspired and encouraged to be passionate about changing the mindsets of stakeholders and the public and showcase the potential of new paradigms. This can be driven by a combination of: (1) creative design, (2) focused academic research and applied technology, (3) external industry engagement and (4) flexible, responsive regulation.

4 Construction and Demolition Waste Management

CDW consists of bulky and heavy materials, such as concrete, wood, asphalt, gypsum, metals, bricks, glass, plastics, soil and rocks. Approximately, 333 million tons of CDW (except for soils) were generated in the EU in 2014, consisting of 300 million tonnes of inert waste, 30 million tons of non-inert waste and 3 million tons of toxic waste (Eurostat, 2018). Nearly 11 billion tons/ year of solid waste are produced globally, implying that each individual produces over a ton on average, and this amount is increasing. In 2025, waste generation is expected to double compared to 2000 (Tons

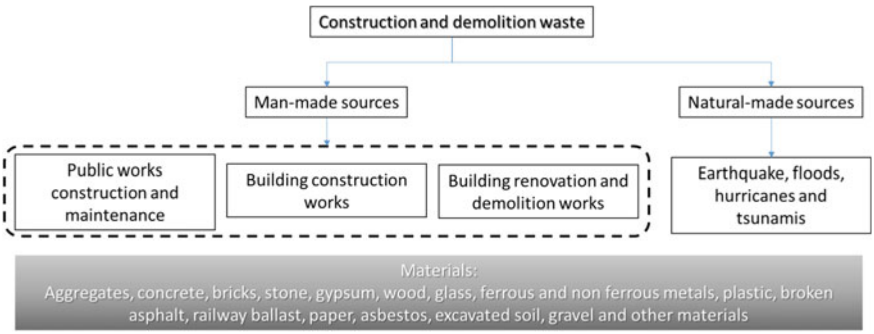

Fig. 2 CDW generic classification based on the source of origin (Menegaki & Damigos, 2018)

of Solid Waste Generated, 2020). Furthermore, by 2050, solid waste generation is predicted to be approximately twice comparing to 2016. CDW, municipal solid waste (MSW) and commercial and industrial waste are three major forms of solid waste (Global Waste Generation, 2018).

The sources of CDW origin are depicted in Fig. 2.

In 2018, China had the largest CDW production (i.e. around 2360 million tonnes). Ma et al. visited 10 different recycling plants and interviewed 25 industry practitioners in China and to produce a list of the challenges in the Chinese CDW management: (1) no tracking and accurate estimation of the CDW (where it comes from, how much is generated, and where it will be used), (2) insufficient waste minimisation design, (3) unregulated landfill practices with high cost, lack of financial or political support and (4) lack of cooperation from the government for the CDW management (Ma et al., 2020).

The USA (i.e. around 600 million tonnes) followed by India (i.e. around 530 million tonnes in 2016) are known as the second and third largest CDW producers in the world after China (Wang et al., 2021). Governments, researchers and businesses have all made efforts to mitigate CDW's negative environmental and economic effects by recycling and reusing it.

The CDW recycling is mainly hindered by, not only, technical and economic aspects, but also political and social aspects. The technical aspects are the lack of background information of CDW (e.g. the origin and amount of CDW) (Ma et al., 2020; Yuan, 2017), the constraints of the project and construction site (Zezhou et al., 2019), the lack of support from off-site recycling (Bao et al., 2020) and the lack of advanced technologies in recycling processes (Chi et al., 2020). The economic aspects include the lack of interaction and coordination in the CDW recycling and supply chain (e.g. nonexistence of platform for trading and information sharing of recycled products) (Aslam et al., 2020) and immaturity of recycling market (Chi et al., 2020; Ma et al., 2020). The absence of audit and oversight from authorities as well as insufficient recycling incentives are amongst the political factors (Chi et al., 2020; Ma et al., 2020). The social aspects, on the other hand, include insufficient

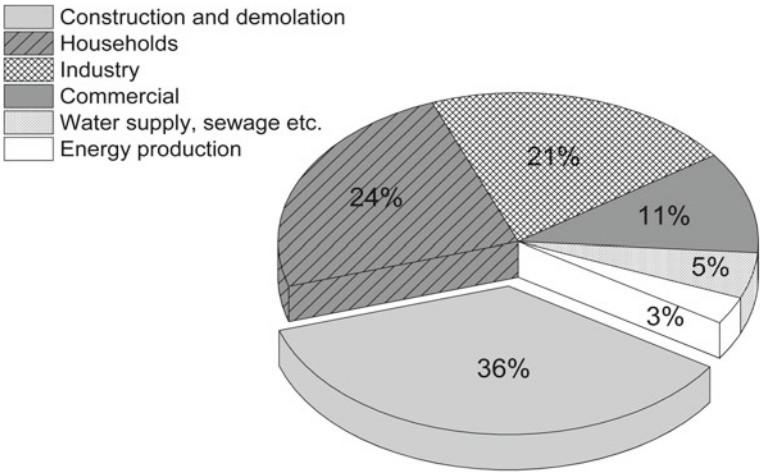

Fig. 3 Categorised sources of global solid waste generation (2020) (Ferdous et al., 2021)

awareness and acceptance of the products from recycled materials by public (Chi et al., 2020).

Figure 3 shows the various classifications for the global generation of solid waste, where CDW is shown to be responsible for the majority of solid waste generation, which will be disposed of in landfills.

Taking into consideration waste disposal facilities, policies and regulations, the amount of CDW created and the corresponding management procedures vary from country to country. For instance, Singapore recycles 99% of CDW each year, whereas China recycles only 5% of the total 2.36 billion tonnes of CDW generated (Lv et al., 2021). Europe also successfully recovered around 90% CDW of the total 870 million tonnes annually (Bonoli et al., 2021). According to the Environmental Protection Agency of the US, 600 million tonnes of CDW were generated in 2018, with 24% ending up in landfills (EPA, 2020).

Circular economy models and 4R framework of reduce, reuse, recycle and recover present as a major gateway to solving the issues with CDW management. Practical, feasibility and technical challenges in CDW management must be addressed and resolved to facilitate the transitioning to a circular construction in practice (Ranta et al., 2018). Reuse of CDW refers to the practice of repurposing building materials, either for the same or a different application. This necessitates efficient CDW collection and sorting techniques, which may be difficult to implement. Recycling of CDW, on the other hand, requires waste collection and sorting technologies, where the high cost of procedures reduces the economic advantage of recycled materials over original materials. Moreover, effective recycling of CDW requires the existence of an organised market for secondary materials to uptake recycled waste. Despite the extensively documented environmental advantages of reuse and recycling of CDW, linear-based processes are still the dominant rule in the construction industry (Ogunmakinde et al., 2021). Nevertheless, based on the principles of circular construction, CDW practices of reduction, reuse, recycling and recovery of secondary raw materials could have positive impacts on the amount of disposed waste, while preserving the natural resources used in the construction industry.

Apart from imposing stringent legislations and fiscal policies, using incentives and tax breaks is crucial for reducing construction waste. These incentives and tax breaks could be funded by penalties and fines for poor sustainable practices, which can be an effective way of achieving sustainable practices in the construction industry. Unlike government that is mainly concerned about environmental aspects of waste minimisation, the contractors are more influenced by financial benefits of waste minimisation (Ajayi & Oyedele, 2017).

Despite the understanding that design stage is decisive in construction waste minimisation, most strategies target construction stage where preventive measures are already late. Well-known, sustainable design appraisal systems such as Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) have not yet considered options for designing out waste, despite covering various design practices for environmental sustainability.

A study conducted by Mahpour (2018) evaluated the environmental impact of on-site sorting, off-site sorting and direct disposal of construction waste. They discovered that the trend towards off-site sorting and direct landfilling was an obstacle to severe environmental problems, but on-site sorting resulted in net environmental advantages. Moreover, they realise that, compared to the existing cradle-to-grave model, construction participants are hesitant to undertake on-site sorting due to space and financial constraints, tight timetables, and more labour and administrative efforts (Mahpour, 2018).

An implementation strategy that incorporates circularity and constructability could help to build on apparent achievements such as the UK Statistics on Waste report (2019), where the overall recovery rate from non-hazardous CDW is reported to be 90%, which is 20% more than the objective of the EC Waste Framework Directive by 2020. However, overall statistics may not be as impressive as they appear; according to the same report, the UK construction industry accounts for more than 60% (130MT/year) of all waste generated in the country. Furthermore, between 2010 and 2016, the rate of CDW generation increased gradually, with no notable increase in recovery rates.

CDW minimisation is the waste management strategy with the lowest negative environmental impact; hence, it should be given top priority in waste management practices. CDW minimisation is highly reliant on resource efficiency measures created during the design stage. Prefabricated modules, for instance, can reduce CDW by 80%, and there are additional solutions, such as building information modelling (BIM) and lean construction, that could have a significant influence on waste reduction (Kabirifar et al., 2020). Approximately one-third of construction waste is resulted from design decisions (Yuan et al., 2011). However, design for waste minimisation has not received sufficient attention, potential due to the lack of training and awareness of industry practitioners, or their lack of interest to environment protection or the absence of regulations on waste reduction (Ma et al., 2020).

There are various barriers to moving to circular construction in terms of CDW management. Some of the more significant ones are listed below:

1. Ineffective CDW dismantling, sorting, transporting and recovering processes.
2. Preferring off-site CDW sorting and landfilling over on-site sorting due to lack of incentives.
3. Inadequate policies and legal frameworks to manage CDW.
4. User preference for new construction materials over reused/recycled ones.
5. Lack of clearly defined national goals, targets and visions to move towards circular economy in CDW management.
6. Inadequate awareness and understanding about circular economy and its potential for the construction industry.
7. Lack of funding to implement circular economy in CDW management, where there is a tendency to manage cost and time rather than CDW.

4.1 Construction and Demolition Waste Valorisation

Recent investigations have proven that employing CDW recycled aggregates (RAs) as a replacement of natural aggregates (NAs) in new construction applications as recycled aggregate concrete (RAC) showed both economic and environmental benefits. According to estimates, utilising RAs instead of NAs in concrete construction saves 10–20% of material costs (Zheng et al., 2017). Moreover, a study conducted on the life cycle assessment of RA and its environmental effect showed that its use in concrete can lead to a reduction of 58% in non-renewable energy consumption and 65% of greenhouse gas emissions compared to use of NA (Hossain et al., 2016). Nevertheless, the mechanical properties of RAC are inferior to the corresponding natural aggregate concrete (NAC), which limits RAC's applications for structural concrete (Wang et al., 2021). In addition to the reduced mechanical performance of the RAC, the process for recycled aggregates production has also limited its widespread utilisation. In the past 20 years, the number of publications on RAC has exponentially increased (Gao et al., 2020; Ismail & Ramli, 2013; Mukharjee & Barai, 2014). A review by Wang et al., (2021) comprehensively investigated RAC and recycled aggregates in terms of their background, recycling, reuse and manufacturing processes, intrinsic defects (e.g., the presence of additional interfacial transition zones (see Fig. 4)) and material characteristics (Wang et al., 2021). They offered techniques aiming to improve the mechanical and long-term performance of RAC based on (i) porosity refinement of recycled aggregates, (ii) old mortar layer reduction on the surface of recycled aggregate and (iii) improving performance without any modifications on recycled aggregate such as the incorporation of reinforcing fibres.

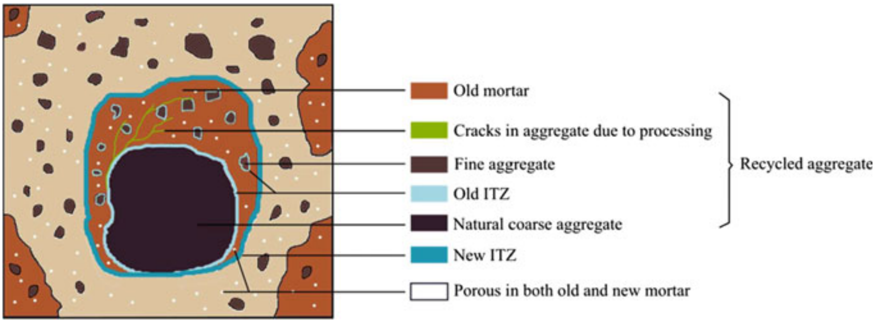

Fig. 4 Schematic of recycled aggregate in recycled aggregate concrete (Wang et al., 2021)

Crushing concrete waste, screening and removing contaminants such as steel reinforcements and plastics are common methods for producing recycled concrete aggregate (Devi et al., 2020). Recycled aggregate accounts for approximately 8% of aggregate use in Europe, with substantial differences between countries. The greatest users are the UK, the Netherlands, Belgium, Switzerland and Germany (Aslani et al., 2018).

The incorporation of recycled coarse aggregate, with the size of 4 mm and higher, in new concrete, has been proven to have compressive strengths that are comparable to natural aggregates, and in some conditions, even higher (Lotfi et al., 2014; Malešev et al., 2010). As a result, suggestions for the use of coarse recycled aggregate in concrete can be found in the European concrete standards, EN 206:2013, annex E and EN 13,369:2012 (Müller et al., 2015).

In general, recycled aggregates include three constituents: original aggregate, adherent mortar (AM) and an interfacial transition zone (ITZ) between AM and original aggregate (Juan & Gutiérrez, 2009). The quality and quantity of AM determine the final performance of recycled aggregates. Considering the concrete source, strength grade (the porosity of the original paste), crushing procedure, particle size distribution and test parameters, the quantity of AM in recycled aggregate concrete can range from 25 to 70%. Moreover, the quality of AM is influenced by the cement strength grade (Liu et al., 2011) and the original aggregate characteristics. Recycled aggregate has a rough morphology with a poor physical and mechanical performance which is attributed to the presence of AM. However, numerous pre-treatments have been carried out to enhance the low quality of recycled aggregate (Shaban et al., 2019). The application of appropriate pre-treatment techniques can yield significant technical benefits at a low cost. Most recycled aggregate pre-treatment approaches have either targeted on eliminating or enhancing the AM. Several standard procedures, including microwave removal, mechanical grinding, thermal processing and pre-soaking in acid, have been employed for an effective removal of AM (Shi et al., 2016). In addition, other techniques such as pozzolanic slurry immersion, polymer impregnation, bio-deposition and accelerated carbonation curing have also been proposed to strengthen the AM by enhancing the weak areas of the RA caused

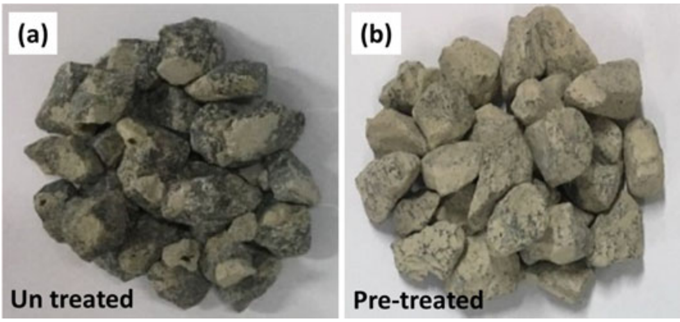

Fig. 5 RCA and pre-treated RCA coated by sulphoaluminate cement (**a** and **b**) (Zhang et al., 2018)

by filling capacity and/or chemical reactions (see Fig. 5) (Shi et al., 2016). For instance, Zhang et al., (2018) suggested that the sulphoaluminate cement surface-treatment improves RA quality (Fig. 5a, b), leading to improved apparent density and reduced crushing value and water penetration. The RAC's mechanical performance and the aggressive materials resistance (i.e. chloride and sulphate) were consequently improved (Zhang et al., 2018). In addition, polymer coating using Sika Tite-BE polymer (Fig. 5c, d) revealed a promising effect on the quality enhancement of RA particles.

While concrete recycling is a well-studied topic, brick waste recycling has been primarily employed as a replacement for natural aggregate. The use of waste bricks (WB) in the form of (i) recycled aggregate, (ii) partial cement replacement and (iii) alkaline activation for precast block manufacturing has all been explored and proven as viable recycling scenarios for waste bricks on small laboratory scale (Fořt & Černý, 2020).

The use of WB as a natural aggregate replacement is the most common scenario in the EU, owing to its simplicity and minimum of additional material processing and treatment requirements. Processed WB is commonly utilised in road construction, which needs large quantities of natural aggregates with low specifications. WB aggregates have also been utilised to make lightweight concrete with a bulk density of less than 1800 kg/m^3 (Zhao et al., 2018). Improved thermal and acoustic insulation were among such material benefits, apart from a lower environmental impact. WBs with a high amount of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and a relatively smaller proportion of CaO have a suitable chemical composition that makes them ideal to be used as supplementary cementitious materials if their grain size distribution is fine enough (Afshinnia & Poursaee, 2015). Given the large quantity of crystalline phase, the pozzolanic reaction of brick powder was found to be less intense than that of conventional supplementary cementitious materials such as metakaolin or ground granulated blast furnace slag (GGBS). However, a good grinding process can enhance the specific surface area and, as a result, improve the pozzolanic activity (Komnitsas et al., 2015). Based on the investigation conducted by Vejmelková et al., (2012), 20% of the cement could be successfully replaced without causing significant material performance deterioration (Vejmelková et al., 2012). WB powder was proven to be suitable for partially replacing cement in lime–cement mortars, resulting in substantial enhancements in compressive and flexural strength (Kočí et al., 2016). Brick waste fine particles (fine fractions with D50 ~50 μm) can also be utilised as a binder material for alkaline activation employing a variety of alkaline solutions such as sodium hydroxide or sodium silicate. This method has the advantage of completely replacing Portland cement, making the use of WB powder more effective than when only partial cement replacement is used (Fořt & Černý, 2020).

5 Circular Construction Practices in the Industry

This section highlights examples and real cases of circular practices and strategies adopted in the Skanska, Costain and STRABAG Joint Venture (SCSJV) sites. SCSJV is working in delivering 26.4 km of High-Speed 2 (HS2) railways, known as the London Tunnels. HS2 is a 140 miles high-speed railway line to serve around 30 million people from London to West Midlands, Manchester, Glasgow, Liverpool, Preston and Wigan. It is assumed to be operational between 2029 and 2033. There are over 200 HS2 construction sites working on delivering variety of structures such as 150 bridges, 110 embankments, over 50 viaducts, 4 stations and over 70 cuttings, making it currently the biggest railway project in UK and Europe. Therefore, it is likely that the construction of the HS2 railway will generate significant amount of construction and demolition waste (CDW) and around 130 million tonnes of excavated earth. Due to its size, complexity and importance, the HS2 project could be a great example of implementing circularity in practice, and therefore, some of its case studies have been chosen to be covered in this chapter.

The government had introduced the High-Speed Rail (London -West midlands) Act 2017 and the Environmental Minimum Requirements (EMRs) documents supported by a series of papers to cover the high-level environmental and sustainability commitments, including (1) Annex 1: Code of Construction Practice; (2) Annex 2: Planning Memorandum; (3) Annex 3: Heritage Memorandum; (4) Annex 4: Environmental Memorandum; (5) Register of Undertakings and Assurances. These documents set out the expected approaches and outcomes when handling excavated materials and waste that arises from the construction of HS2. An estimated value of 130 million tonnes of soil needs to be excavated to enable the HS2 railway line construction. However, over 95% of the excavated soil will be reused, recycled or recovered and the unsuitable materials will be classified as waste and sent to landfill. Therefore, the waste producers, i.e. construction contractors, are obligated under the law to apply the appropriate waste hierarchy method in relation to reducing the waste and applying circular construction waste management methods.

SCSJV is one of the JVs working in delivering the final 26.4 km of the HS2 route from Northolt to Euston via Old Oak Common Station, including 21 km of twin bore tunnels for the construction of which SCS will be running seven tunnel boring machines (TBMs).

This part covers how the SCSJV are implementing circular economy practices on site. Below are a detailed list of interventions towards circularity and reduction of waste.

- **Area West—West Ruislip Portal (WRP): Reusing temporary works concrete**

West Ruislip Portal used approximately 4800 tonnes of concrete for piling platform and pile breakdown as part of their temporary works which means, the concrete will be removed once the work is completed. Therefore, in order to minimise the construction waste and reduce material transportation, it was decided to crush the concrete as 6F5 (which is an unbound, coarse recycled aggregate) and reuse it for other purposes. This led to 26tCO2e carbon emissions savings from transportation, and there was no additional need to order 6F5 for the other works on the West Ruislip Portal.

- **Area West—Northern Sustainable Placement Area (NSPA): Reused excavated materials from Copthall**

Copthall Green Tunnel is a 550 m of cut and cover tunnel, and it is one of the areas that will generate significant volume of excavated materials, approximately 852,000 m^3 of soils which had to be reused in line with the environmental and sustainability commitments of the project. In order to successfully manage the potential impacts of waste and materials, it was decided that the arising soils will be used as an embankment fill for a road embankment, approximately 80,000 m^3 which will later be landscaped with trees and shrubbery, for the construction of NSPA, approximately 140,000 m^3. Another 140,000 m^3 of the arising soils will be used on the spot to cover the Copthall tunnel walls and cover slabs, as a required layer on top of the concrete box structure.

To comply with the High-Speed Rail (London-West Midlands) Act 2017, an area was created approximately 3 km away from the actual working area where the inert waste would be placed and conically mounded for up to 18 m. Excavated materials that will be stored in the NSPA are mainly London clay, and once completed it will be used to enhance the local ecosystem by providing a rich diversity of woodland and a variety of types of grassland habitats. The habitats created will consist of broadleaved woodlands, wet woodlands, wood pasture, parkland, scrubland, scattered trees, seasonal and permanent ponds. Northern sustainable placement area will also be used as a natural flood management method to control the rainwater and reduces the risks of flood and support water filtration through proposed wet woodlands in the low-lying areas. The NSPA is an effective way of reducing the transportation of the large volumes of the arising soils and materials on public roads. The materials from Copthall Tunnel will be transported to the NSPA using conveyors to save over 21.8t of CO_2e from HGV movements between the sites and blocking narrow roads within the area. This will also help to save over 21.8 tonnes of CO_2.

- **SCS logistics Hub—Willesden: transporting materials by trains to facilitate the construction of residential buildings**

In September 2021, SCS launched its first logistics hub in Willesden, which is used to transport approximately 5.6 million tonnes of inert excavated materials. To be able to transport these materials, it has been estimated that around 34,000 sets of lorry movements would have been required to carry out this operation. Instead, the SCS team will utilise 4,150 wagon trains with 20 T capacity to transport the materials to Barrington in Cambridgeshire, Cliffe in Kent and Rugby in Warwickshire. The materials will be reused for redevelopments of residential buildings. This will not only help to minimise the landfill waste, but it also cuts lorry movements on the road, thus reducing the carbon emissions by 40%.

- **Transformation of London clay into construction resources**

A feasibility study to explore the possibility of producing useful construction resources from excavated material is being led by SCS. The project named Re-purposed Excavated Arising Loop (REAL) (Papakosta et al., 2020) aims to assess the potential to transform excavated London clay spoil into calcined clay for use as Supplementary Cementitious Material (SCM) in concrete; and expanded clay for use as Lightweight Aggregate (LWA). Successful implementation and uptake of this circular economy approach could result in minimised waste streams to landfill, improved resource efficiency and reduction of imported materials. However, there is a wide range of literature on the suitability of several clays for use in concrete, there is little information specifically for London Clay as a potential SCM.

London Clay could also be utilised as expanded clay pellets serving as lightweight aggregate for different uses such as infill, insulation or in low-grade lightweight concrete. While several clays are used worldwide to produce expanded lightweight aggregate, there is only one documented study to manufacture clay aggregate using London Clay as part of Crossrail project (Boarder & Owens, 2014), where excavated London Clay was converted into expanded clay aggregates in the laboratory and used in concrete. The study indicated that the resulting aggregates led to low compressive strengths concretes, which suggests that while the expanded London Clay aggregate may not be suitable for structural concrete, non-structural applications could be considered, such as mass concrete fills and concrete blinding.

- **Carbon savings**

As well as minimising waste to reduce the environmental impact, SCSJV has also been implementing and changing the traditional construction methods to contribute to carbon savings. Some of these are listed in Table 1.

Table 1 Interventions for carbon savings across SCS sites

What	Benefits/Savings
Replacement of plant and vehicles to low impact hybrid machines including use of renewably-powered equipment	Solar pod station that can be used to charge radios and handheld tools. 20% fuel saving per annum compared with diesel counterparts (i.e. for hybrid dozer and excavator). The hybrid excavator is saving over £9000 in fuel costs per year. The dozer has an electrical drive system which offers up to 25% more fuel efficiency translating to a saving of about 4.5 L of fuel per hour. Approximately 22,000 kg of CO^2 saved from one solar pod charging station in 4 months (roughly £5000 fuel costs savings)
Cement replacement in concrete works	The concrete mix was prepared by replacing the cement content with 70% of GGBS (Ground Granulated Blast Furnace Slag) in capping beam and slab. This led to a saving of around 157 T of carbon emissions
Carbon savings by cutting road movements	As for the Earthworks tasks, there are high volume of materials importing and waste materials removal, approximately (25,000 T materials import) and (34,000 T of muck away); therefore, to reduce the lorry movements on roads and cut down on carbon emissions, SCS agreed with the contractor to implement a single holistic approach, which means, the same lorry that offloads the materials, takes the waste materials, reducing the carbon by 1240 trips
Low carbon piling mat	The concrete piling mat chosen is an environmentally friendly mix which uses GGBS and fly ash. Additionally, a 6F5 layer was installed underneath the concrete slab to avoid the use of mesh. This led to 79% of carbon savings as opposed to the traditional method

6 Conclusions and Prospective

In the shift to net-zero carbon, circular principles play a critical role in meeting carbon emission targets. Embracing circular strategies in the construction industry will prove pivotal in driving financial and environmental opportunity to design out waste, enhance asset productivity and achieve sustainable development goals. In order to fulfil all the possible economic opportunities, the circular economy approach should be considered not only as a sustainability consideration but also as a business factor. In the construction industry, circular economy pillars such cradle to cradle, regenerative design, eco-efficiency, eco-effectiveness, reverse logistics and zero emissions can enhance closing material loop by reuse and recycling. Closing the loop implies that no material is left hanging in the cycle. Material reuse as is key methodology for closing the loop. Similarly, recycling of products or their component parts could ensure their continuous use over time. This would enhance material recovery and maximise the product value. Most construction materials (e.g. steel, concrete, aluminium and wood) can be recycled at the end of their useful lives suggesting that recycling is important in closing the material loop. Repair and refurbishment of materials can also be considered in ensuring closed loop. Broken materials or structures can be repaired while old materials can be restored. Furthermore, it is critical not to restrict circularity to the reuse and recycling of construction materials but rather to keep the wide scope of circular concepts in mind. For instance, there is a critical need to address life cycle impacts across various factors, which would necessitate dynamic impact models that account for technology advancement and innovation. Prefabrication of materials or component parts can be a strong approach in closing material loop in the construction industry. With prefabrication, building components are produced of-site and are assembled on site. This allows for appropriate inventory of materials and waste materials emanating from the production process can be returned into the system thereby ensuring no material leftovers. Therefore, it is important that materials or products are designed for ease of conversion, reuse and recycling. This would reduce the amount of waste that is sent to landfill. The implication is for construction professionals to incorporate into their design the circular economy pillars identified to enhance closing material loop in their design and to ensure that durable materials are specified for construction projects.

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