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Circular Economy strategies for concrete: implementation and integration

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A R T I C L E I N F O

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A B S T R A C T

Concrete is the world's most widely-used anthropogenic material, and Circular Economy strategies will be key to addressing the myriad challenges that face its use today and into the future. Despite a rapid growth of research interest in developing Circular Economy strategies for concrete, this has mostly focussed on technical and environmental issues at the material and product scale. Holistic approaches considering wider social and political aspects as well as system-scale perspectives have been relatively neglected. This article uses a narrative review to investigate three outstanding questions to help address this gap: how concrete's material, product and system-scale attributes influence the interpretation of Circular Economy principles; how the full range of Circular Economy strategies can be implemented for concrete; and what the likely implementation issues will be when integrating different Circular Economy strategies (such as design for durability, component reuse and material recycling). From a product-scale perspective, it is argued that greater specificity is needed around the growing diversity of concrete materials and products in Circular Economy discourse - their properties are often distinct and hence specific strategies are not necessarily universally applicable. At the same time, a solely product-centric Circular Economy perspective is insufficient for concrete, and only joint consideration of structural and systemic perspectives will yield satisfactory solutions. 'Soft' perspectives of social, political and legal aspects cannot be viewed simply as an added bonus, but are essential to reconciling the 'hard' issues of technical, environmental and economic aspects that dominate discussions. Whilst concrete can and should have a key role in a Circular Economy, its success will require more than just extensions of linear economy thinking.

1. Introduction

Concrete is the world's most-used anthropogenic material with annual production estimated to be > 20 GT/year (Miller et al., 2016) and rising. At the same time, its sustainability credentials are under serious scrutiny. The sustainability drivers for concrete are mostly focussed on the urgent need to decarbonise the cement industry (Schneider, 2019), as >70% of the greenhouse gas (GHG) emissions from concrete production are attributed to cement production (Miller et al., 2016). Reductions of at least 24% compared to current levels of direct GHG emissions from the cement industry are required by 2050 in order to have a >50% likelihood of staying below 2 °C global average temperature rise (relative to pre-industrial levels) (IEA, 2016), as set out in the Paris Agreement. Many believe that much more stringent reductions are necessary and instead aim to achieve net zero GHG emissions by 2050 (Cembureau, 2020b; Global Cement and Concrete Association, 2020), drawing on a broader array of technologies to achieve this. Alongside consideration of climate change, there is a strong interest in reducing waste along the concrete life cycle, and a small yet growing focus on its wider societal benefits and impacts around the Sustainable Development Goals (SDGs) (United Nations, 2015). The principles of a Circular Economy - and the strategies which they have informed - are well-placed to address the aims of a broader interpretation of sustainable development beyond carbon and waste (Schöggl et al., 2020). There is also a growing argument that Circular Economy principles can be in synergy with decarbonisation efforts in the cement and concrete industries, whilst also presenting economically advantageous opportunities (Ellen Macarthur Foundation, 2019; Favier et al., 2018).

The dominance of decarbonisation in sustainability considerations is reflected in the policy landscape around cement and concrete. There are a growing number of decarbonisation roadmaps (Habert et al., 2020;

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Scrivener et al., 2018b; IEA, 2016; Lehne and Preston, 2018; Favier et al., 2018), including those developed by the industries themselves (Cembureau, 2020b; Global Cement and Concrete Association, 2020), complemented by the emergence of standards such as PAS 2080:2016 "Carbon management in infrastructure" (BSI, 2016). By comparison, Circular Economy plans have emerged that specifically target these industries, but arguably in less detail and with less influence than their decarbonisation counterparts. Within the European region, the European Union's Circular Economy Action Plan (European Commission, 2020) is accompanied by a specific masterplan for energy-intensive industries, including cement (European Commission, 2019). Standards are also emerging – British Standard BS 8001:2017 presents a "Framework for implementing the principles of the Circular Economy in organizations" (BSI, 2017), albeit not specific to the cement and concrete industries. The response from industry to state-led moves towards a Circular Economy has been broadly welcoming - the European Cement Association's response to the EU Circular Economy Action Plan Roadmap (Cembureau, 2020a) supports several Circular Economy innovations along the concrete lifecycle. The Mineral Products Association's (the industry body representing cement producers in the UK) report to the UK government (Mineral Products Association, 2019) states the industry's capability to support a Circular Economy.

The development of the aforementioned policies and position papers demonstrates the growing recognition in both government and industry that Circular Economy is a philosophy through which to address broader sustainability issues in society, including in the cement and concrete industries. However, the implementation of a Circular Economy philosophy is limited by an understanding of how to apply these principles across the concrete life cycle, and the socio-economic systems it is embedded within. Whilst a significant amount of literature exists that is relevant to Circular Economy strategies for concrete, the majority of this research has a detailed albeit narrow focus – on technical, environmental and economic aspects of a few key strategies (e.g. recycling). This is consistent with the Circular Economy research field as a whole, in which social dimensions have broadly been neglected in comparison to techno-economic aspects (Moreau et al., 2017; Clube and Tennant, 2020). In between the perspectives for change focused on the whole industry, such as roadmaps and action plans, and detailed perspectives on specific material and product scale issues, there is a knowledge and thinking gap around the middle ground where perspectives are joined up (Pomponi and Moncaster, 2017) – addressing how technological and other strategies can be implemented and integrated in practice. A recent perspective from Miller et al. (2021) evaluated Circular Economy strategies for the cement industry primarily from a decarbonisation viewpoint, and highlighted some examples of co-benefits and unintended consequences from adoption of strategies. It was also flagged that more investigation is needed around the topic of implementation and integration, if transitions are also to be socially, economically and politically viable (Miller et al., 2021). This review article makes an original contribution to the evidence base by addressing three sequential topics, which are important yet relatively neglected:

1. How concrete's material-level, product-level and system-level attributes affect the interpretation of Circular Economy principles
2. How the full range of Circular Economy strategies can be applied to concrete, beyond the most widely promoted strategies of low-carbon binders and concrete recycling
3. How complexities may arise from integrating different Circular Economy strategies over the concrete life-cycle. Structural-level and systems-level perspectives are used to identify synergies and trade-offs which are not visible from a solely product-level perspective

A brief justification of terminology and definitions will be given first (Section 2.1), along with a description of the approach used for this study (Section 2.2). Section 3 describes factors at the material-scale, product-scale and system-scale which affect the application of Circular Economy strategies to concrete. Section 4 reviews the application of Circular Economy principles (reduction of material through specification and design; long-lasting design; maintenance, repair and refurbishing; reuse and remanufacturing; recycling) into strategies for concrete, with discussion included within each sub-section. Section 5 explores the issues around implementation and integration of different Circular Economy strategies for concrete, arranged into sub-sections exploring political, economic, social, technical, environmental and legal aspects. Finally, Section 6 gives concluding remarks and a summary of research needs.

2. Key definitions and approach

Given the range of Circular Economy interpretations (Kirchherr et al., 2017, Mcdowall et al., 2017), the model used in this article will be described and justified, and definitions given for other key terms. Following this, a description of the approach used for the rest of this article is given.

2.1. Key definitions

Circular Economy is used here to refer to an inclusive model of embedding the production-consumption system within the biosphere, not separate to it (Fig. 1) (Velenturf et al., 2019b). Whilst many different interpretations or definitions are used in theory and practice (Kirchherr et al., 2017), this model is considered the most appropriate to apply to cement and concrete (Marsh et al., 2021). The industrial by-products commonly used to produce concrete (e.g. metallurgical slags), as well as concrete itself, interact with the biosphere in different ways – for example, through carbonation and weathering processes. In addition, the sheer mass of concrete stocks in buildings and infrastructure – estimated to be ~0.4 Tt (Elhacham et al., 2020) – means that concrete now exists on a comparable scale to biomass stocks. Therefore, it is logical to consider concrete (and related input and output materials) alongside stocks and flows of natural materials within the system boundaries of the biophysical environment.

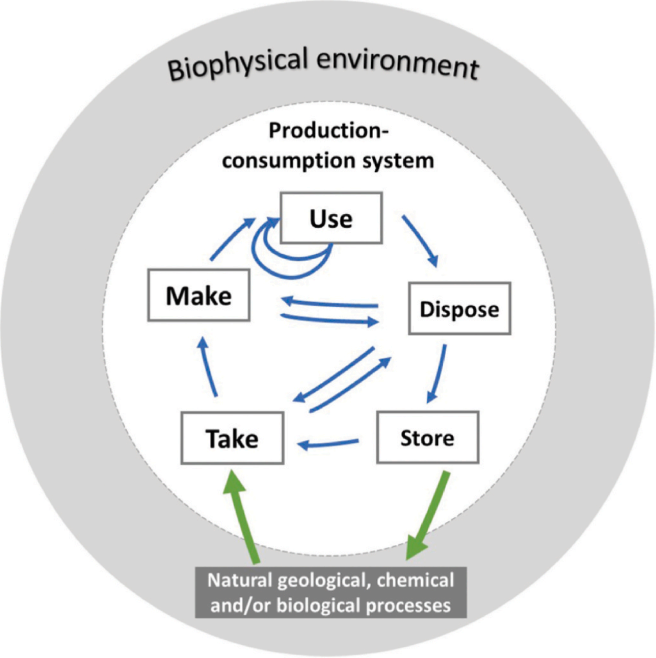

Fig. 1. An integrated model of resource flows for a Circular Economy, showing the flows of industrial materials (thin blue arrows) and natural materials (thick green arrows). Reproduced from Velenturf et al. (2019b) with permission from the Royal Society of Chemistry.

A holistic Circular Economy manifesto demands broader consideration of products in socio-economic systems, not simply ‘better’ products. Moreover, it fosters a mindset of humans as integral actors in the biophysical environment; and, through a mentality of stewardship, an aim of improving the biosphere rather than simply harming less (Velenturf and Purnell, 2021).

Resource flows are key to describing and comparing between different Circular Economy principles and strategies; four types of actions on resource flows can be categorised:

1. Narrowing = reducing the volume of materials used in the economy
2. Slowing = extending the time between manufacturing and end-of-use
3. Closing = limiting the loss of materials between end-of-use and production
4. Reintegrating = integrating materials back into the biophysical environment, with neutral or beneficial effects on natural capital

The first three categories are described by Bocken et al. (2016); reintegration (Velenturf et al., 2019a) is added here as a fourth category, in line with the holistic model of Circular Economy described above. Waste is also key to describing resource flows throughout life cycles but is a versatile term with different interpretations depending on context. Drawing on the concepts presented by Blomsma (2018), waste in this article is defined as material stocks whose value has been temporarily lost through the lack of a process to restore its value.

Concrete is a ceramic composite, made of a cementitious binder and aggregates. Reinforced concrete also typically contains steel reinforcement (rebar). In common usage, it is an implicit (and unstated) assumption that the term cement refers to Portland cement systems, which remain the most widely used type of cement. However, in its truest sense, cement is an inclusive term that describes a range of binders, including Portland cement as well as other systems such as alkali-activated cements, magnesia cements and others. In this article, the more inclusive latter definition will be used – whenever a specific cement system is referred to, this will be stated explicitly. Cement typically dominates the cost and embodied carbon of concrete, whereas aggregate dominates the mass. Over 70% of cement produced globally is used to produce concrete (Cao et al., 2020), with the majority of the remainder used to produce mortar – a mix of cement and sand. Whilst the majority of concrete stocks are present as bulk materials, substantial amounts of particulate matter are generated through the concrete lifecycle, and is estimated to be responsible for 5.2% of particulate matter emissions <10 μm and 6.4% of those <2.5 μm (Miller and Moore, 2020). Alongside the impacts on human health (Miller and Moore, 2020), the size distribution of concrete stocks is highly influential in determining the potential interactions (both beneficial and harmful) with the biosphere, and will be explored more in Sections 4.1.3 and 4.5.

The terms “product” and “component” need specific interpretation when applied to concrete structures. Concrete is a composite material, which is then assembled into a structure – therefore, individual structural elements can be considered either as a product or a component, depending on the context within the lifecycle (Fig. 2). Likewise, the cement and aggregates used to produce concrete can be considered as products in themselves, as well as components within concrete. When a change in perspectives is made between treating a concrete element as a component within a building, or a product itself, this will be made explicit. Structures refer to both buildings and non-habitable constructions, including infrastructure. Systems refer to the production systems (including supply chains) of cement and concrete, and the wider construction sector. Distinctions between perspectives at the material scale, product scale and system scale will be highlighted throughout.

2.2. Approach

The remainder of this article forms a narrative review (Baumeister and Leary, 1997). This seeks to synthesise the state of knowledge and identify critical areas for further research within the following scope: the material, product and system-level attributes of concrete in a Circular Economy; the application of Circular Economy strategies to concrete; and, life-cycle synergies and trade-offs driven by a Circular Economy for concrete. The contribution to knowledge arises from the novel perspectives provided on existing and emerging issues in a wide range of related topics. Keyword searches including “cement” and “concrete” along with “circular economy” and the Circular Economy strategy terms listed in Section 4 (“reduction of material”, “long-lasting design”,

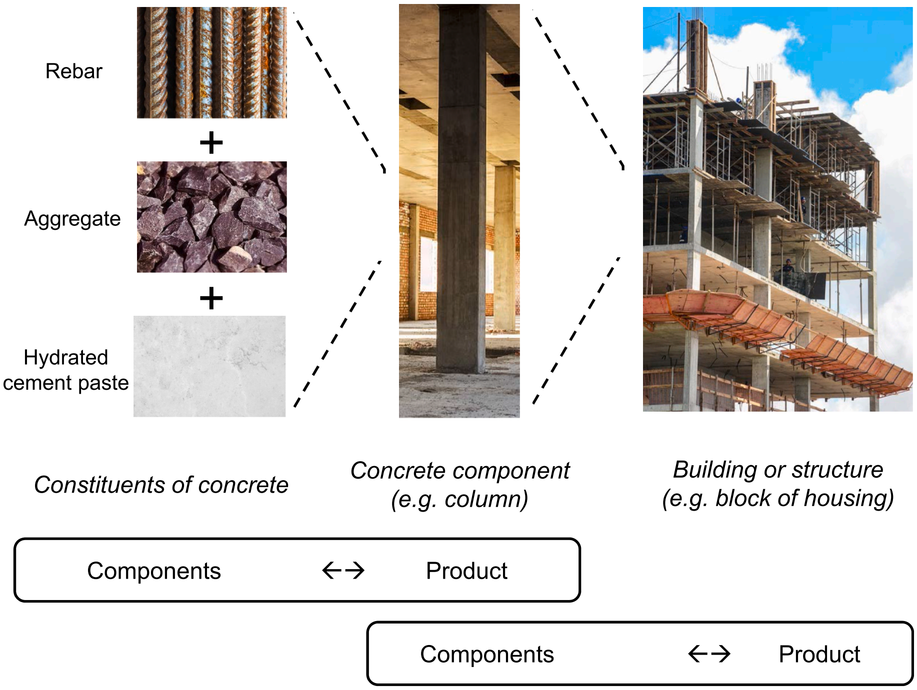

Fig. 2. The nesting of components within products for concrete buildings or structures. Dashed lines represent ‘zooming out’ to a larger physical scale.

"maintenance", "repair", "refurbishing", "reuse", remanufacturing", "recycling") along with synonymous terms, were used to identify relevant academic and grey literature around the state-of-the-art in the topics considered. This qualitative evidence synthesis was then used as a platform for exploring outstanding and/or neglected issues.

3. Material-, product- and system-scale attributes of concrete

Circular Economy strategies are not 'material-agnostic' – they are largely a response to three factors: a given material's physical attributes, its production-consumption systems and the resources available. Before evaluating the range of Circular Economy strategies applicable to concrete, it is first necessary to evaluate how the aforementioned three factors affect the interpretation and implementation of Circular Economy principles for concrete. This evaluation encompasses three scales (Fig. 3):

1. Material-scale i.e. material attributes across the range of angstroms to metres
2. Product-scale i.e. structural elements and buildings themselves
3. System-scale i.e. the cement, concrete and construction industries

The majority of thinking and implementation of Circular Economy principles has focussed on a relatively small number of industrial materials (i.e. steel, copper, plastics and precious metals). For some attributes, it is valuable to highlight how these differ for concrete compared to other key industrial materials, and how this affects interpretation of Circular Economy principles. Comparisons are focussed on steel, as (like concrete) it is another high volume, foundational industry, and the structural material for which Circular Economy thinking is arguably most well-developed.

This section is not intended to be a comprehensive, systematic evaluation of such factors – the reader is signposted to detailed considerations of specific issues elsewhere in the literature. Rather, attributes are highlighted in order to inform the following evaluation of circularity strategies and their implementation.

3.1. Material-scale

The following three sub-sections describe material-scale factors affecting the application of Circular Economy strategies to concrete.

3.1.1. Cement and concrete production are essentially chemically irreversible

Clinkerisation (for Portland cement production) and the hydration reaction (for setting of Portland cement-based concrete) are both complex chemical reactions involving several phase transformations, and are essentially irreversible. The composite nature of concrete consists of aggregates and hardened binder, which are chemically distinct. As a result, recycling of concrete is thus largely limited to re-processing as inputs in the production of concrete and other products, rather than a return to its original state before re-forming. Whilst there is scope for some use of recycled concrete powder as a precursor in clinker production (Schoon et al., 2015), this is limited to a partial replacement and represents a re-processing rather than chemical reversal of clinkerisation per se. This is a fundamental difference between concrete and structural metals, which can be melted down and then re-cast. Despite its common practice, it is acknowledged that steel recycling is not a trivial exercise – in particular, the presence of alloying compounds can necessitate additional processing steps, resulting in further exergy losses (Ignatenko et al., 2007). Nonetheless, global recycling rates for steel are ~85% (using a descriptive recycling rate and ignoring obsolete stocks) (Oda et al., 2013). In contrast, whilst there is substantial variation in national recycling rates, the extent of concrete recycling is typically much lower (Gálvez-Martos et al., 2018).

3.1.2. Cement production is chemically versatile

A considerable extent of chemical flexibility exists for producing cements which fulfil required performance characteristics. By tailoring the composition and feedstock materials, there is great scope for driving down the cradle-to-gate embodied carbon and energy of cement, as well as the opportunity to use a wide range of different resources (including industrial by-products and wastes) for production. These technical developments will be facilitated by upcoming moves towards standards for concrete which allow for specification on the basis of performance, rather than composition (Beushausen et al., 2019). The wide range of technical possibilities have arguably resulted in a focus on engineering low-carbon binders, and less on routes to material efficiency throughout the design and life cycle. By comparison, structural steel has a much narrower compositional range, and hence a narrower range of potential precursors (i.e. pig iron and steel scrap). Due to the unavoidable exergy losses in heating and forming processes (amongst others) (Gonzalez Hernandez et al., 2018), energy efficiency measures in isolation are insufficient for the steel industry to meet emissions targets, even with high levels of recycling. This has forced a focus on material efficiency measures, such as component reuse, in the steel industry (Milford et al., 2013). By comparison, the greater compositional versatility of cements and therefore concrete, has arguably resulted in a greater focus on decarbonisation through material chemistry, and comparatively less attention on downstream opportunities for material efficiency (e.g. geometrical optimisation, component reuse).

Cement's versatility in production opens challenges as well as opportunities. As will be described in Section 4.1.3, the use of wastes containing hazardous elements in cement poses potential barriers to concrete recycling at end-of-use.

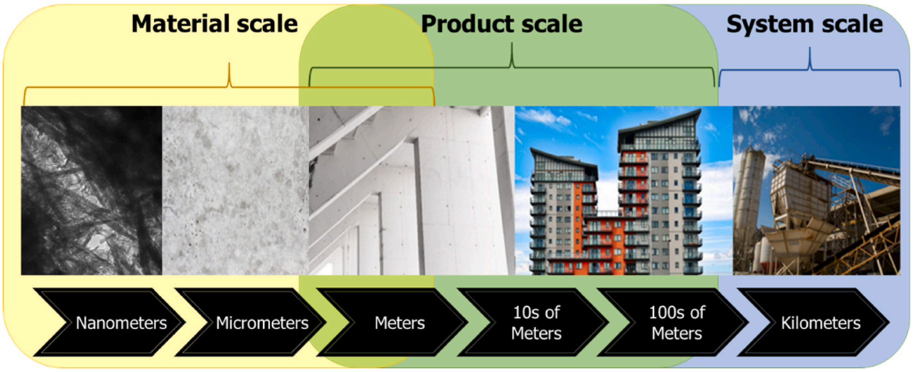

Fig. 3. The different scale perspectives used in this article, and their approximate association with different length scales.

3.1.3. *Concrete production can use a wide variety of materials as aggregates*

Concrete is highly robust and versatile, in terms of the wide range of materials that can be included as aggregates. Because of this, concrete is commonly advocated as an end-of-use application for downcycling materials, either when a higher value application cannot be found or recycling is not widespread. Examples include fibre-reinforced polymers (Yazdanbakhsh et al., 2018), mixed plastic waste (Saikia and De Brito, 2012) and rubber (Li et al., 2020). This can be advantageous from the life-cycle perspective of the downcycled material, and can even be beneficial for certain physical properties of concrete. However, there are open questions around how the inclusion of downcycled material in concrete might affect the viability of different end-of-use options. Concrete is a highly engineered ceramic composite – it is a trade-off common to many composite materials that performance advantages during service life can come with disadvantages at end-of-use. Moreover, there is also the question of whether the dissipation of resources into harder-to-recover forms is ultimately desirable – this is addressed in Section 4.1.3. The question of what constitutes the best option depends heavily on the choice of system boundaries, highlighting once again the need for a system-level perspective.

Whilst the incorporation of such novel waste materials as aggregates in concrete has yet to reach widespread adoption, the concept leads onto a wider observation about the potential pitfalls in some Circular Economy perspectives. The idea of a hermetically-sealed industrial cycle may be appealing in principle; but, the reality is that in some applications, material is effectively embedded into the environment. For example, a major application for recycled aggregate (which is of insufficient quality to be used in concrete production) is sub-base in road pavement (Purnell and Dunster, 2010); this material may remain in-place for several decades, in direct contact with the sub-grade soil below. The recycled aggregate is clearly performing a useful engineering function in infrastructure, and yet one could argue this is also an anthropogenic material stock embedded in the biophysical environment. By accepting that the boundaries between the 'human' and the 'natural' are not so neatly drawn, designers can incorporate the potential for materials to eventually be safely reintegrated into the biosphere again.

3.2. *Product-scale*

The following two sub-sections describe product-scale factors affecting the application of Circular Economy strategies to concrete.

3.2.1. *Reinforced concrete and un-reinforced concrete have different structural functions and degradation mechanisms*

Reinforced concrete has far greater tensile strength than unreinforced concrete (which in design is assumed to be zero). This allows for reinforced concrete to be used in more demanding structural elements such as beams, making it more valuable than unreinforced concrete and hence more desirable for reuse. Reinforced concrete is nonetheless a minority within overall concrete use – whilst there are no definitive figures, it is estimated that only 25% of cement globally is used in reinforced concrete (Scrivener et al., 2018b).

The flipside of this greater material functionality is that the presence of steel reinforcement makes concrete vulnerable to additional threats to longevity – in particular, atmospheric CO_2, or chlorides present in deicing salts or sea water, can lead to corrosion. The degradation mechanisms associated with the interactions of reinforced concrete with the environment can reduce the loading capacity and shorten that element's physical lifetime, depending on concrete mix design and the exposure environment. The net effect of this degradation is vast - it is estimated that the total costs of steel corrosion in reinforced concrete stands at around 4% of GDP on average for industrialised countries (François et al., 2018). This difference in value and physical lifetime between reinforced and unreinforced concretes influences the relative suitability of reuse and recycling strategies, considered in more detail in Section 5.4.

3.2.2. *Lifetimes of concrete elements and structures are often not limited by physical obsolescence*

Many concrete structures are demolished not because of physical obsolescence (i.e. the point of breakdown beyond viable repair), but rather due to the other types of obsolescence that determine product lifetime: technical, functional, economical, legal and desirability (Ashby, 2013). Whilst this raises questions about the underlying incentives and business models which make it desirable to demolish a structurally sound building, it gives opportunities for reuse and remanufacturing of the constituent concrete elements which have not reached physical end-of-life. This broadly also applies for structural steel elements, for which the concept is better developed (see Section 4.4).

3.3. *System-scale*

The following four sub-sections describe system-scale factors affecting the application of Circular Economy strategies to concrete.

3.3.1. *Concrete is a high volume and low (perceived) value material*

Concrete has the highest annual production volumes of any anthropogenic material, and is at least one order of magnitude higher than annual steel production (Fig. 4). Within the current socio-economic paradigm, concrete is characterised as a low value, high volume, low embodied carbon (per unit mass) material. This perspective has arguably resulted in over-production and inefficient use throughout the life cycle. The high volume and low (perceived) value of concrete, along with its (relatively) high physical density as a material and high degree of spatial distribution, have together tended to skew the viability of end-of-use options towards a linear life cycle. At the same time, concrete's ubiquity and its wide range of applications offers a multitude of opportunities for innovation.

3.3.2. *Raw materials for concrete production are vulnerable to local scarcity, not global scarcity*

The basic raw materials for Portland cement and concrete production (i.e. clays, limestone, gypsum, aggregates) are essentially unlimited and also accessible – there is no global scarcity (Scrivener et al., 2018b). Because of the low value and high volume use of sand and coarse aggregates, scarcity is instead manifest at the local scale (Ioannidou et al., 2017, 2020). This local scarcity has resulted in destructive and/or illegal aggregate extraction, causing environmental and social problems at the

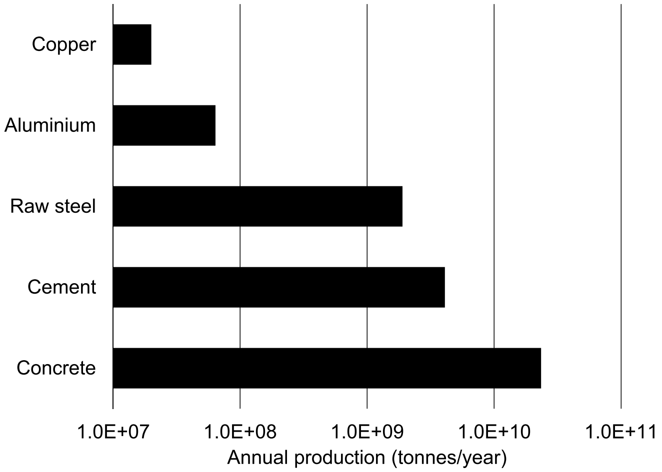

Fig. 4. There are orders of magnitude of difference between the annual production of different metallic and mineral-based materials. Production data are 2019 estimates from U.S. Geological Survey (2020), except for concrete production which is a 2012 estimate from Miller et al. (2016).

local scale (Torres et al., 2017; UNEP, 2019). These local issues have so far achieved comparatively little attention relative to the global issue of climate change, yet will need to be resolved to achieve a Circular Economy.

In contrast, global scarcity has been a prominent policy driver for development of Circular Economy strategies for precious metals (high value, low volume). Caution must be taken in transferring Circular Economy strategies which have been developed for materials with very different manifestations of scarcity and other system-level attributes, such as for critical and biological materials.

3.3.3. Waste concrete is high volume but low harm

Concrete waste is a high volume, high physical density and low harm waste – it typically goes to centralised landfill sites, with limited dissipation into the wider biosphere. Considering the impacts of concrete waste, it is crucial to consider not only the flows into the biosphere (as well as the large volume of stocks already there), but also the ability of the biosphere to absorb these wastes into natural biogeochemical cycles (Velenturf et al., 2019a). In the case of concrete, there is the potential for benefits, particularly around carbon sequestration (Cao et al., 2020) - as well as negative impacts.

In contrast, much of Circular Economy thinking around waste has developed for high profile waste materials such as plastics, which are (by comparison) low volume, low density and high harm. There's hence a need to challenge the assumption that reintegrating all anthropogenic material flows into the biosphere is highly harmful, given it can be neutral or even positive, depending on the material and context (explored more in Sections 4.5 and 5.5).

3.3.4. Cement production is highly centralised, concrete production is more decentralised

The cement industry operates on a high volume, low margins basis – this has led to a small number of high-output factories, whose ownership is dominated by a small number of large multi-national companies. This gives advantages and drawbacks regarding technological lock-in. On the one hand, changes to cement plants (or construction of new ones) require very large capital investments, and so are not easy or quick to make. On the other hand, once a change is made, benefits can then quickly cascade vertically down the supply chain.

In contrast, concrete production is far more decentralised (Fig. 5), with production typically at the local level of batching plants (or prefabrication factories), with on-site production widespread for the informal sector in developing countries. This difference in the supply chain distribution makes changes easier to enact for a given site, but less easy to cascade horizontally along the supply chain.

4. Applying Circular Economy principles into strategies for concrete

Circular Economy strategies for concrete have so far developed unevenly across the range of material, product and system scales, with a relative neglect of the system-scale perspectives. In addition to being an essential principle of a Circular Economy approach, systems-based thinking has been argued as necessary in order to achieve net-zero greenhouse gas emissions in the cement industry (Miller et al., 2021). There is also need for more detailed consideration of how contextual differences in concrete use affect the application of Circular Economy principles into tangible strategies – in particular, the distinctions between: buildings and infrastructure; reinforced and unreinforced concrete; and construction in highly industrialised and industrialising countries.

This section seeks to give an overview of the Circular Economy strategies being developed for concrete in relation to each Circular Economy principle, and highlight neglected aspects in the implementation of these strategies. Estimates of mitigation potential of individual strategies (in terms of carbon emissions, waste generation, or other impacts) are highly dependent on a range of contextual factors, including location and choice of reference scenario for comparison. Whilst location-specific case studies can be helpful for guiding decision-making in a given region, there is a risk of such findings being interpreted to be universally applicable. For this reason, the reader is directed towards sources which consider the mitigation potential either in generic terms, or at a global or regional scale.

To structure the navigation of these issues, the framework of Circular Economy principles and terminology presented by the Ellen Macarthur Foundation (2012) has been employed, with the addition of reduction of material (Fig. 6). Some of these strategies (i.e. reduction of material, recycling) are well-established in the literature and will be considered only briefly to place in context, with links provided to in-depth analysis elsewhere. In each sub-section, a brief description of the underlying Circular Economy principle will be given, followed by the strategies which have been developed for concrete, and observations of important and/or neglected aspects.

4.1. Reduction of material through specification and design

Reduction of material use is a design stage principle to narrow resource flows. For concrete, this is arguably the most well-developed principle, and can be broken down into the following stages (from largest to smallest length scales) (Fig. 7):

1. Reduction of concrete volumes in structures (product-scale)
2. Reduction of cement content in concrete (material-scale)
3. Reduction of clinker content in cement paste (material-scale)

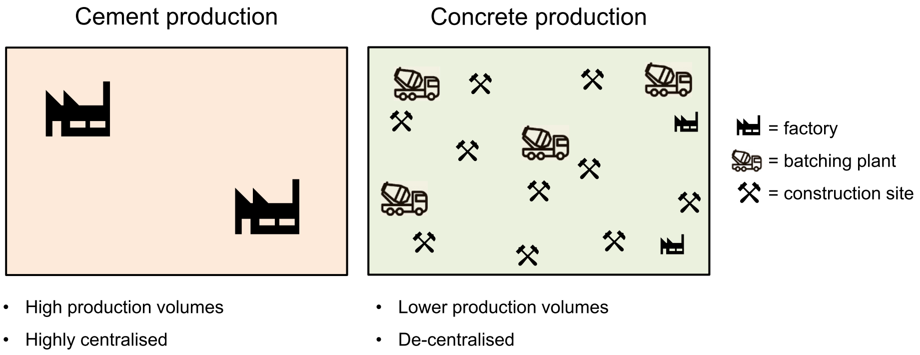

Fig. 5. Cement production is a higher volume and more highly centralised process than concrete production, which takes place at a smaller scale in a more spatially diffuse manner at batching plants, pre-cast concrete factories and on construction sites.

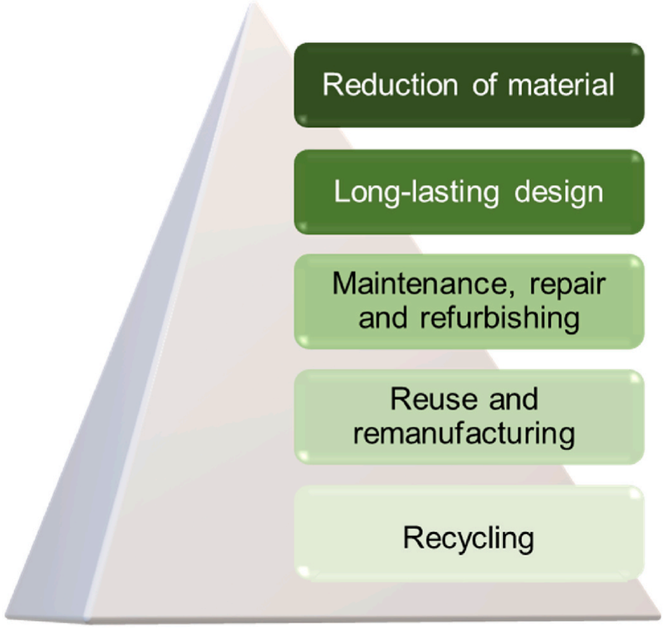

Fig. 6. The hierarchy of Circular Economy strategies considered for concrete.

The interaction between these constituent strategies is a demonstration of how important it is to think beyond the product-scale. Even if only considering embodied carbon, the best design must consider the integration of structural design (product-scale and system-scale), concrete mix design (material-scale) and cement type (material-scale) – each of these are briefly described in the following sub-sections. The decarbonisation and dematerialisation potentials for these strategies are evaluated in several cement and concrete sector decarbonisation roadmaps at a global scale (Scrivener et al., 2018b; IEA CSI, 2018; Lehne and Preston, 2018) or a regional scale (Favier et al., 2018, Cembureau, 2020b).

4.1.1. *Reduction of concrete volumes in structures*

Efficient structural design aims to achieve the required structural function of an individual element (and structure as a whole) with the minimum necessary volume of material. Many approaches can be used to achieve this, spanning a spectrum of technological maturity and extent of commercial adoption. Firstly, there is the appropriate use of safety margins - ensuring that the design is not excessive (or “overly conservative”) for the given loading requirements is a technically straightforward way to avoid redundant material use in structures (Favier et al., 2018). Secondly, innovations around the use of concrete can aid material efficiency for particular design constraints, such as the use of steel-concrete composites in prefabricated, lightweight flooring modules (Ahmed and Tsavdaridis, 2019). Lastly, in recent years, geometrically optimised structural elements have re-emerged as a more material-efficient alternative to standardised elements (Favier et al., 2018). Digital fabrication offers great opportunities for designing geometrically optimised concrete components (Agustí-Juan and Habert, 2017), and emerging structural technologies such as fabric formwork (Hawkins et al., 2016) and 3D printing (Buswell et al., 2018) offer routes for manufacturing them.

A socio-political factor indirectly affecting the inefficient use of concrete is the commissioning of construction projects which are essentially unnecessary. Sometimes this happens as a result of corruption (Elinoff, 2017). In other cases it happens with increasing affluence, to display wealth beyond the point where it adds to social and individual well-being (Wiedmann et al., 2020). Sufficiency-based approaches are emerging in Circular Economy literature which advocate for eliminating excessive consumption and production in global society (Bocken and Short, 2020), but the reduction of ‘redundant’ or ‘unnecessary’ construction is still under-represented in research.

4.1.2. *Reduction of cement content in concrete*

Within concrete, the most carbon-intensive component is the cement (Miller et al., 2016), and therefore much effort has focussed on how to reduce the proportion of cement in concrete. This can be achieved by optimising the mix design of concrete, via reducing water content and improving particle packing (John et al., 2018, 2019). Comparing between concretes, the recommended metric to compare the efficiency of cement use in concrete is kg cement/m^3/MPa, for a given strength class of concrete (Favier et al., 2018; Damineli et al., 2010). The spread of values for this ‘binder intensity’ index for concretes with comparable strength shows there is a lot of potential to reduce the cement content of concrete without a detrimental effect on performance (Damineli et al., 2010). The use of prescriptive requirements for minimum cement contents in the cause of durability performance has placed a limit on the reduction of cement content, but the evidence behind these requirements is now increasingly being questioned (John et al., 2019; Wassermann et al., 2009). However, at this length scale it is not just material aspects at play. Depending on the structural context, it can be more beneficial to use a higher cement content, higher strength concrete mix, so that a smaller overall volume of material is required. As a result

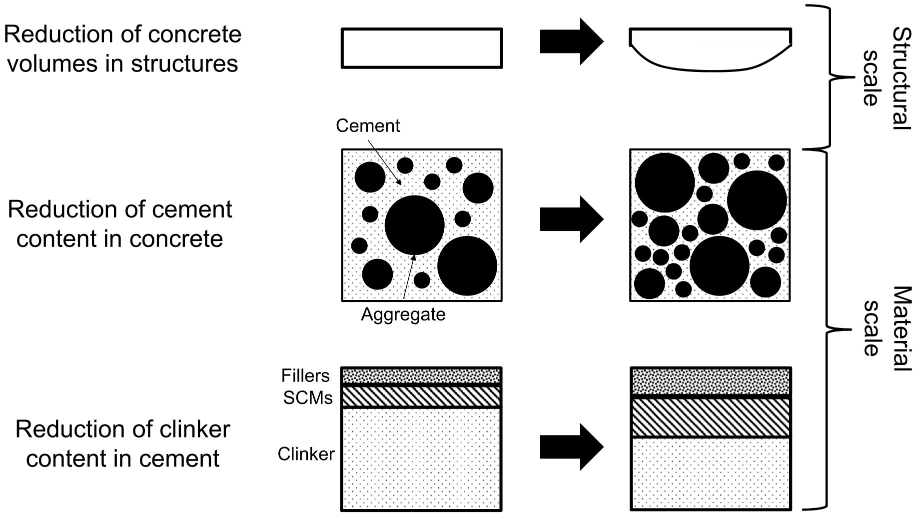

Fig. 7. Strategies for reduction of material use in concrete, over different scales.

of this complexity, selecting a material on the basis of lowest impact per unit mass of material does not necessarily result in the lowest overall impact for a structure (Habert et al., 2012). And hence, optimising the concrete mix design requires understanding of the structural function in a given environment, and requirements of a given member (Purnell, 2012; Kourehpaz and Miller, 2019). These considerations are also applicable to the amount of reinforcement in a given concrete member (Garcez et al., 2018).

4.1.3. Reduction of clinker content in cement paste

The reduction in clinker (the main component of Portland cement) content through adoption of supplementary cementitious materials (SCMs) and limestone is a key strand of the cement industry's roadmaps for decarbonisation, and is comprehensively covered elsewhere (Scrivener et al., 2018b; Favier et al., 2018; Schneider, 2019). Two emerging aspects of this discussion are particularly relevant to circularity. Firstly, the attribution of impacts to SCMs which are recognised as by-products rather than wastes (Chen et al., 2010; Hossain et al., 2018). Secondly, the influence of transportation on their overall impacts. Transportation is a relatively minor influence on life cycle analysis (LCA) impacts in conventional concretes (Göswein et al., 2018) - but for low-carbon concretes with a high proportion of SCMs, transportation has a substantial influence, both when comparing between sources from overseas (Hafez et al., 2020) and between sources within the same country (Göswein et al., 2018). This also relates to issues of resource criticality as applied to concrete (discussed in Section 3.3.2). Combined with the overall limitations on net global supply of industrial by-product SCMs relative to cement production, the transportation issue also provides a supporting argument towards a greater use of calcined clays as SCMs in general (Scrivener et al., 2018a).

A different driver for reducing clinker content is the valorisation of hazardous wastes. The theory is that hazardous elements can be immobilised through incorporation in the binder phase, preventing their dissipation into the wider environment. An additional benefit is displacing extraction of raw materials. However, the viability of this concept in practice can be highly limited, depending on the waste in question. In the case of air control pollution residues from municipal waste incineration, the leachability of hazardous elements (inc. Pb, Zn) from the hardened binder is an unresolved concern (Bogush et al., 2020), notwithstanding the detrimental effect of other chemicals (inc. alkalis and chlorides) on the properties of the binder itself (Stegemann, 2014). Concerns about leachability are magnified when waste concrete is crushed into smaller particles and dust, raising questions about whether such additions might reduce the viability of end-of-use recycling due to dust-mediated pollution. Such valorisation can be argued to be a relatively convenient way of creating value from such hazardous wastes in the short-term. However, in the longer term it arguably decreases value and increases waste, given that the further dilution and dissipation of those elements makes it harder to recover their potential value. Furthermore, it prevents or delays the potential to reintegrate that concrete back into the biosphere.

4.2. Long-lasting design

Increasing longevity is a design-stage strategy for slowing resource flows by extending the technical lifetime of components and products (Figge et al., 2018). Increasing structures' lifetimes results in only a small reduction of volumes of in-use stocks, but does reduce flows of material and waste production over time (Miatto et al., 2017), and hence can reduce environmental impacts whilst providing the same functions (Miller, 2020). For concrete, this can be achieved through strategies at the material and product scale to ensure that concrete is durable and effectively protected against the relevant degradation mechanisms for a given service environment. These include considering the environmental threats that can compromise longevity, and specifying the correct cement and concrete mix design to mitigate potential durability threats (thereby enabling a balance between initial cost and resource efficiency vs. longevity) (Yang et al., 2020). These measures will extend service-life, in turn reducing concrete consumption required for replacement structures and also increasing the reuse potential for concrete components.

In the development of novel, low-carbon concretes, most attention is given to their cradle-to-gate embodied carbon – however, their material durability (and hence structural longevity) should not be neglected (Bernal and Provis, 2014). The benefits of lower cradle-to-gate embodied carbon should not be outweighed by shorter technical lifespans, resulting in premature replacement and hence a higher cradle-to-cradle impact (Fig. 8). The field data does not yet exist to conduct a like-for-like comparison in longevity of structures made with novel and conventional concretes. For the use of various waste materials as aggregates, current evidence suggests that durability performance (relative to natural aggregate) can be enhanced or diminished depending on the exact waste and degradation mechanism, and there remains significant knowledge gaps, especially around long term performance (Hossein et al., 2022). The resilience of structures made with non-conventional concretes to specific environmental hazards, such as seismic activity, merits special attention (Welsh-Huggins Sarah et al., 2020). Nonetheless, the benefits of increased longevity have been modelled: taking carbonation into account, a 50% increase in the longevity of concrete structures in the USA would have resulted in an estimated 14% reduction in cumulative $CO_{2(eq.)}$ emissions over the time period from 1900 to 2015 (Miller, 2020).

At the product-scale, Design for Adaptability (DfA) is an approach that emphasises the design of products which can be modified to meet changing requirements (Kasarda et al., 2007). In the context of buildings, examples can involve designing the interior layouts to be adaptable without requiring major structural alterations (Geldermans, 2016). The DfA approach can also be applied to infrastructure (Gilrein et al., 2021). By designing structures to be adaptable to different functional requirements in the future, the functional lifetime can be extended and hence premature obsolescence avoided.

At the system-scale, a social factor which indirectly influences longevity is corruption. It is well-established that inadequate quality construction reduces buildings' technical lifespans and can often cost lives (e.g. in earthquakes) (Ambraseys and Bilham, 2011). Thus, the development of rigorous and effective regulation and inspection of buildings is a Circular Economy strategy and, given the high costs of its absence, arguably a neglected one.

4.3. Maintenance, repair and refurbishing

Maintenance, repair and refurbishing are all in-service strategies for slowing resource flows, by extending the technical lifetime of products

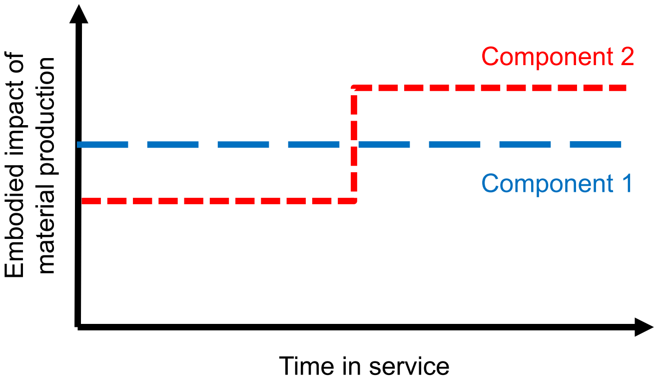

Fig. 8. If a component (#2) has a lower embodied energy of production but a shorter lifespan, the overall embodied energy of material production could be higher than for a higher embodied energy, but longer lasting, component (#1).

and components. For the context of concrete, these in-service strategies have different interpretations based on whether a structure is a building or infrastructure, and also on the nature of the service environment:

- Maintenance is the general upkeep of structures, and practices to prevent damage to components (such as applying protective coatings in some environments).
- Repair and refurbishment are the repair of limited damage to a concrete component, or the replacement of a damaged component wholesale with a new one.
- Refurbishment is more applicable to infrastructure where it is known that certain components receive higher levels of degradation – for example, bridge decks (Suwaed and Karavasilis, 2017).

There is a need to ensure that these in-service strategies 'keep up' with innovations upstream in the concrete lifecycle. For example, the availability of protective coatings that are effective for novel, low-carbon concretes.

4.4. *Reuse and remanufacturing*

Reuse and remanufacturing are both product end-of-use strategies, intended to slow resource flows by continuing the use of still-functional components from end-of-use products in new products. Reuse is defined as the use of a component or product again for a similar function, and may involve various actions to prepare for reuse such as checking, cleaning and repairing of parts (Defra, 2011; Den Hollander et al., 2017). For the concrete context, an individual concrete structural element can be considered to be a product. The reuse of structurally sound individual elements (sourced by deconstruction of a structure at end-of-use) in new construction can displace production of the equivalent amount of new material and hence reduce flows of new resource into the economy. Fivet and Brütting (2020) suggested three generic conditions for components to be reusable: reversible, modular and transformable.

Remanufacturing follows a fully documented process to disassemble a product into its constituent components, which are checked, cleaned, fixed and replaced as necessary, and then reassembled into the same product offering a similar or better guarantee regarding the functioning of the product (Priyono et al., 2016; Lieder and Rashid, 2016, European Commission et al., 2017). For the context of construction, a structure can be considered to be the product, made up of many constituent components, including (but not limited to) structural elements. For structures, remanufacturing has much in common with refurbishment but they are distinct strategies: in refurbishment, an end-of-life component is replaced to extend the lifetime of the overall structure; whereas in remanufacturing, a structure has reached end-of-life but its still-functional components are used to manufacture another structure (see schematic explanation in Fig. 9). Reuse of structural elements is the most-explored route within these two strategies, with arguably less relevance for remanufacturing of buildings. Both strategies fall within a Design for Disassembly (DfD) approach, wherein disassembly refers to the removal of structural elements for reuse in other structures (whereas deconstruction implies a subsequent rebuilding of the same structure but elsewhere) (O'grady et al., 2021). It has been argued that to maximise the circularity potential of DfD for buildings, both the 'intrinsic properties' at the material-scale (e.g. sufficient strength and durability of an individual structural element) and the 'relational properties' at the product-scale (e.g. how straightforward it is to disassemble connections between structural elements) need to fulfil requirements (Geldermans, 2016). This highlights the role of buildings systems in determining the circularity potential of concrete, and illustrates again the importance of thinking across different scales.

In the construction cycle, the reuse strategy is encompassed within design for deconstruction. Reuse is arguably a high-risk, high-reward strategy. The most commonly-identified risks include (Tingley and Davison, 2011): specifying reused elements, the availability of a market for element reuse, and the financial and time burdens in deconstruction (relative to demolition). Prominent amongst material-based technical concerns is the quality of reclaimed elements, and how these could be specified with confidence in a new structure (Akinade et al., 2020). Reuse is also the greatest departure from typical business models in construction, and feasibility of reuse is highly dependent on both the design decisions made 'upstream' in the concrete life cycle, and also the effective reporting and flow of information 'downstream' throughout the construction lifecycle (see more in Section 5.6). This has prompted innovation in technological enablers, such as material passports (Luscuere, 2017). Whilst many technical differences exist between reuse of concrete elements compared to reuse of steel (which is arguably more developed), many of the social, economic, and regulatory barriers are common to both (Rakhshan et al., 2020; Dunant et al., 2017). Nonetheless, the potential rewards are great – concrete prefabricated elements can be designed to be disassembled, and their reuse could result in substantial savings in embodied carbon over the construction cycle (Jaillon and Poon, 2014; Eberhardt et al., 2019).

Industrialisation status is likely to influence the feasibility of reuse

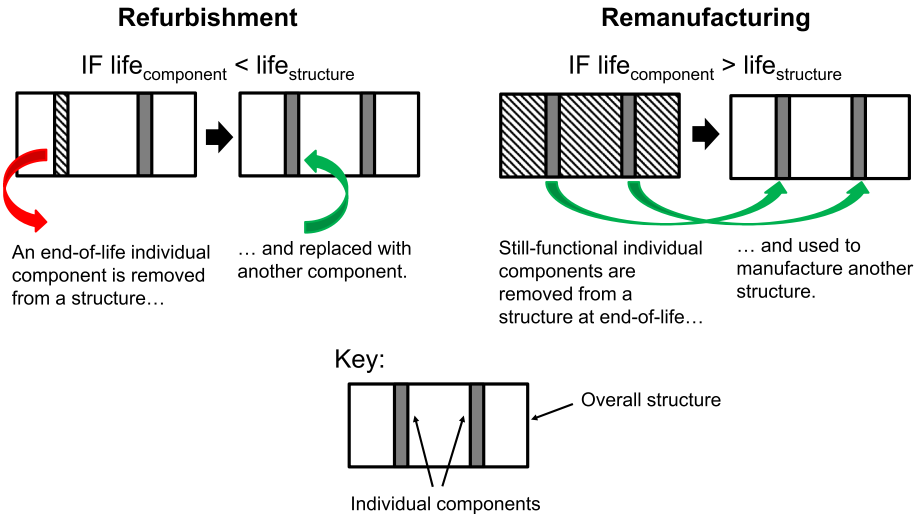

Fig. 9. Schematic distinction between refurbishment and remanufacturing for structural components in building/infrastructure products. Hashed line infills are used to indicate that an individual component or overall structure has reached end of life.

strategies across different regions. For ‘steady state’ regions which have a relatively mature concrete building stock, there is potential for ample reuse opportunities as buildings are deconstructed at the end of their functional life - or more pessimistically, their desirability life (i.e. the point at which changes in fashion or taste have caused a building to seem unattractive (Ashby, 2013)). This supply of reclaimed structural elements could then be used to partially meet the demand for structural elements in new construction. In contrast, ‘rapidly growing’ regions are likely to have a much younger concrete building stock, and the number of concrete buildings coming to the end of their functional lifetime is likely to be much smaller that the number of new buildings under construction at a given time. In other words, there will be a greater temporal mismatch between older buildings coming to the end of their lifetime, and the construction of new buildings. Whilst the supply and demand of reused structural concrete elements in different demographic regions for future decades has yet to be modelled, the above hypothesis is plausible on the basis of predicted growth of building stocks in industrialising and highly industrialised regions (Krausmann et al., 2020). Key caveats to the scalability of reuse is that even in highly industrialised regions, building stocks are expected to continue to grow towards 2050 (Marinova et al., 2019), and the volume of cementitious materials generated at buildings’ end of life is still a small fraction of material demand on a year-by-year basis (Kapur et al., 2008). So, whilst reuse can be a highly resource efficient strategy at the building level, it should approached with caution in terms of immediate, global applicability.

4.5. Recycling

Recycling is an end-of-use strategy to close resource flows, by reprocessing materials to use in another product and hence avoid both waste and extraction of raw material. Arguably, recycling is the second most widely applied Circular Economy strategy for concrete. Recycling demolished concrete structures typically involves crushing concrete at end-of-use, and using the coarse material to replace natural aggregate in fresh concrete. This is considered downcycling, as the recycled aggregate has less value and function than the concrete from which it was recycled from. There is a spectrum of value within downcycling: “recycled concrete aggregate” is higher quality and used in structural concrete, whereas “recycled aggregate” (the majority fraction) is lower quality and typically used in road sub-base (Purnell and Dunster, 2010). Despite opportunities for recycling of concrete (even in low value applications such as backfilling), landfilling does still occur (Zhang et al., 2022).

Beyond coarse aggregate, there is increasing attention paid to recycling of fine aggregate and powders generated during the crushing process. However, the technical benefits of recycling fine aggregate and powder in new concrete is disputed, with a variety of evidence on their effect on mechanical properties and durability (Evangelista and Brito, 2019). Separation processes to improve the quality of coarse recycled concrete aggregate also have the side-effect of producing a higher proportion of less valuable fines (Schoon et al., 2015). Such dependencies between the quality and quantity of different size fractions of recycled concrete aggregate are another demonstration of the need for system-level thinking to make the best decisions for material processing (Villagrán-Zaccardi et al., 2022). A promising development to improve the functional value of the fine fraction (relative to an application as a fine aggregate or filler) is the use of enforced carbonation to transform cement paste into a supplementary cementitious material; however, its feasibility will rely on the development of efficient techniques for the separation of fines (Zajac et al., 2021). Eco-efficiency comparisons between natural and recycled aggregates are especially context-dependent, with impacts strongly determined by distance and mode of transport (Göswein et al., 2018; Marinković et al., 2010). As a result, it is difficult to make universal statements about whether the use of recycled concrete aggregates has undisputed net benefits for circularity.

Aside from the most well-known wastes of concrete demolition waste, there are numerous other sources of waste along the cement and concrete life cycles - for example, cement kiln dust (Kaliyavaradhan et al., 2020), fines generated from natural coarse aggregate production (Guimaraes et al., 2007), and concrete slurry waste (Kaliyavaradhan and Ling, 2017). Whilst these material flows have all been subject to research in how they can be valorised in cement or concrete production, the emphasis should be on waste prevention as far as possible. In terms of the influence of industrialisation status, rapidly growing countries with a younger concrete building stock will likely be more limited in the proportion of demand for new construction that can be met using waste concrete flows (in the same way that was argued for reuse strategies in Section 4.4).

The concept of engineered disposal of waste concrete into the biosphere is a more speculative - and controversial - development. Whilst arguably downcycling, those concrete stocks are still performing a valuable function for society - carbon sequestration. As a alkaline silicate mineral(s) which exists on the earth’s surface in large stocks, opportunities for enhancing the geochemical weathering of concrete are gaining attention (Renforth, 2019). Whilst the potential of carbon sequestration using concrete waste on an urban site has been demonstrated (Washbourne et al., 2015), there remain many outstanding questions about the feasibility and scalability of such an approach. In particular, there is a trade-off between reducing particle size to increase specific surface area and therefore carbonation rate, whilst minimising the generation of potentially polluting small particles. Beyond carbon sequestration, there is evidence demonstrating benefits to the local biosphere can be achieved through the use of concrete, such as habitat creation via artificial reefs (Baine, 2001; Taylor et al., 2020). Given the large scale of current (and future) flows and stocks of waste concrete, the potential for engineered disposal of concrete to improve or remediate the biosphere is a neglected research area which deserves greater consideration (Velenturf and Purnell, 2021).

5. Implementation and integration of Circular Economy strategies for concrete

Many of the material and resource efficiency strategies described in the previous section have evolved in isolation from each other. What distinguishes Circular Economy beyond being simply a collection of different reduction strategies is its whole system approach (Kirchherr et al., 2017). Implementation is used here to describe the undertaking of a given strategy in isolation, whilst integration refers to how different strategies are implemented together, across the concrete lifecycle. It is anticipated that both synergies and potential conflicts may arise from integrating different Circular Economy strategies over the concrete life-cycle, which are not evident when considered in isolation or solely from a product-level perspective.

What constitutes a sustainable implementation of Circular Economy strategies generally varies between different contexts (Velenturf and Purnell, 2021). The PESTEL (political, economic, social, technological, environmental, and legal) framework is a well-known approach to analysing contextual particularities, and is used herein to navigate the factors affecting implementation and the potential synergies and conflicts arising from integration. Technical, environmental and economic considerations have typically dominated discussions around concrete; in contrast, the social, legal and political aspects have been relatively neglected. Whilst in practice issues can straddle numerous PESTEL categories, the PESTEL framework is nonetheless a straightforward and informative way of exploring a breadth of issues. PESTEL analysis has previously been used to evaluate strategies in the materials and construction industries in a diverse variety of topics, including the use of timber (Kremer and Symmons, 2015), construction productivity (Pan et al., 2019) and waste management (Turkyilmaz et al., 2019). This section is not intended to provide a systematic evaluation, but rather to highlight important and neglected issues that will need to be addressed if a concrete Circular Economy is to become a reality.

5.1. Political

Within the Circular Economy community the split between those observing incremental and radical change to the political-economic system is becoming more evident, backed up by practical examples (Reike et al., 2018; Johansson and Henriksson, 2020; Velenturf and Purnell, 2021). Reike et al. (2018) introduced the idea of a reformative Circular Economy, in which current political-economic systems – and the industrial structures and lifestyles that they shape – can largely remain unchallenged while creating triple bottom line wins for economy, society and environment. This is where the global consensus lies within the subject area of Circular Economy (Velenturf and Purnell, 2021). In such a Circular Economy, production and consumption systems largely stay the same, albeit with greater emphasis on resource efficiency primarily through recycling. For the cement and concrete industries, it is therefore expected that the majority of future strategies applied in the immediate future will be 'more of the same' (e.g. carbon taxes for cement producers (Di Filippo et al., 2019)). This will incentivise technical strategies which do not change underlying business models (see Section 5.2). A similar argument applies to the demand side: the acceptability of demolishing a structurally sound building - evident in an extreme case in the high turnover of housing in Japan (Barlow and Ozaki, 2005; Wuyts et al., 2019) - is partly determined by the political consensus in wider society. The question of which policy mechanisms might be most appropriate to stimulate Circular Economy practices is highly dependent upon the jurisdictional context, and discussion on Circular Economy policies can be found elsewhere (Domenech and Bahn-Walkowiak, 2019; Zhu et al., 2019). However, a general comment can be made that systems-based thinking is required here too, in order to prevent neglect of social and economic consequences and ensure that interventions are effective across the whole concrete supply chain (Miller et al., 2021).

Cement and concrete provide a clear demonstration of the limitations of a Circular Economy that relies solely on resource recovery. For reasons previously described, the underlying chemical processes in how cements are manufactured and harden (Section 3.1.1), together with the heterogenous nature of waste concrete itself (Section 4.5), make it highly challenging technically to achieve full recycling of concrete. For those same reasons, and also given the very broad range of concrete mix designs and construction contexts, it cannot be assumed that secondary production of mineral-based concrete constituents results in reduced energy costs compared to primary production. Considering the vast scale of the current stocks and flows of concrete in the global economy, closing resource loops for concrete with recycling is likely to demand energy inputs beyond what can be generated sustainably. Moreover, whilst plant and site-level practices for waste prevention and material recovery are evolving (Sealey et al., 2001; Xuan et al., 2018), recycling is unlikely to consistently achieve 100% material recovery. And so, some level of additional primary raw materials input would be required to maintain the size of the resource economy. Given historical evidence for the coupling of construction minerals consumption with industrial growth (Steinberger et al., 2010), the prospect of 'green growth' would seem unlikely (Parrique et al., 2019). As such, the reformative Circular Economy narrative is closely aligned with 'weak sustainability' in which natural capital is allowed to continue to degrade over generations (Bond et al., 2011). Consequently, the narrative in Circular Economy is shifting towards transformative approaches that envisage an overall reduction of resource use, in line with 'strong sustainability' (Schröder et al., 2019; Reike et al., 2018). For concrete, this would be manifest in the widespread deployment of transformative strategies such as design for minimal resource use, reuse and refurbishment - ultimately leading to a reduction in per capita concrete consumption in highly industrialised countries.

Alongside the environmental crises the world is facing, the construction industry is also facing a 'productivity crisis' which is most acute in highly-industrialised regions (Barbosa et al., 2017). Enhanced productivity and a more circular construction industry are arguably mutually conducive in many respects. Nonetheless, there is a risk that the political landscape will shape construction strategies in a way that misses opportunities for circularity by adopting a mindset of 'build more, build cheap', albeit without an evolution in approach beyond outdated technologies and processes. This potential conflict is also relevant to the balance of standardisation and customisation (see Section 5.4). The potential benefits of a more circular construction industry are evident – the political question is whether the benefits are judged to be worth the wait.

5.2. Economic

The broad Circular Economy principles are to slow, narrow and close resource loops within economies and to integrate resource flows back into natural biogeochemical cycles. A key challenge for companies is how to practically interpret these principles in order to fulfil the three generic aspects of a business model: value proposition, value creation and delivery, and value capture (Bocken et al., 2016; Nußholz et al., 2019). The construction industry currently contains 'pure product' models (e.g. a contractor buying concrete blocks from a building supplies merchant) and 'pure service' models (e.g. a sub-contractor hiring a day labourer), as well as some with an element of both (e.g. a batching plant providing advice along with the concrete itself). The general trend in Circular Economy business models has been a move away from 'pure product' business models towards service-based models (there is a sliding scale between these two endpoints) (Tukker, 2004).

Depending on the circularity strategy used, concrete structural elements will have different value propositions and hence business models (Iacovidou and Purnell, 2016):

1. Design for reuse = "product lease" business model
2. Design for recycling = "product related" business model

In the first case, by decoupling the value proposition from the volume of concrete produced, the component manufacturer is incentivised to reduce material volume as this is then associated with cost rather than profit. A more ambitious business model for reuse would be an 'access and performance' or 'product service system' model (Bocken et al., 2016), but this is far more speculative as it is a further departure from current business models.

The current supply chain for concrete depends on the product and material. For reinforced concrete, the contractor typically buys the concrete from a batching plant and then produces the components themselves by casting on-site. For un-reinforced concrete (e.g. blocks, pavers, pipes), the contractor typically buys these from a supplier. These differences in supply chains can create complications in the adoption of new business models. For example, a ready-mix concrete supplier could not operate a "product lease" or "product related" business model: they do not manufacture the end component themselves, and hence would neither have control over its casting and placement on-site, nor the full information required for reuse downstream in the life cycle. A greater move towards pre-fabricated components (supported by digital manufacturing technologies including 3D printing) could help resolve some of these issues, as it will facilitate a greater degree of vertical integration in the supply chain.

The business cases for Circular Economy strategies typically feature a broader range of benefits (inc. social, environmental) returned over a longer timescale, relative to linear economy business cases (Velenturf and Jopson, 2019). Given that cement and concrete producers currently rely on economy of scale business models, it may be advantageous to develop several Circular Economy business models simultaneously. This would allow companies to both spread the risk and allow sufficient time for benefits to be measured. For example: in the current market, reuse is most favourable for temporary structures (Minson, 2020). The market for temporary structures may provide a 'testing ground' for companies developing reuse, before introduction to the mainstream market.

5.3. Social

The design of a given structure and its constituent elements is the result of a design process, and the inputs of many contributing practitioners. In reality, practitioners' decision-making is not purely a matter of 'hard' (i.e. technical, economic, environmental) considerations – there are also cultural and social aspects. Construction is generally a conservative industry, for understandable reasons – budgets are often large, errors can have catastrophic results, and resolving problems during service-life can be extremely expensive and time-consuming. Minimising risk is therefore a strong driver (Gorgolewski, 2008) – practitioners are unlikely to risk conflict or reputational damage over innovative technical solutions whose success and safety cannot be guaranteed. Whilst reasonable caution is understandable and advisable, there is a secondary risk - that technical risks might be overplayed by industry actors whose existing business models might be challenged by the emergence of alternatives. The construction industry can at times be adversarial (Hart et al., 2019), and so the perceptions of risk need careful scrutiny in addition to the technical risks themselves. Another aspect is clients' and the public's perceptions of Circular Economy innovations. Practitioners in China expressed doubt in the willingness of clients and the public to use buildings using recycling or reused materials (Jin et al., 2017). It is not yet known what public perceptions and preferences are of more radical strategies such as reuse of structural elements, and critical approaches to assessing whether new structures are truly essential – linking up to the complex debate on human needs vs. wants (Daly and Farley, 2004; Redclift, 2005). These choices about the built environment also take place within a wider, ongoing debate about the choice between mainstream and alternative development pathways (Hickel, 2019). On a project-level scale, in order to facilitate implementation of technically proven innovations, it will be necessary to gain a greater understanding of these 'soft' influences on practitioners' and clients' decision-making. This evidence base would then provide a rationale for targeted engagement with practitioners in order to improve confidence and accelerate implementation.

The adage that 'what gets measured, gets managed' applies strongly to sustainability. In order to measure the effects of Circular Economy strategies, a wide array of Circular Economy indicators are being developed. However, these indicators typically reflect the biases towards material and environmental metrics (and neglect of social issues) that are prevalent in the field as a whole (Corona et al., 2019; Moraga et al., 2019). In order for an inclusive vision of a Circular Economy to be realised, the full spectrum of issues need to be measured. Routine implementation of such holistic assessments would benefit from construction practitioners having greater 'Circular Economy literacy', which is arguably lacking at present (Adams et al., 2017). This could be addressed through integration in higher education and continuing professional development for construction professionals, following on from improvements in 'carbon literacy' in recent years.

5.4. Technical

At the scale of concrete structural elements, if concrete has been identified as the most appropriate material, and 'design to reduce' has been explored, there are two remaining strategies for enhancing circularity (as described in Section 5.2): 'design for reuse', which favours geometrical standardisation, and 'design for recycling', which favours geometrical optimisation. Each has its advantages and disadvantages (Fig. 10). But to a large extent this is a design choice – by definition, one cannot standardise geometry and customise/optimise geometry simultaneously. The choice of which is more appropriate is highly context dependent – both on the application of the structure in question and its service environment (and hence degradation mechanisms, partly determined by whether the concrete is reinforced or not). Design for durability will play a key role in the implementation of these strategies, as they will not be attainable if the concrete properties are compromised. In cases where the physical lifetime of the concrete element is likely to exceed the product lifetime of the structure (e.g. an inland block of flats), design for reuse would be optimal. In cases where the physical lifetime of the concrete element is likely to be the limiting lifetime on the structure as a whole (e.g. a coastal bridge), then design for recycling would be more appropriate, in combination with refurbishment to replace obsolete elements where possible. The crucial observation here is that the choices made at design stage then open and close doors to other strategies further down the lifecycle. The flow of information will be key to determining the extent to which downstream opportunities can be fulfilled (explored more in Section 5.6).

Considering the material itself, a widely-acknowledged barrier to the wider adoption of non-conventional concretes is a lack of long-term data for their durability performance (Alexander et al., 2017). The most practical solution is to develop a detailed understanding of the underlying chemical degradation mechanisms, and how these are affected by concrete characteristics and environmental conditions (Angst et al., 2012). In some cases, this will require development of new testing methods - the majority of test methods were developed for concrete made using Ordinary Portland Cement and are not necessarily appropriate for non-conventional concretes. For example, typical accelerated carbonation tests have been shown to underestimate the carbonation resistance of alkali-activated concrete (Bernal et al., 2012). Lastly, the 'push' of innovations at the material-scale are not isolated from the 'pull' of innovations at the structural-scale and in manufacturing processes. Rather, they can be heavily interdependent, meaning that integration of different strategies is not trivial. For the example of 3D concrete printing (3DCP), which can produce elements with optimised structural geometry: most development in 3DCP has been done with Portland-based cements. It is a further challenge to adapt the admixtures and mix designs for novel, low carbon cements so that these are compatible with 3DCP. This demonstrates the very real need for the whole life cycle perspective that Circular Economy brings, in order to identify synergies and prevent problems arising from integration of different strategies.

5.5. Environmental

Examination of the environmental impacts of concrete is typically dominated by carbon dioxide emissions. This highly focussed approach has so far yielded effective improvements in the embodied carbon of concrete products. However, the drawback of this highly focussed approach is the risk of several 'blind spots' in other areas of environmental impacts – such as habitat destruction.

As understanding and access to data improves about the holistic environmental impacts of concrete in different contexts, it is likely that on occasion difficult decisions will have to be made about which strategy to implement when trade-offs exist. For example – is it desirable to use an industrial waste with no other valorisation routes as a cementitious precursor, if using a cement made with virgin raw materials instead would yield lower embodied carbon? Such questions have no easy answers, and tackling them will require pragmatism about what a Circular Economy means in practice, beyond a platonic ideal.

For example, such a discussion is emerging in the offshore wind sector where the first generation of wind turbines is reaching end-of-use (Jensen et al., 2020). Fully removing the concrete foundations is technically challenging, with limited environmental benefits from material recycling. Alternatively, old foundations could function as artificial reefs, adding environmental value in terms of biodiversity and economic value by creating breeding grounds for fishing stocks (Smyth et al., 2015; Fowler et al., 2020). Unless foundations are designed for use in multiple wind farm lifecycles, safely reintegrating the concrete

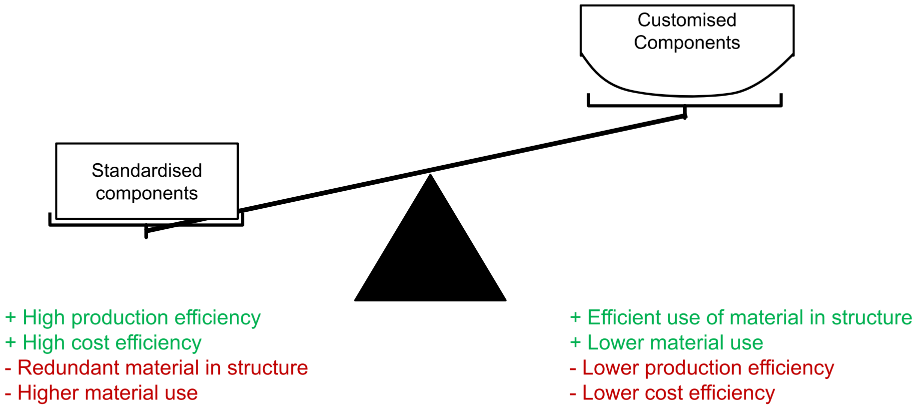

Fig. 10. The trade-offs between using standardised and customised components in construction.

foundations into the environment at end-of-use may be a preferred option depending on the context. In areas of low environmental value and poor fishing stocks, there may be synergies with reintegrating resource flows into the environment, but there may be trade-offs with the safety of marine navigation and fishing access.

5.6. Legal

The construction industry contains flows of information, as well as flows of material and carbon. At each life cycle stage, practitioners need the tools to evaluate different design options for enhancing circularity, as well as the information to feed into those tools (Section 5.3). For example: in order for practitioners to have the legal confidence to specify reclaimed elements for reuse in a new structure, they will require data of sufficient quality about those elements to make a decision. The resilience of Circular Economy strategies going round the lifecycle thus depends on maintaining the requisite flow of information between practitioners. This is not trivial, as practitioners change within and between life cycle stages in construction. Development of the data infrastructure needed to manage knowledge of resource flows has already begun at the national scale, such as those in Taiwan (Chen et al., 2017) and the United Kingdom (Jensen et al., 2011; Velenturf, 2019). Emerging technological solutions have the potential to make these information flows more resilient, such as blockchain, which is already finding applications to facilitate traceability in the minerals industry (Cartier et al., 2018). Adequate data systems and processes are hence a crucial part of the infrastructure to underpin a Circular Economy construction industry.

On a practical level, agreement of contracts determining liability are identified as a potential barrier for reuse strategies (Hart et al., 2019). Recertification of elements may help resolve many of the technical and data aspects of reuse; however, satisfactory legal arrangements between clients, different design parties and reclaimed element vendors is yet another aspect which will need to be developed.

6. Concluding remarks and outlooks

Circular Economy for the concrete industry, and construction in general, would seem to have a bright future: the underlying principles are receiving growing support from both governments and industry, the potential benefits are widely acknowledged, and many of the strategies have been proven in principle or are already in use. The outstanding challenges have been framed in this article within two groups: firstly, how best to implement the most appropriate Circular Economy strategies across a wide range of products, applications, locations and service environments; and secondly, how to integrate different strategies across the overlapping life cycles of different materials and products. Within the breadth of the varied challenges, the following paragraphs summarise some of the key research priorities highlighted in this article.

In non-technical research needs, research is urgently needed to identify the amount of concrete that is considered essential for development needs. Crucially, this exercise should include alternative development pathways that do not simply emulate the materialistic and concrete-intensive model of many highly industrialised countries. And conversely, to identify opportunities to improve wellbeing which do not require new construction. In education, there is a need to improve knowledge of concrete technologies and Circular Economy principles for both designers and on-site workers. Research in how to disseminate knowledge and upskill workers effectively and inclusively will be valuable to this end. Understanding the behavioural drivers that affect engineers', clients' and the public's decision-making around Circular Economy strategies (particularly for radical strategies such as reuse) will help guide research to provide an evidence base that is persuasive to decision-makers, alongside research to assure safety of such novel strategies. Policy mechanisms will be crucial to implementation and are already in use in several regions. More research is needed to evaluate how policies can stimulate Circular Economy practices in the most effective way, with particular attention to creating economic environments and legal frameworks that are conducive to Circular Economy business models.

In technical research needs, confidence in the long-term durability of non-conventional concretes remains a significant issue. A greater understanding is needed around the chemical degradation mechanisms of concretes in general, but particularly for non-conventional concretes. This will likely require a fundamental revisiting of durability testing methods. In a similar vein, it is also important to ensure that repair strategies (e.g. protective coatings) can be applied to structures built with non-conventional concretes. A more speculative topic of interest is the potential for engineering of concrete wastes to have a beneficial effect on the biosphere. Whilst recycling ranks at the bottom of the Circular Economy hierarchy, the vast flows and existing stocks of concrete waste mean that improving recycling technologies will still be valuable. This includes improving the separation efficiency of aggregate from cement paste in demolition waste, and further developing processes to maximise the functional value of those recovered materials.

Finally, three overarching recommendations are given for more constructive ways of thinking about concrete's role in a Circular Economy, which are common to all the issues considered:

1. Circular Economy strategies are not material-agnostic. What is appropriate for one material is not necessarily appropriate for another - this applies both to transferral of strategies between concrete and other materials, as well as between different types of concrete and concrete products. One-size-fits all approaches will rarely be appropriate for such a widely-used and versatile material as concrete.

2. Materials (including concrete) are not apolitical. Political and social value systems underpin the legal and economic environments in which the business models of construction and construction materials develop. Social and political aspects thus cannot be partitioned from technical and environmental aspects. If society is to be serious about the pursuit of a Circular Economy, challenging questions about the role of dominant political-economic and cultural paradigms cannot be avoided.
3. Circular Economy strategies cannot be viewed solely from the perspective of materials or products. System-level perspectives are needed in order to identify the potential synergies and trade-offs when different circularity strategies are integrated, as well as to minimise the risks of detrimental technological lock-in and/or premature failure of innovations.

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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