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Social, Economic, and Environmental Evaluation

Adopting Digital Manufacturing for Circularity in Cementitious Products

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Table of contents

Preface

This report presents the social, economic, and environmental evaluation of digital manufacturing innovations to enhance the circularity of cementitious products. Cementitious products come in various forms and dimensions, ranging from ready mixes to construction product inputs such as cement blocks, cement roofing slates, cement pavement slaps, cement pipes and concrete. In technical terms, cementitious materials blend with water and other solutions to form a pliable paste that forms into concrete when mixed with such aggregates as mortar, limes, or cement. In other words, cementitious materials are essential components of concrete. A typical concrete mix is made up of 60-75% aggregates, 15-20% water, and only 10-15% cement. Aggregates, water, and other resources that go into cement production, including the energy used to form concrete are exhaustible natural resources that are rapidly depleting.

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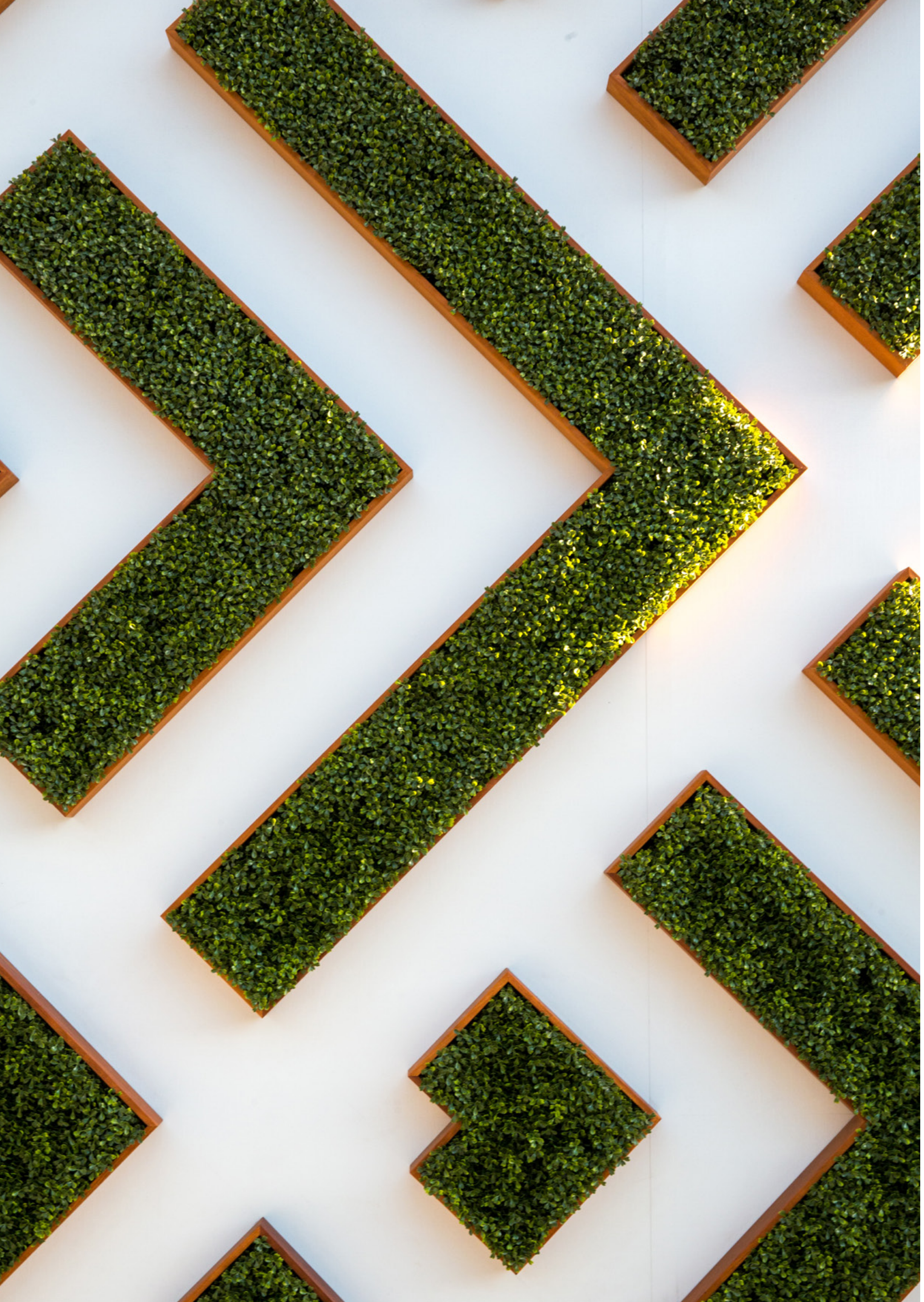
Concrete is a critical building material. Over 52 billion tons of it are produced annually worldwide. Sand and gravel are significant components of concrete. The volume of sand and gravel consumed each year makes it the second most used natural resource after water, making it unsustainable because of the enormous environmental implications and the existential threats posed to the construction industry from natural resource depletions and attendant interruptions to the raw materials supply chain. At the same time, concerns over the disproportionate amount of natural resources consumption the construction sector accounts for, the sector also contributes significantly to solid wastes, as it accounts for more than 25% of global solid wastes and 40% of global carbon emissions. This makes the business-as-usual linear practices of the global construction industry where raw materials are extracted, processed and consumed, highly unsustainable on many fronts. The opportunity presented by digitalisation and additive manufacturing to decouple construction output from natural resource consumption intensity on one hand and, on the other, to recycle and reuse construction wastes is a potential critical sustainable safety net that global construction must wholly embrace. It provides the sector with additional scope to apply and deepen circularity in the conduct and practice of international construction.

Aside from the environmental burdens associated with current construction industry practices, other compelling reasons exist for seeking to implement circularity and digital manufacturing in global construction practice. Significant savings are achievable when C&D wastes are digitally manufactured into construction products. This denotes efficiency if materials destined for landfills have found their usage in new products. C&D waste occurs from construction, renovation, repair, and demolition of houses, large building structures, roads, bridges, piers, and dams. C&D wastes consist of wood, steel, concrete, gypsum, masonry, plaster, metal, and asphalt.[1] Also, natural resources embodied in C&D wastes, such as the energy depleted sourcing and transporting the materials for processing is saved in the sense that their reuse prevents locating and processing of virgin materials. Digital manufacturing, in facilitating mass production of the construction products, unit prices fall, and products become affordable, enhancing social sustainability of widening access and leaving no one out. Similarly, significant employment and income generating opportunities are inherent in the circular economy, particularly given the labour-intensive and relatively low-skill nature of the circular economy, particularly at the upstream operational levels.

Based on a laboratory study of the digital manufacturing of cementitious blocks, this research evaluates the social, economic, and environmental benefits associated with the circularity of cementitious products using digital manufacturing. The market readiness of cementitious construction products is considered using blocks digitally manufactured from Construction & Demolition (C&D) wastes. This was done using closed and open-ended questionnaire surveys to gauge the acceptance and perceptions of global construction stakeholders and bring to the attention of policy makers the challenges sustainable products like digitalised additive manufactured blocks face in the marketplace to understand and reach for appropriate actions.

[1] https://environmentagency.blog.gov.uk/2021/03/28/construction-and-demolition-sites-do-you-know-whats-in-your-waste/



1.0 Introduction

The construction industry delivers the infrastructure that societies worldwide depend on to function effectively and efficiently (Lenz, 2018). Nevertheless, the conventional linear practices of excessive resource extraction, utilization, and waste disposal associated with construction do have significant implications for global environmental sustainability and have been identified as constituting one of the major causes of rapid depletion of global natural resources (Ebohon, 1996). The construction industry is resource-intensive and accounts for 40% of world energy and 30% of raw materials while generating 25% and 40% of solid wastes and carbon emissions respectively. Global consumption of building materials tripled from 6.7 billion tons in 2000 to 17.5 billion tons in 2017; concrete, aggregates, and bricks are the most commonly used building materials (Huang, et. al., 2020). According to the UNEP (2022),

> **"**
> **Our use of sand brings us up against the wall**

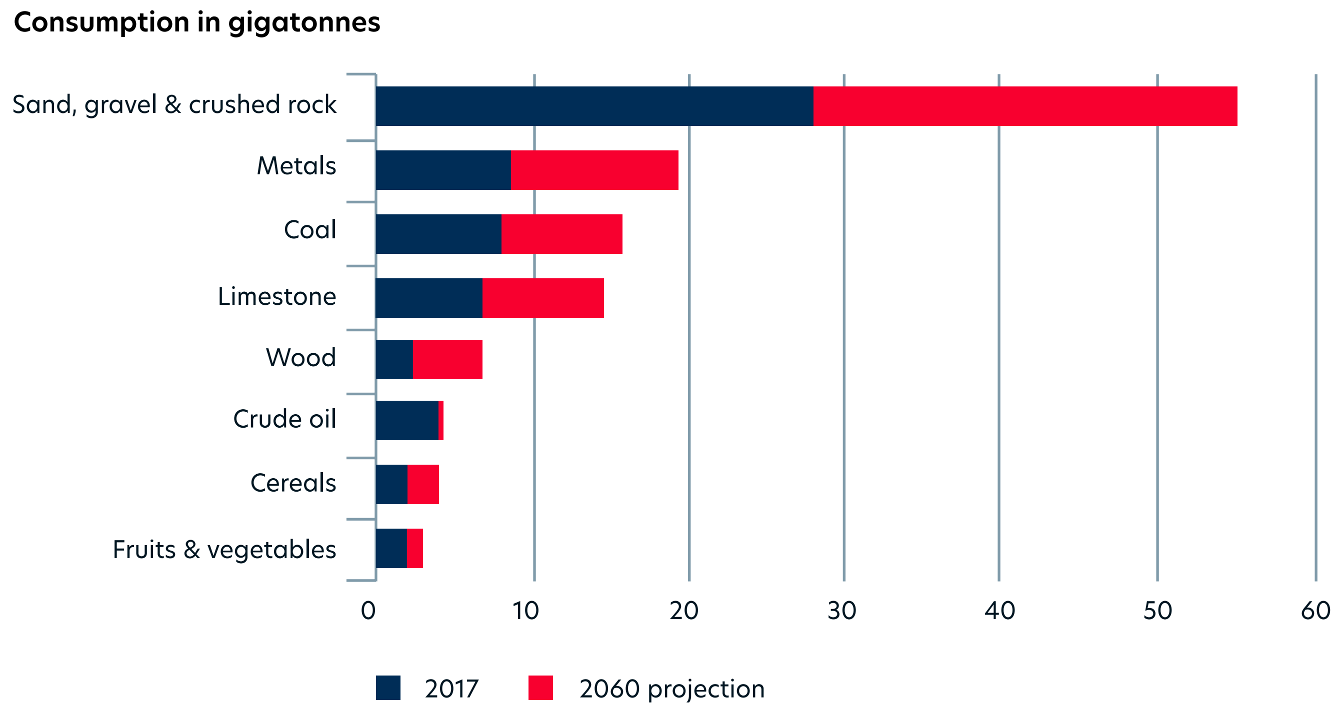
"Our use of sand brings us up against the wall ", depicting the quantity and nature of the demand for sand and gravel that sees up to 50 billion tons of the natural resources harvested annually (UNEP, 2019). Putting this into context, it shows that sand and gravel is the world's second most consumed natural resources (UNEP, 2022).

The growth in demand for sand and gravel mirrors the growth, not only in global population but also the rate of urbanisation resulting in soaring demand for infrastructure and services and by extension, building materials (Schiller and Roscher, 2023). Presently, 55% of the global population live in cities and this is forecast to rise to 68% by 2050 (UN DESA, 2018). Most of the growth is expected in developing countries, which host rapidly growing emerging economies and poorer countries where infrastructure deficits are most pronounced and deepening the inequality between and within countries (Pandy, et. al., 2021; UN, 2020). The common underlying characteristic between these economies is that they seek socio-economic growth, and the nature and pattern of this growth often manifests itself in infrastructure demand and provisions. India, China and Nigeria, for example, are expected to account for 35% of projected growth in global urban population by 2050, when they are expected to add 416 million, 255 million and 189 million, respectively, to the urban population (UN, 2018).

These parts of the world are also experiencing greater demand for building materials given the high correlation between urbanisation and consumption of construction activities (Schiller and Roscher, 2023). Indeed, the construction sector, according to Dellink (2020) estimates, accounts for 65% of all non-metallic minerals, 15% ferrous metals and 3% non-ferrous metals. According to Greenpeace International, sand and gravel constitute 79% of total material extraction from riverbeds, and this is estimated at more than 30 billion tonnes annually, exceeding fossil fuels and biomass extraction. This reemphasises the earlier point that sand and gravels combined, rank after water, as the most-used resources in the world by weight, and as Figure 1 shows, this trend is set to continue as demand is projected to double its 2017 levels by 2060, as global population growth and rates of urbanisation continue to intensify.

[2] https://www.greenpeace.org/international/story/19351/sand-depletion/

Figure 1: **Projection of Global Growth in Construction Raw Materials by Types**



Source: Global Material Resources Outlook to 2060. Economic Drivers and Environmental Consequences

2.0 Evaluation of the Environmental and Socio-Economic Consequences

2.1 Environmental Consequences

Large-scale extractions of natural resources entail severe environmental, economic, and social consequences. The largest natural reserves of industrially applicable sand are at the bottom of rivers and lakes, on the sea floor, and on beaches and riverbanks. For example, the UK has one of the largest construction aggregate dredging industries in the world, accounting for 25% of total annual consumption of sand and gravel while accounting for 50% of total consumption in London (Bide et al., 2016; The Crown Estate-MPA, 2021). Severe environmental degradation and adverse socio-economic consequences accompany the uncontrolled extraction of non-metallic mineral resources by the construction sector (Kondolf et al., 2014). Riverbeds are undergoing rapid depletion of natural sediments, and as sand is removed, everything that lives in the sand is destroyed, including the eggs of fish, turtles and crocodiles, which compromises the biodiversity and regenerative capacity of riverine ecosystems around the world (Koehnken et al., 2019). According to Torres et. al (2021), degradation to the ecosystem related to sand mining endangers species and ecosystems such as wetlands, rivers, coastal dunes, or seagrass meadows. Figure 3 shows the prevalent method for sand and gravel mining in developing

Figure 3: **River Sand Mining in India**

Source: https://www.indiatimes.com/explainers/news/explained-how-llegal-sand-mining-is-damaging-national-sanctuary-597014.html countries and in this case, in India.

As mining intensifies, the water-holding capacity of rivers declines rapidly, and the impacts of this can be observed from increased flooding around the world that continues to destroy farmlands, properties and livelihoods. For instance, sand mining along the Yangtze River in China was blamed for the catastrophic flooding that displaced millions of people in 2009 (Yu et al., 2009). Removal of riverbed materials alters natural habitats and water structure, which has far-reaching ecological consequences (Kondolf et al., 2014). A typical example is that many fish species rely on clean gravel beds for spawning; sand and gravel mining disrupt the reproductive cycles, reducing fish populations and eventual extinction (Koehnken et al., 2019).

Additionally, the eliminating of riparian vegetation destroys wildlife corridors and sanctuaries for birds, mammals and reptiles (Sreebha and Padmalal, 2011). Structural changes to river channels also threaten sensitive aquatic biota like macroinvertebrates that require specific substrate types (Koehnken et al., 2019). Consequently, excessive mining has been linked to sharp declines in biodiversity, evidenced in Ghana, where sand mining in Pra-River Basin of south central Ghana caused fish catches to plummet by up to 80% (Kusimi et al., 2014). According to Sreebha and Padmalal (2011), removing riparian vegetation also destabilises riverbanks and increases turbidity from soil runoff. Such effects often manifest in severe erosions to riverbanks erosions, widening water channels exacerbating beach erosions (Kondolf et al., 2014, UNEP, 2019), and damaging infrastructure and service (Willis and Griggs, 2003).

Aside from the environmental implications of raw material consumption intensity of the construction sector, the socio-economic consequences are also pronounced. River sand mining also has wide-ranging social implications for communities and local well-being. When the water level rises, local flood risks and occurrences increase, and scarcity of portable water and compelling long-distance travels in search of drinking water (UNEP, 2019). The burden usually falls on women and children who might forfeit education and gainful employment and income generating opportunities searching for water (UNEP, 2019). Indeed, Behera (2020) found gender inequalities in the share of burdens associated with displaced livelihoods, showing that women disproportionately experience the responsibilities associated with displaced livelihoods and water scarcity, hence worse health effects (Behera, 2020). In worst-case scenarios, flooding associated high level water rises following from exploitation of sand and gravel has forced outward migration. Where this is the case, communal clashes often occur, especially where there are disruptions to food production and supply (UNEP, 2019). Tourism is not exempted, and when mining degrades scenic riverbanks, wetlands and beaches, tourism suffers (UNEP, 2019).

Lower water tables caused by excessive mining of sand and gravel constitute severe environmental problems, as it affects water quality. This further exacerbates the issues of water borne diseases. The case of Vietnam is instructive. There, frequent outbreaks of child diarrhoea were linked to degraded water quality from excessive sand mining (2016, Lee, et. al. 2020). It also causes rivers to change course, forcing long distance travels to fetch water and other services the rivers provide. Similarly, erosions to riverbanks and the attendant erosions effects exacerbate impacts of landslides owing to losses of vegetations to erosions (Hackney, 2020). The overall environmental impacts of excessive sand and gravel mining can be seen in the work of Kresojević et al., (2023); they found in the case of Puerto Rico that sand and gravel mining aggravated the impacts of Hurricane Maria's catastrophic flooding in 2017. In this incident, houses and other critical social infrastructure and services were either destroyed or rendered unsafe and unusable, deepening poverty and widening inequality due to the damage to basic socioeconomic amenities (Kondolf et al., 2014; Pandey, et. al. 2021).

2.2 Socio-Economic Consequences

Economic impacts of intensive river mining for sands and gravel often manifest themselves in loss of employment and income-generating opportunities in the long run. This is particularly the case where livelihoods depend on rivers for transporting goods and services or other river ecosystem services such as fisheries and leisure, as employment and income-generating opportunities are lost as a result of the ecological damage. Where riverine habitats have been destroyed, a noticeable decline in river ecosystem services, such as the decline in fish stocks, is inevitable, and this has undermined food and income security for both subsistence and commercial activities (Kusimi et al., 2014). Cambodia is a case in point where the fishing industry has collapsed due to excessive sand and gravel mining in the Mekong river (Flynn and Srey, 2022). The economic effects are not limited to households but also affect inflows of government revenue, particularly at the local level.

Evidence of overexploitation of sand and gravel has emerged, and construction companies have reported significant delays in difficulties in getting supply through. For example, Dubai now imports these resources from Australia, while India's consumption of sand has tripled since 2000 and is still growing. The case of Denver International Airport project is another illustrative example where the increase in cost from $2.8 to $4.8 billion at completion was partly attributed to the scarcity of sand, gravel, and crushed rock together with attendant delays, affecting other costs considerations (USGS, 2017). This has implications for the affordability of construction products when such costs are passed on to consumers in the form of higher prices. The findings by Alabi and Fapohunda (2021) show that increases in the costs of building materials have made delivery of affordable housing difficult in South Africa. It is evident that the sequence of overuse of resources the rapid rates of resource depletion and attendant pollution and degradation of the natural capital results in market instability and higher price levels (EMF, 2013).

Other than cost escalation associated with the rapid rate of depletion in natural resources and attendant economic consequences, scarcity of materials has introduced organised crime and racketeering into sand and gravel mining and supply with the use of child labour and reported attacks and killings reported around the world (Mahadevan, 2019; UNEP, 2019, Amnesty International, 2016) . A study on India found that 418 people lost their lives and another 438 were injured between December 2020 and March 2022, and these incidents were all related to sand mining for the Indian construction industry (Singh, 2022). Of particular interest is the finding that in 49 cases, the victims were not necessarily sand miners but people who drowned in the deep pits created in the river because of sand mining (Singh, 2022). In the words of Pascal Peduzzi, a Director at the United Nations environment programme and author of a study on sand mining, "as price of sand goes up, the 'mafias' get more involved" (UNEP, 2019). It is worthwhile noting the fact that the incidence of organised crime in sand mining has results in several killings reported around the world, including South Africa, India, Kenya, Mexico, Gambia, and Indonesia (Beiser, 2017).

Globally, it is increasingly recognised that, on all fronts, the connection between growth in construction activities and demand for natural resource inputs must be decoupled from each other. It is pertinent to recognise that actions have been taken worldwide to regulate sand and gravel mining and reduce the intensity of material use in the global construction industry (UNEP, 2019, and Torres et al, 2017). These efforts are important and necessary but are insufficient to successfully decouple global construction outputs from intensive consumption of raw materials. First, most C&D waste recovery efforts are concentrated in developed economies, leaving out emerging economies where materials consumptions are most intense (Llatas, 2011; Nagapan et al. 2012; Wang, 2018). Secondly, even in developed economies where C&D waste recovery is realised, such as in the UK, the bulk of the waste, which is mainly forms of concrete, ends up in landfills (Vieira, et. al. 2016). This implies that that there is much scope for recovering more of the values that reside in the raw materials used in construction and are intrinsic in manufactured construction products.

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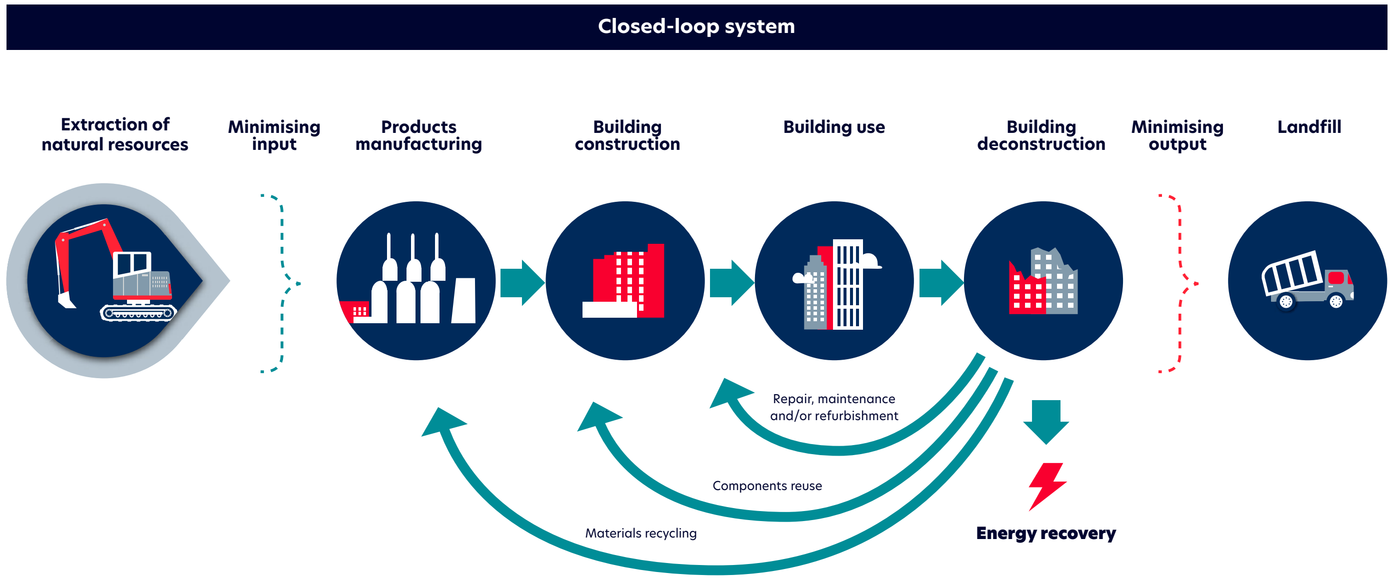
[3] Amnesty International Report 2015/16 – Gambia. https://www.refworld.org/docid/56d05b56c.html [accessed 14 September 2023]

3.0 Moving global construction from linearity to circularity

The linear model upon which global construction has operated for centuries now works on the assumption that natural resources will always be available, abundant, and easy to obtain, and the free market has the power to internalise all costs (Murray, et. al., 2017, Ebohon, 2022). Related to construction, the linear model allows the global construction industry to consume natural resources and produce buildings that when their physical or economic lives are exhausted, would be deconstructed and discard as wastes. As made known in this study, the values are unrecovered, and the process incurs significant pollution effects. The linear construction industry model functions on a supply chain that is inherently wasteful and polluting (Urbinati, et. al 2017).

The circular economy approach, on the other hand, is a regenerative system that aims to maintain the use of materials and components for as long as possible while also preserving their value. In other words, under circular construction practice, the industry should optimise resource use to preserve and enhance natural assets because of the finite nature of most resources it consumes, and at the same time, manage inflows of renewable resources (EMF, 2013). The industry also should, from the onset, identify and mitigate negative externalities right from the preconstruction design stages of built assets. Figure 4 distinguishes between the conventional linear model that global construction must depart from, and the circular economy framework the industry must adopt in the interest of sustainability, and also for its own existence. Hence, there is an existential necessity for global construction to embrace circularity.

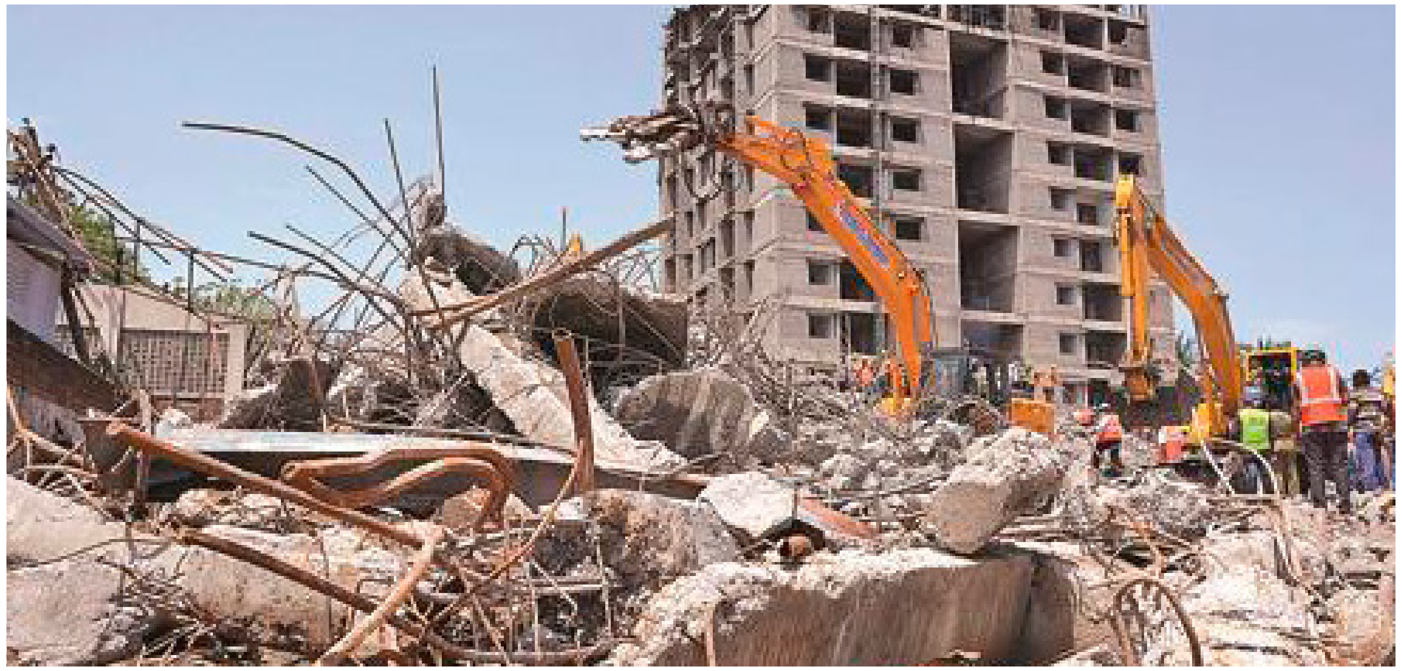
Figure 4: Extraction of natural resources



Source: Rahla, et al (2021).

Under the current linear construction practice, the culture is one of production, consumption, and disposal, generating large volumes of solid waste in the process. According to a 2020 report by the World Bank, global C&D waste was estimated at between 10-12 billion tons annually, accounting for 30% to 40% of total annual global wastes. As Figure 5 reveals, C&D wastes vary between various composite materials of cement, cementitious materials and gypsum, bricks, concretes, ceramics, irons, pipes, wood, glass, stones, and plastics. C&D wastes occur for various reasons that cut across the infrastructure design, procurement, planning, construction, operation and demolition process, but it is widely assumed as the incidence of design failure made possible by the linear model that the global construction industry has operated until now. When infrastructure exhaust either physical or economic lives, and require modernisation or change in use, it is decided between refurbishment or redevelopment as the best option. Under the linear system, resultant construction wastes are subject to no recovery or recycling process but are transported to landfills together with the values residing in the materials (Rees, 1999). Additional to these residual values, which included significant amount of embodied energy and associated carbon emissions, further environmental costs are incurred in the energy and carbon emissions implications of the journeys between sites and landfills.

Figure 5: Typical Construction and Demolition Wastes



Source: https://dreamcivil.com/construction-waste/

Figure 5 evidence the forms or composition of C&D wastes explained earlier, but suffice to say that generally, aggregates predominate C&D wastes, and the higher the level of development proxied by higher infrastructure demands, the higher the share of C&D in total solid wastes generated. Also important to note, is that the proportions of C&D wastes recycled vary within and between countries but markedly higher in some developed and middle income countries than in less developed countries (Alsheyab, 2022). For example, the estimated volume of C&D wastes for the US in 2018 was 544 million tonnes and only 76% was recovered. This leaves about 132 million tonnes ending in landfills. In the UK, a total of 3.2 billion aggregates was consumed by UK construction industry between 2008 and 2022, and of this total, only 28% derived from recycled and secondary sources. The forecast for 2022 to 2035 indicates that demand will grow by 900,000,000 tonnes to 4.1 billion tonnes of aggregates. As with the previous period, a relatively small proportion of this will derive from recycled and secondary sources.

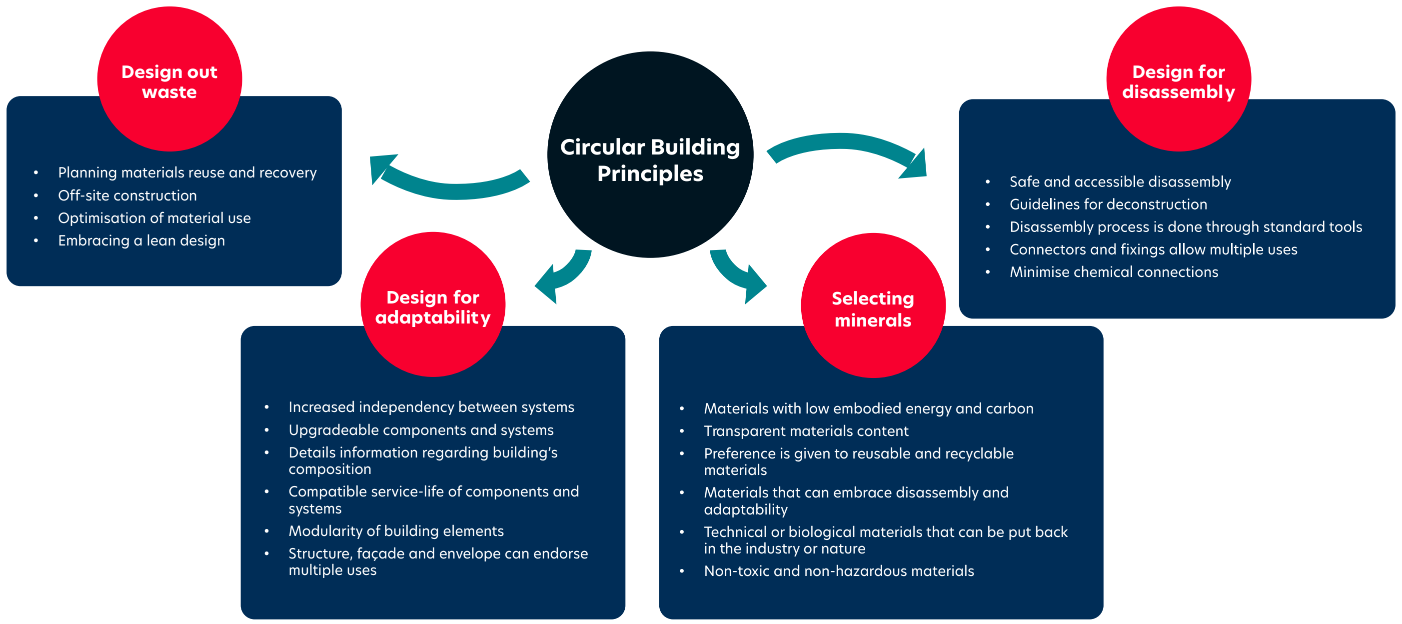
The European Union generates about 850 million tonnes of C&D wastes annually (Saez, and Osmani, 2019), representing 40% of total solid wastes. What these scenarios demonstrate is the scope that exists for recycling, recovery, and reuse of C&D wastes.

The scope for further recycling, recovery and reuse of C&D wastes is further demonstrated when the cases of middle income countries like China and India are considered. In China, C&D wastes account for between 30% to 40% of total wastes, but only about 5% of this total is recycled. Across Chinese cities, only Shanghai manages a recycling rate of 15%, the rest achieve between 3% and 10% (Huang, et al. 2018). India is no exception; it recycles only 1% of the annual 150 million tonnes of C&D wastes (CSE, 2020). As with China, India's limited focus on recycling C&D wastes explain the low C&D wastes recycling capacity that currently exist in the country, and as a result, C&D wastes indiscriminately disposed. This is widely practiced, posing significant environmental problems and natural hazards to households, particularly children (Cook, et. al., 2022).

The circular economy approach to global construction remains an effective strategy that can be deployed to decouple existing and expected growths in global construction activities from intensive consumption of natural resources (Liu and Ramakrishna, 2021). Estimates show that circular strategies can lower demand for natural resources by one third globally (WEF, 2023), and a study by the Dutch government puts potential savings from circular strategies as high as 30% (Schut et al., 2015). Evidence abounds that preventing waste disposal and improving material efficiency and recovery could lower emissions across the building lifecycle by around by as much as 40% (Material Economics, 2018), justifying the innovation involving digital manufacturing for circularity in cementitious products.

The principles of the circular economy are evident in Figure 4. They reveal circularity as a system that emphasises keeping, for as long as possible, the value added to raw materials through processing stages of extraction right through to manufacture and distribution in order to eliminate wastes and save on natural resource consumptions (Haas et al., 2015, Kalmykova, et al. 2018). This is why circularity is seen as a combination of lifecycle and system thinking (Arzoumanidis, et. al., 2021; Bruce, et al., 2023). It is system thinking for two important reasons. First, circularity allows for better understanding of the nexus between the built and natural environments, and in this example, why the construction industry is overtly resource intensive. Secondly, it provides a framework for articulating and implementing efficient solutions for decoupling growth in construction activities from material consumption. Like lifecycle thinking, circularity demands construction designs that provide scope for recycling and reuse of building components; this relieves the natural environment of pressure for more resources by global construction.

Figure 6: Designing for circular economy



Source: Rahla, et al (2021).

Figure 6 indicates the process of mainstreaming circularity into global construction industry practice. The process begins at the preconstruction stage with conscious decisions to design out wastes. This requires attention to be paid to the selection of materials and built asset designs. Materials likely to cause less harm to the natural environment and the ecosystems, and flexible designs of built asset are the emphasis. The significance of this to the circular economy framework is in permitting easy disassembling and reassembling and increasing the scope of recycling and repurposing materials for multiple reuses.

Adopting the circular economy approach in construction can bring significant benefits to the environment and the construction industry itself. As the case of China demonstrates, these benefits manifest themselves in cost savings, increased access to materials, and reduction in pollution (Liu, and Ramakrishna 2021). As Figure 7 reveals, if China were to maintain current growth rates in construction activities, and implement circularity, it will save 18% and 39% in the costs of accessing construction materials by 2030 and 2040 respectively. The most dramatic change occurs in reductions in the consumption of virgin materials, which, estimates show, will decline by 18% and 71% by 2030 and 2040 respectively. Similar benefits are expected in reductions to the costs to society from particulate emissions. In the case of PM2.5, 9% and 58% reduction in societal costs are possible by 2030 and 2040 respectively while 18% and 72% costs reductions are possible by 2030 and 2040 respectively.

Figure 7: A circular built environment: the benefit for China's Cities

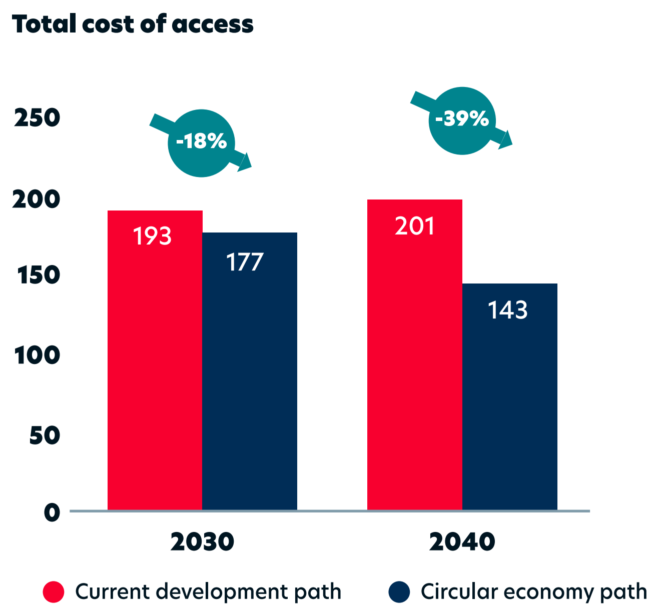
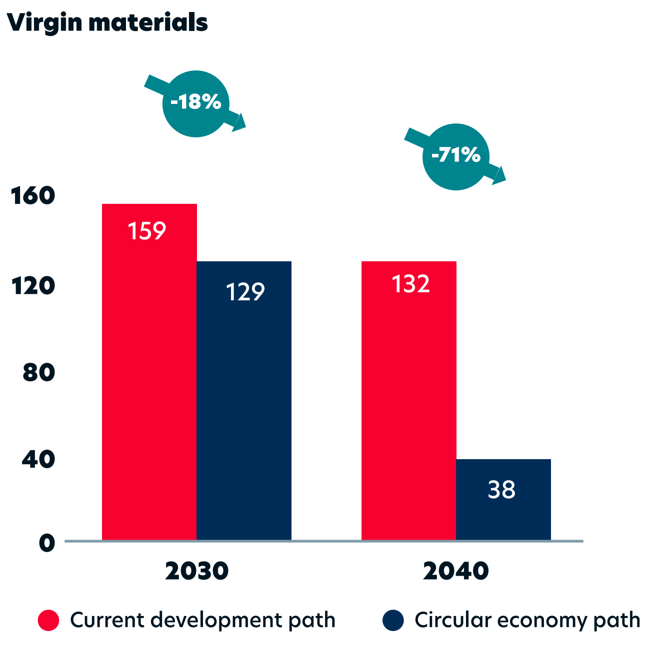
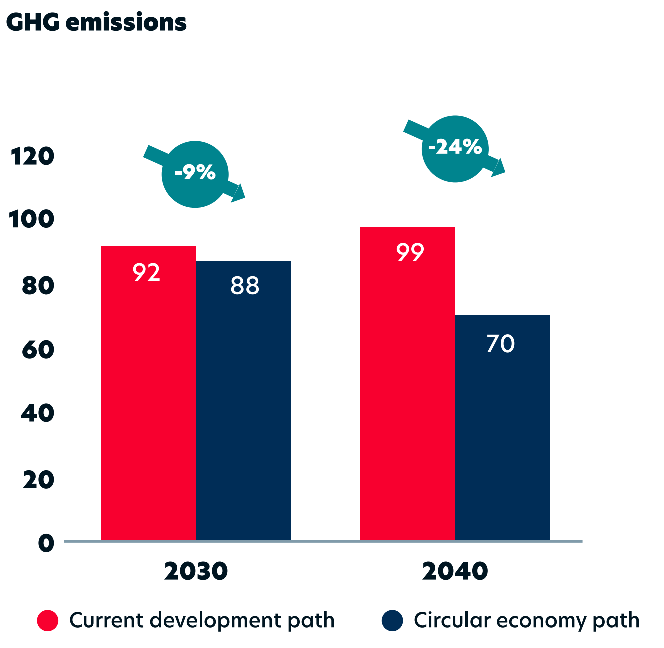
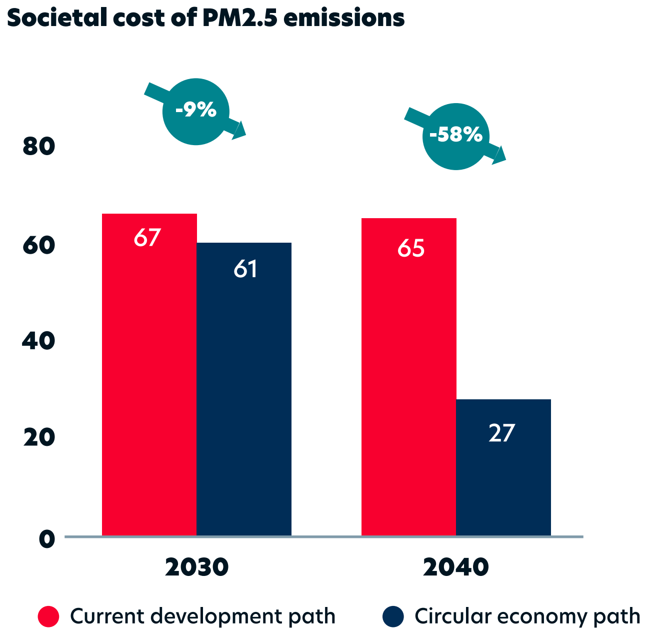
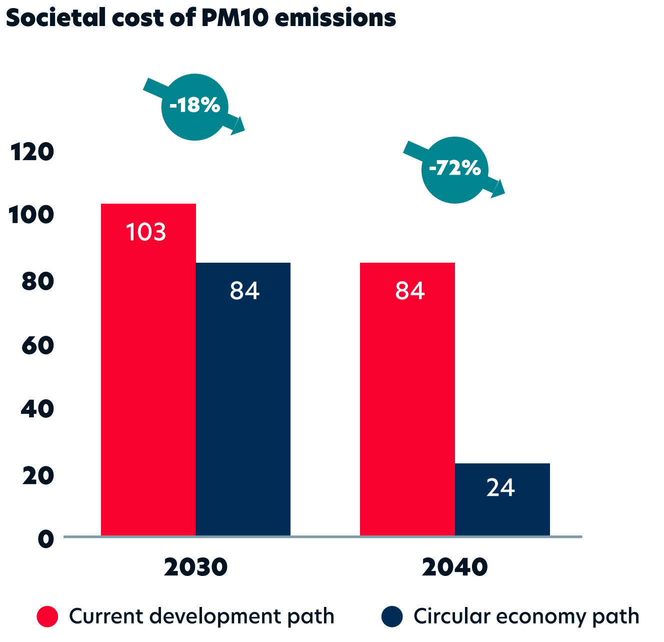


Figure 7: a circular built environment: the benefit for China's Cities (continued)









Source: Rahla, et al (2021).

Our findings provide evidence that confirms the benefits of adopting the circular economy approach in global construction practice. Further shown is that the circular economy presents more scope of enhancing and recovering the economic values by repurposing C&D wastes for reuse in global construction. Finally, circular economy presents an effective means of disrupting the strong correlation between growth in construction activities and intensity in raw material use.

4.0 Operationalising Circularity in Recycled Aggregates

Three approaches were adopted in this study. The first was to experiment with different mixes of cementitious materials to find the optimum mix that will deliver the equivalent or better performance in terms of strength and water absorption, compared to products made from virgin materials. The experimental process, findings, and analysis are presented in Figure 14.

The second approach was to apply additive digital manufacturing and evaluate the socio-economic and environmental benefits of enhancing recycling through digital additive manufacturing.

The third approach is to address key research gaps around lifecycle impacts, economic viability, social acceptance, and regulatory barriers associated with digital fabrication methods. This was achieved by a triangulation research method using a quantitative and qualitative questionnaire design to ascertain the opinions of industry stakeholders and policy makers. As cementitious products like concrete remain fundamental to urban infrastructure worldwide despite the ecological footprint, it is crucial to ascertain the acceptance of such promising sustainability strategy of repurposing C&D wastes into new products for reuse in global construction.

4.1 The Traditional Manufacturing of Cementitious

To accomplish this part of the project of carrying out environmental and socio-economic evaluations between the digital and the traditional or conventional manufacturing of cementitious products using recycled materials, there is a need to present the laboratory experimental analysis of the recycled construction materials manufactured traditionally.

This is in line with the aim of the project to enhance the reuse of recycled materials from construction & demolition (C&D) wastes. Hence, the mix proportions, physical properties, including the mechanical strength and the water absorption of the recycled materials were analysed and are presented.

4.2 Recycled Materials

The recycled materials from construction and demolition (C&D) wastes used in the experimental procedure were obtained from the industry collaborator, the Sheehan Group, an Oxfordshire-based company that specialises in recycling of demolition construction wastes into new concrete form. The research team on this project, from the Centre for the Integrated Delivery of the Built Environment (IDoBE) at London South Bank University (LSBU) visited the industry collaborator to discuss the type and sizes of recycled materials needed for this project and to observe how the recycled aggregates are being processed before delivery. This deliberation of the LSBU team was led by the Principal Investigator and the Director of IDoBE with the representative of the company. Figures 2 and 3 show the recycled fine and coarse aggregates delivered from the company respectively. The recycled aggregates were further cleaned and sieved in the laboratory and repurposed according to their dimensions to produce the test specimens.

Natural aggregates, both fine and coarse were collected for the laboratory experimental works as well. For the natural aggregates used in the experimental analysis, sea-won coarse and fine aggregates were found suitable for the concrete mixes. Ordinary Portland cement (OPC) with a 28d nominal compressive strength of 52.5 MPa was used as a binder for the experimental process, which is in conformity with BS EN 197-118 (CEM 1 52.5R). Tap water was used for the mixes while various water/cement ratios were implemented to achieve the best mix for the experimental product. Polycarboxylate polymer-based superplasticizer was employed in the laboratory work; it is necessary to provide effective workability at a low water/cement ratio of the mixes.

5.0 Laboratory Experiment: Mixing Procedures and Test Methods

5.1 Mix Design

After many laboratory mixing trials and samples of mixes reviewed from previous research works on recycled concrete aggregates (RCA) such as the concrete mixtures composition from Guo et. al., (2018) as shown in Table 1, six main series of mix proportions were designed in this experimental programme. The main aim of designing series of mixes was to compare the strength capacity attained by the samples manufactured from the natural aggregates to that manufactured from the recycled aggregates. Table 2 shows the six mix proportions including the control mix containing 100% natural fine and coarse aggregates. Mixes 1 and 4 consist of 100% recycled aggregates which is a full replacement for natural fine and coarse aggregates. In these mixes, the water/cement ratio varies from 0.68 to 0.6 respectively while Mix 4 contains higher polymer-based superplasticizer to cater for the reduced water content. On the other hand, there is 50% replacement of natural aggregates by the recycled aggregates in Mixes 2 and 5. In Mix 3, there is 70% replacement of natural aggregates while the water/cement ratio remains at 0.6.

Table 1: Concrete Mixtures Composition

Mixture notation	Mixing water (kg/m3)	Cement (Kg/m3)	NCA (Kg/m3)	RCA (Kg/m3)	River sand (Kg/m3)	Additional water (Kg/m3)
Control	155	316.17	2041.13	0	738.40	0
RB-75	155	316.17	1154.93	886.20	738.40	20

Source: Guo et al., (2018)

Table 2: Series of Concrete Mixtures Composition and the Control Mix

	Mix Design A - w/c 0.6 - all Kg/m3 except admixture					
Material	**100% Natural materials (Control)**	**MIX 1 100% RA**	**MIX 2 50/50**	**MIX 3 30/70**	**MIX 4 100% RA**	**MIX 5 50/50**
w/c	0.60	0.68	0.68	0.60	0.60	0.60
52.5 Cement	310	310	310	310	310	310
Free water	185	210	210	185	185	185
FA	730	0	365	219	0	365
CA 4/10	1075	0	537.5	322.5	0	537.5
RFA	0	730	365	511	730	365
RCA 4/10	0	1075	537.5	752.5	1075	537.5
Admx (l)	1	2	2	3	4.5	1

Notes: Control: 100% natural aggregates, Mixes 1 – 5: Contain recycled aggregates, Mixes 1 and 4: Contain 100% recycle aggregates.

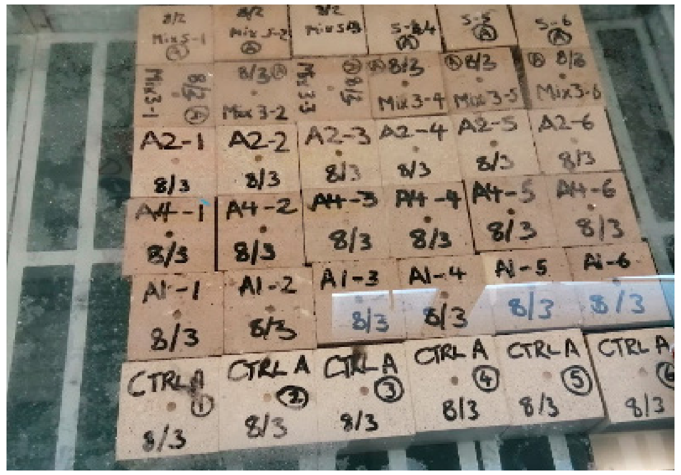
5.2 Mixing procedures

The mixing of the concrete components was accomplished using a pan mixer of 0.05 m3 capacity as shown in Figure 10. The fine aggregate, coarse aggregate, and the cement were dry mixed for about 2 minutes. Then, water and superplasticizer were added and further mixed for another 3 minutes to achieve a homogeneous mix. Consequently, for each mixture, three replicates of 100 mm cubes were produced. All the specimens were cured in a water tank at 20 ± 2 °C until testing at 7 and 28 days. Figure 12 shows the fresh concrete in cubes before they were demoulded after 24 h. Figure 13 shows the cubes immersed in water in a curing tank. It can be observed here that the concrete cubes manufactured from recycled aggregate are darker in colour than those manufactured from the natural aggregates, as evident in Figure 13.

Figure 11: Pan Mixer of 0.05 m3 Capacity Employed for Concrete Mixing.

Figure 12: Fresh Concrete in 100mm Cubes

Figure 13: Experimental Analysis of Properties of Recycled Aggregate Concrete

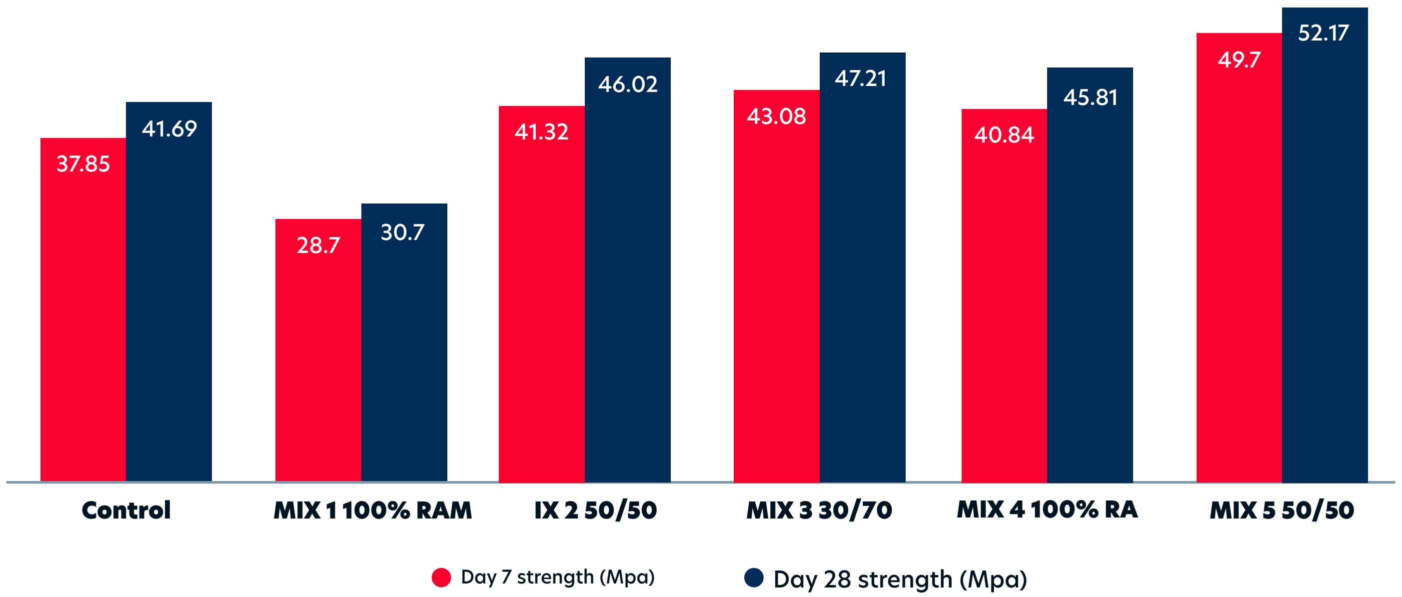


The compressive strength test carried out on 100 mm cubes was undertaken using a hydraulic press ELE International, ADR-Autotest machine with 2000 kN maximum capacity. All the tests in the experimental programme were carried out at a testing age of 7 and 28 days. The results of the compressive strengths of the specimens manufactured from mix designs of concrete using different proportions of natural and recycled aggregates are shown in Figure 14.

The results of the compressive strengths of the specimens manufactured from mix designs of concrete using different proportions of natural and recycled aggregates are shown in Figure 14

5.3 Analysis of Test Results

Figure 14: **Compressive Strength Results of Different Concrete Mix Design of Recycled Aggregates**



The compressive strength values presented in Figure 14 are the average values of three samples from each mix. It is apparent that all the samples tested were of the same compressive strength, consistently increasing with time. All the samples exhibit good strength development, as the day increases, with the lowest compressive strength of 28.7 MPa reached after 7 days from mix 1 samples, which contained 100% recycled aggregates. **This is significant in itself because from a priori-theorising it is believed that recycled aggregates are weak and unsuitable for producing cementitious products for reuse in construction. It is this belief that either discourages recycling and circularity in the construction industry, explaining why most C&D wastes end up in landfills.**

Indeed, it is of particular significance that the compressive strength value of 40.84 MPa and 45.81 MPa were achieved from Mix 4 samples of 100% recycled aggregates at 7 and 28 days respectively, demonstrating higher strength than the control samples produced from virgin materials. To illustrate this significance further, what was achieved in Mix 4 samples of 100% recycled aggregates at 28day test was a 9.9% higher strength than that obtained from samples produced with natural or virgin materials. This dispels the assumptions underpinning the exclusion of C&D wastes in recycling and reuse in construction products manufacture.

To illustrate this significance further, what was achieved in Mix 4 samples of 100% recycled aggregates at 28day test was a 9.9% higher strength than that obtained from samples produced with natural or virgin materials.

Other areas of concern are whether or not the ultimate recycled cementitious Mix 4 can be digitally used to 3D print cementitious products and what the socio-economic and environmental benefits can be expected to materialise, as a result. The concerns are that using digitally manufactured recycled construction products will costs more relative to the set up cost, and the uncertainties surrounding its adoption and wider use in the industry. This study, albeit under laboratory conditions, shows that these concerns are largely unfounded. In conclusion, it has been established that on structural integrity, functional integrity, and costs, there is no reason for discriminating against the use of recycled aggregates in global construction activities. **Thus, recycled aggregates compete and perform equally well in comparison to natural aggregates at a right mix design.**

5.4 Designing Block Mould to the Derived Right Mix

The next step was to digitally design an appropriate production mould that can be used to produce blocks out of the 'right mix' derived from our experiment. In designing the mould, it was decided to explore the possibility of further reducing constituent materials such as mortar without compromising the structural integrity of the building components produced from the blocks. This will not only lead to reductions in the amount of materials but also associated energy and carbon emissions, further decoupling growth in construction outputs from increased materials consumption. As the case of China shows, such savings can be very significant (Liu and Ramakrishna, 2021). Generally, significant environmental, economic, and social benefits can be achieved when C&D wastes are recycled into cementitious products and reused in place of natural materials.

5.5 Initial Design and Testing

An initial interlocking block design is presented in Figure 15. Aside from the conventional size, attempts were made to further reduce resource use by designing out the need for bonding mortar, hence the cylindrical interlocking features of the lego legs.

This produced in 3D format and printed in resin for testing in order to determine its durability when in use without a bonding agent. The 'Builder Extreme 1000 Pro' shown in Figure 16 was used to produce prototypes in Figure 17, which were subjected to structural integrity tests.

Figure 15: Interlocking Features of the Block

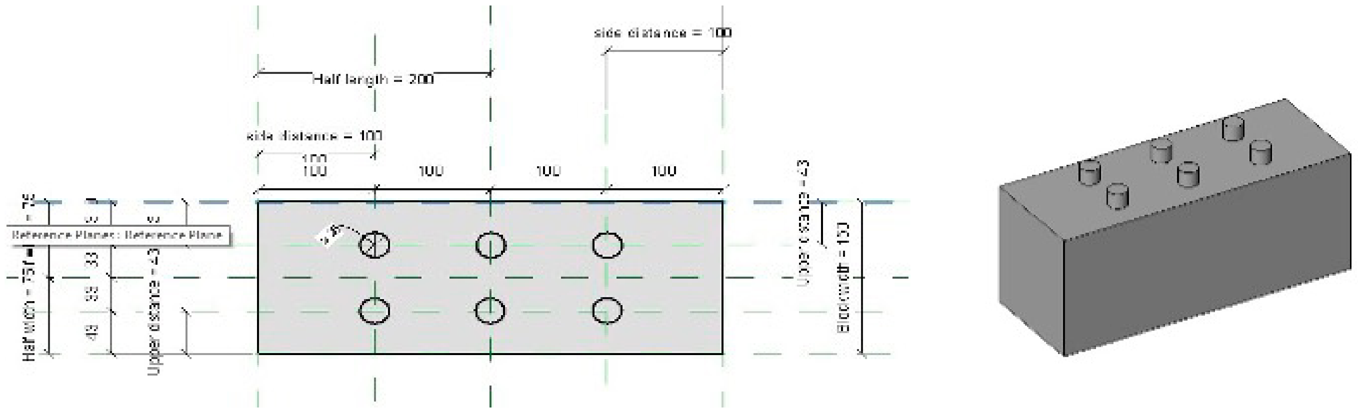


Figure 16: Builder Extreme 1000 Pro

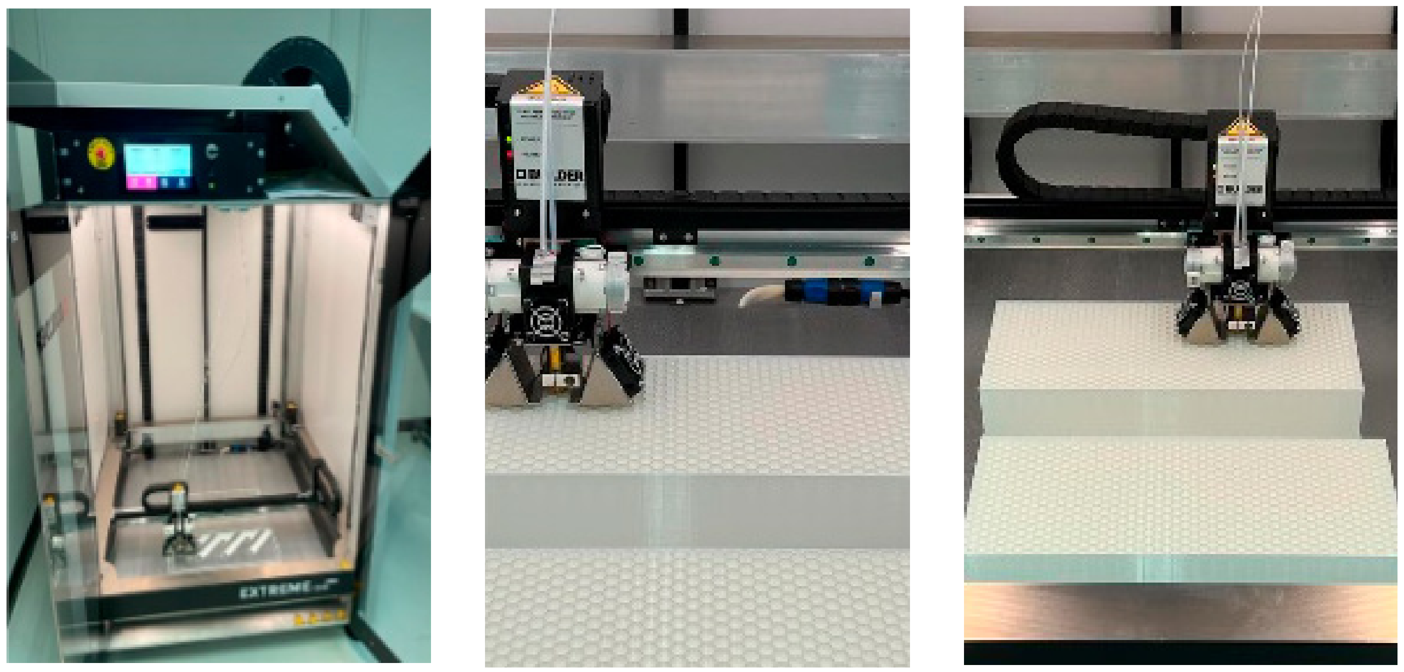
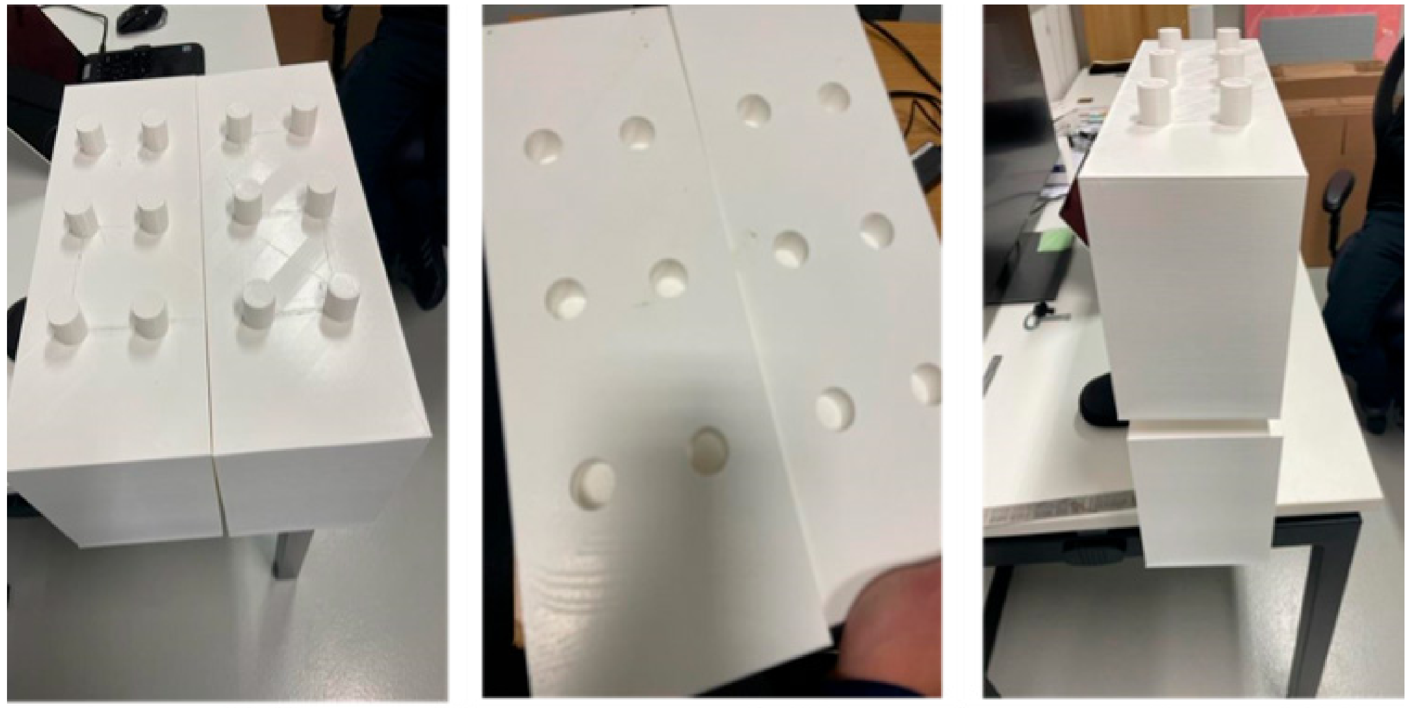


Figure 17: Resin Cylindrical Leg Prototype of Interlocking Blocks



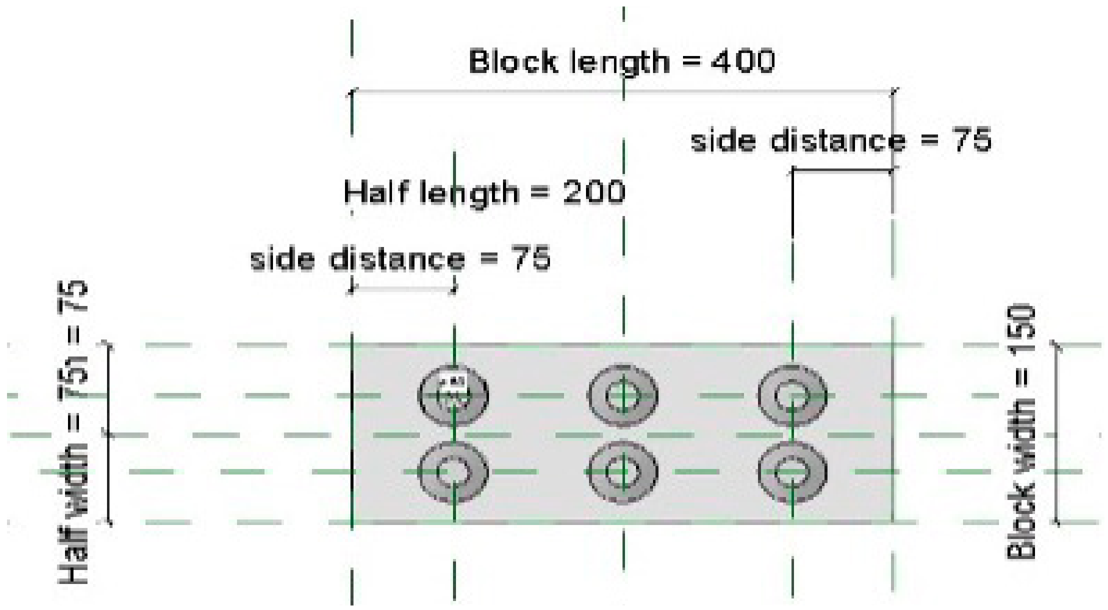
A: Top of brick

B: Bottom of brick

C: Bricks assembled

The parameters of the initial block design had to be changed, having performed inadequately with regards to structural integrity. The cylindrical legs snaped, it shows that it may require special packaging to protect the lego legs given the performance during testing. A new design was configured, as presented in Figure 18, where the lego legs were changed to conical shapes that were wider and shortened.

Figure 18: Resin Conical Leg Prototype of Interlocking Blocks



The conical shaped lego legs were found to have improved the structural integrity of the blocks. Based on this, a resin mould was designed, as shown in Figure 19. The rationale is to ensure consistency in size, length, and quality during production using the optimum or right mix, as found in the study.

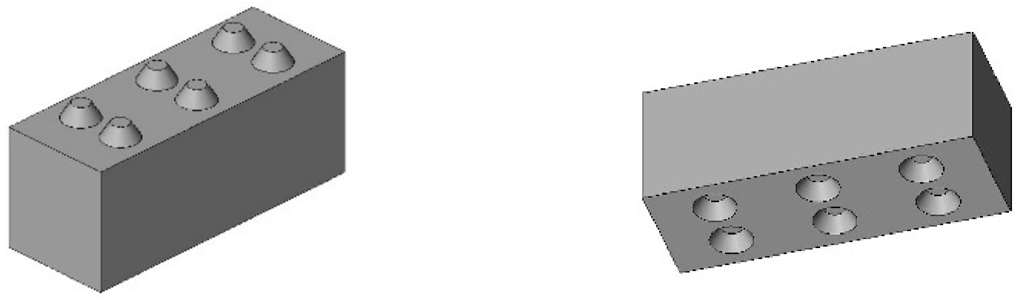
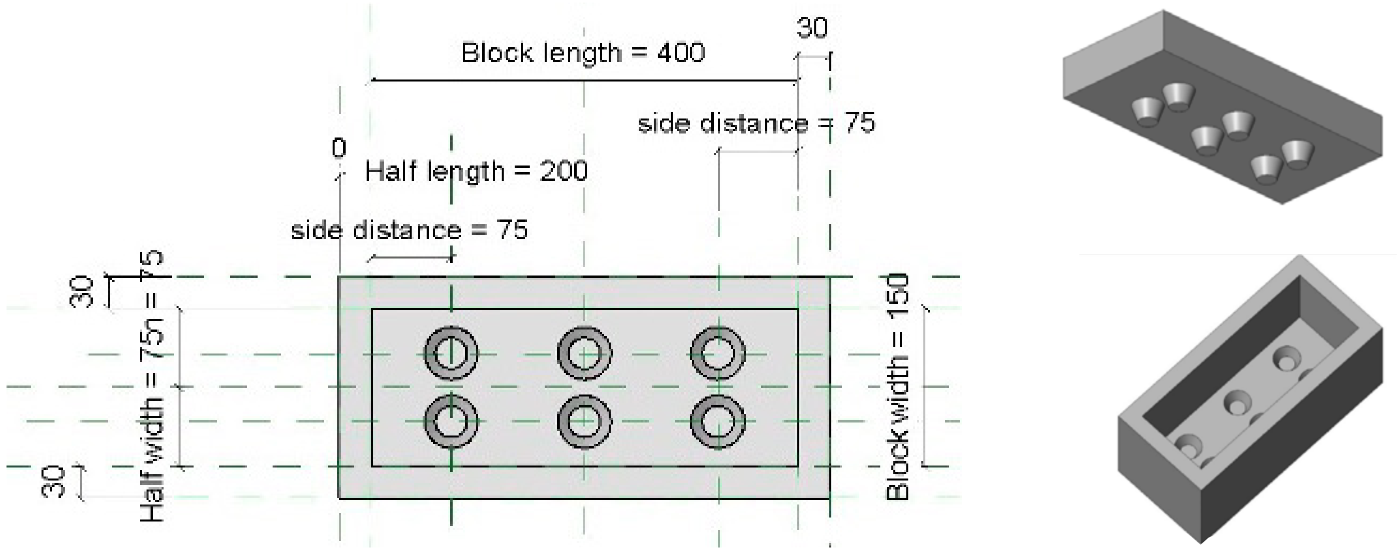


Figure 19: **Resin Mould of the Conical Leg Prototype of Interlocking Blocks**



This mould is expected to enable consistent traditional production of blocks using recycled aggregates. However, traditional construction methods such as erection of formwork and bricklaying are labour intensive, time consuming, and associated with significant wastes, particularly where quality controls can be difficult, resulting in mistakes and attendant reworks (Shahparvari, 2019). It was decided to explore using additive digital manufacturing to produce the block and evaluate the environmental and socio-economic attributes relative to traditional block.

6.0 Additive Digital Manufacturing of Cementitious Blocks

The application of additive manufacturing in the construction sector is gaining momentum owing to its versatility in handling complex construction tasks effectively and efficiently on site (Tay et al., 2017).

Also known as digital or automated construction, this method of construction is where robotics is programmed to deposit materials continuously in a desired 3D format (Tay et al., 2017).

6.1 Pattern Comparison

Several studies have highlighted the importance of layer deposition patterns in influencing the structural integrity and mechanical properties of additively manufactured cementitious structures. For example, Le et al. (2020) demonstrated that raster patterns with alternating print directions exhibit higher bond strength between layers compared to unidirectional raster patterns. In this study, this improvement is seen as a design strategy to better interlocking of the filaments in the bidirectional raster patterns. Similarly, Bos et al. (2016) experimentally found that varying the layer orientation angle from 0° to 90° in extrusion-based 3D printing of cementitious materials can significantly affect the flexural and compressive strength. Their results showed that a 0°/90° alternating pattern produced superior mechanical performance compared to 0° or 45° orientations.

When working with recycled aggregates, material variability can affect the flowability, consistency, and structural integrity of the printed material (Tam et al., 2018). Recycled aggregates often have a heterogeneous mix of particle sizes, shapes, and material properties depending on the source (Katz, 2003). This makes it challenging to achieve a consistent feedstock. Compatibility between the cement mix and aggregates is also critical, as differences in moisture absorption, thermal expansion, and interfacial bonding can cause flaws such as cracking and poor adhesion (Sanjayan et al., 2018). Developing an optimized mix design is therefore essential but challenging (Panda et al., 2017). The mix must balance suitable rheological properties for printing with sufficient strength in the final structure.

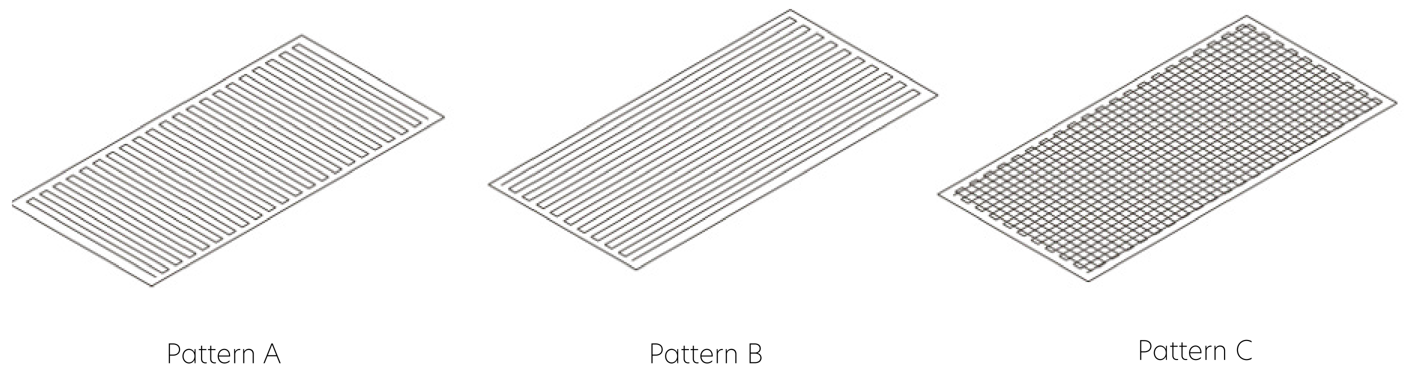
During the printing process, achieving consistent extrusion and layer bonding is difficult but crucial for structural integrity (Bos et al., 2016). The irregular surface and variable composition of recycled aggregates poses risks of poor interlayer adhesion (Le et al., 2019). Voids between layers can act as weak points in the printed structure (Weng et al., 2019). As printing is scaled up from prototypes to larger structures, maintaining print quality, material consistency, and stability are also concerns due to factors like moisture and temperature gradients (Kazemian et al., 2017).

Based on these findings, experimenting with different layering techniques when casting the cement geometry designed in phase 1 of the project could provide valuable insights. As discussed by Cao et al. (2018), the layered nature of additive manufacturing can lead to anisotropic behaviour and weaknesses between print layers. Testing lengthwise, crosswise and alternating patterns as proposed allow systematic evaluation of the impacts of build direction on the structural integrity and load-bearing capacity of the cement cast.

The alternating deposition pattern may strengthen interlayer bonding by enabling better overlap and mechanical interlocking between the filaments (Lee et al., 2020). However, the crosswise pattern could potentially introduce points of weakness or flaws perpendicular to the loading direction (Bos et al., 2016). Comparing the performance of casts printed with these different patterns will therefore help optimise the layer orientation to withstand multi-axial stresses and avoid unforeseen failure modes.

Overall, given the precedents in the existing literature, experimentally validating the effects of layer patterning is a prudent step before finalising the manufacturing process (Mostert and Kruger, 2022). The lessons can be used to refine the layering approach, enhance interlayer adhesion and achieve uniform strength in the cementitious structure.

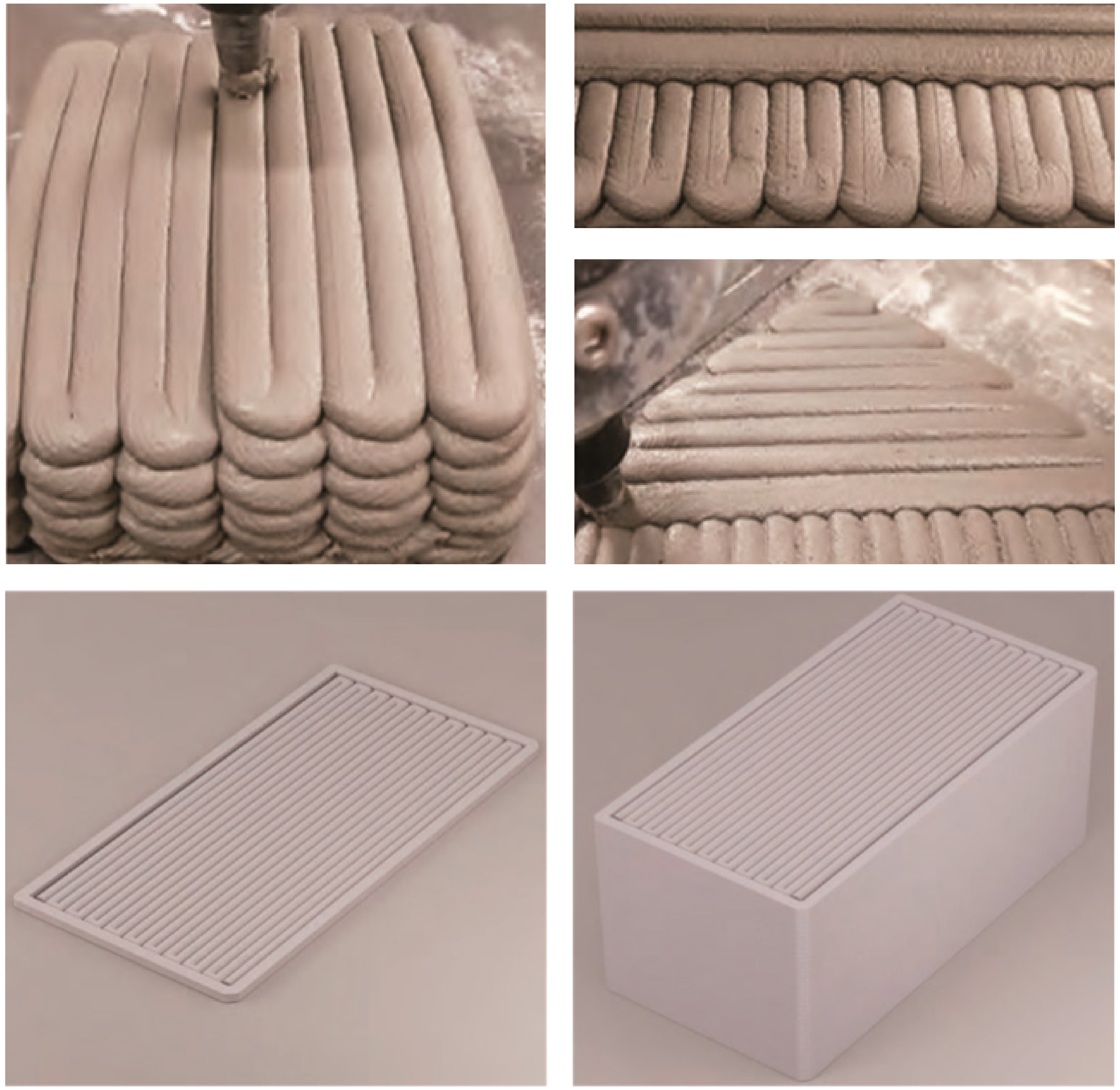
Figure 20: Options of Unidirectional and Multidirectional Layering Patterns



Using different infill patterns (unidirectional, bidirectional), we can reduce the amount of the material used, with a reduction of carbon emissions during production (Van Der Putten, 2019). This is particularly the case as there is no mould required with additive digital manufacturing. The flexibility allowed by the digital manufacturing system supports the development of a custom cementitious mix with recycled aggregates, for use in robotic additive manufacturing to achieve a tridimensional shape.

6.1.1 Pattern A

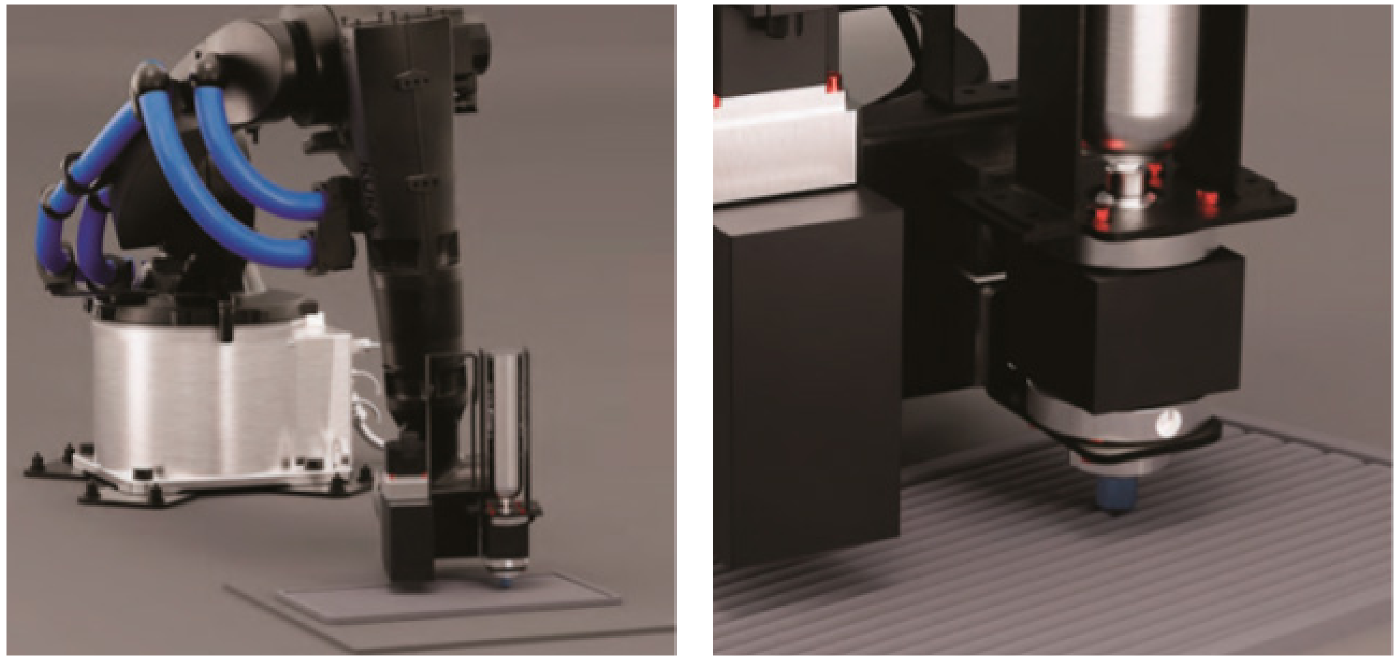
Figure 21: Printing Process Pattern A



(a) Simulation of the deposition
Simulation of the deposition of the 1st layer to create a 3D printed block using recycled aggregates. The type of pattern developed from the toolpath will help to reduce the amount of material used, hence reduction in CO_2 emissions.

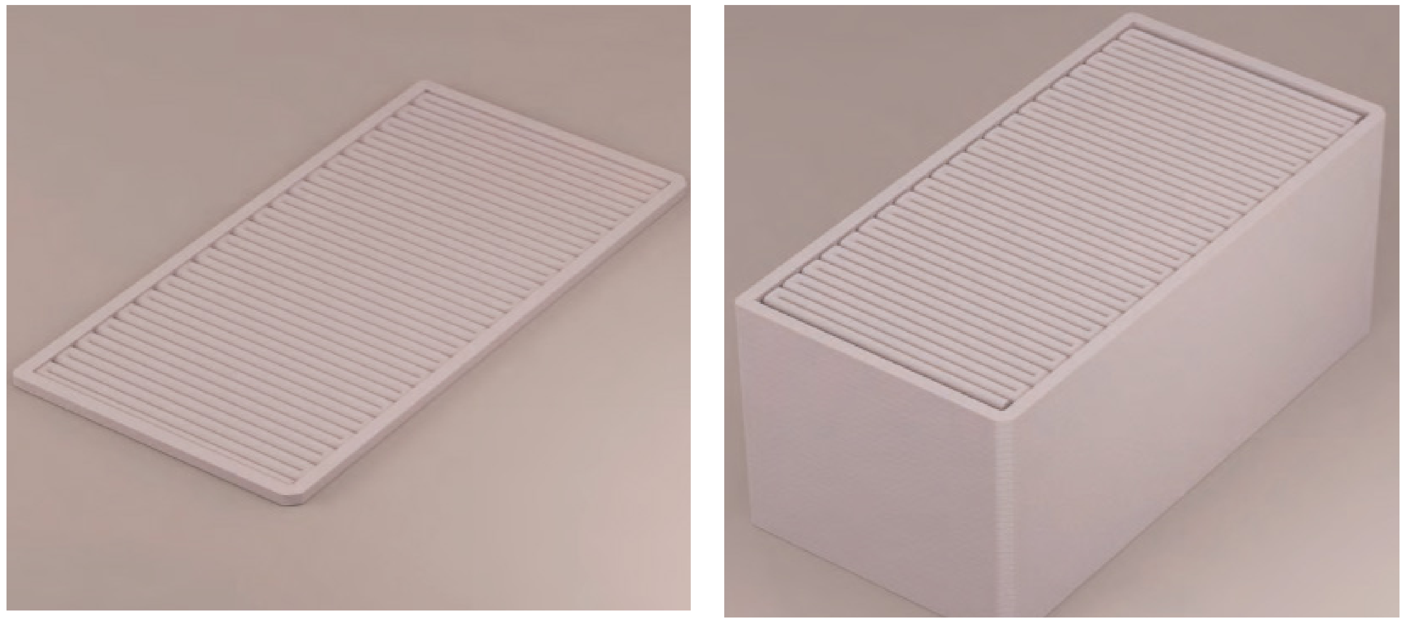
(b) Simulation of full deposition
Simulation of full deposition to create a 3D printed block using recycled aggregates.

Figure 22: Robotic Simulation of Pattern A



6.1.2 Pattern B

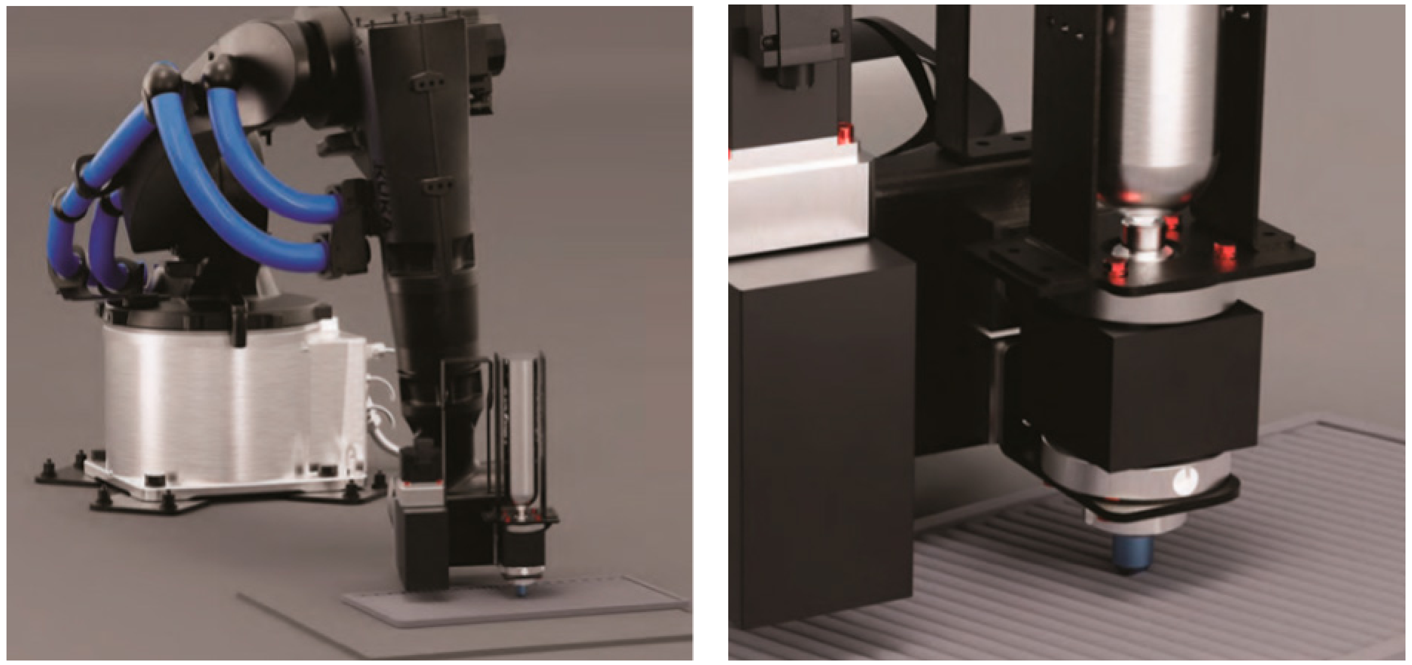
Figure 23: Printing Process Pattern B



(a) Simulation of the deposition
Deposition of the 1st layer to create a 3D printed block using recycled aggregates. The type of pattern developed from the toolpath will help to reduce the amount of material hence reduce the CO_2 emissions.

(b) Simulation of full deposition
Simulation of full deposition to create a 3D printed block using recycled aggregates.

Figure 24: Pattern B Robotic Simulation

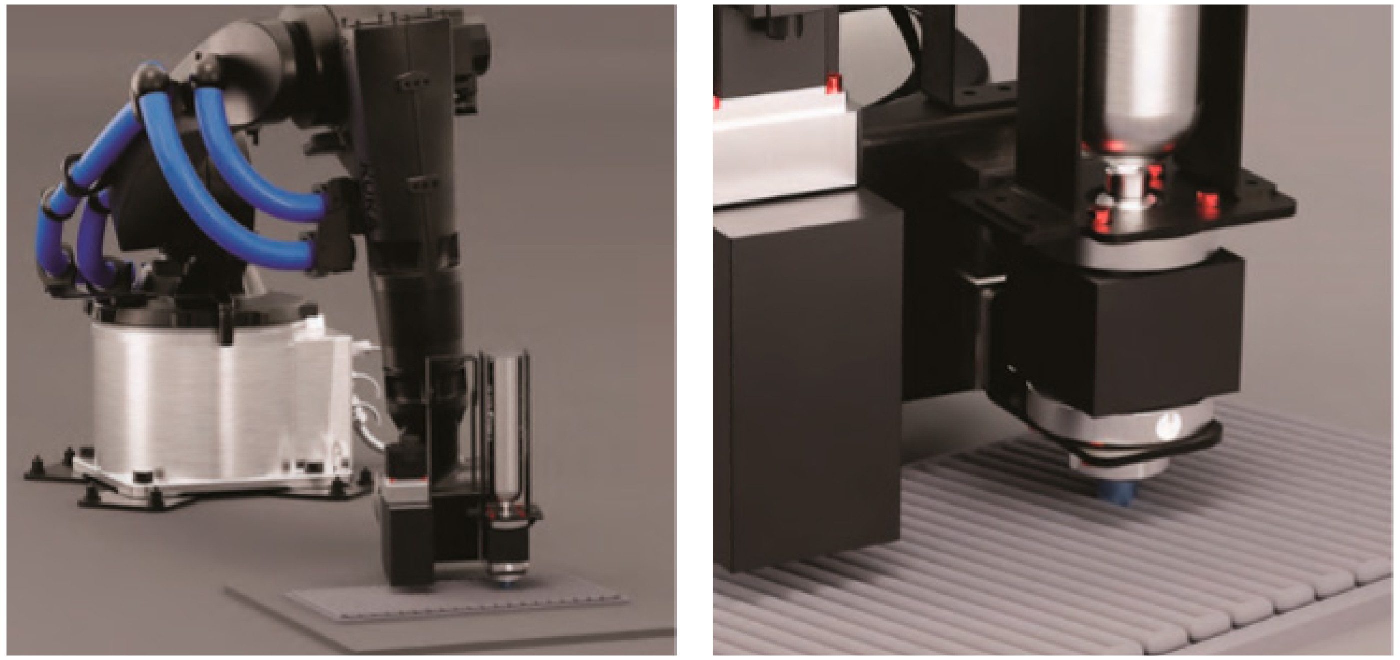


6.1.3 Pattern C

(a) Simulation of the deposition
Simulation of the deposition of the 1st layer to create a 3D printed block using recycled aggregates. The type of pattern developed from the toolpath will help to reduce the amount of material hence reduce the CO_2 emissions.

(b) Simulation of full deposition
Simulation of full deposition to create a 3D printed block using recycled aggregates.

Figure 25: Pattern C Robotic Simulation



7.0 Environmental and Socio-Economic Evaluation

Additive digital manufacturing or 3D printing introduces major disruptions to conventional construction processes owing to the unique capabilities to address seemingly protracted and complex construction problems. One of such problems is the limited opportunities for the application of recycling and reuse of C&D wastes, hence the limited scope for implementing circularity in the construction sector. However, the additive digital manufacturing process, by allowing combinations of materials, permits the upcycling of separate construction and demolition wastes into new and desirable construction products (De Jesus, 2019), thereby reducing C&D wastes faster than it would otherwise have been possible.

The free form digital manufacturing widens the scope and forms that cementitious products could be produced (Tay et al., 2017), allowing products to be manufactured to order (Bos et al., 2016). In particular, it enables complex interlocking shapes and forms to be manufactured such that they are easily deconstructed, recycled and reused after products, in their current usage, would have served their purpose (Agustí-Juan et al., 2017). As a result, digital fabrication allows the recovery of more raw materials value, as well as intrinsic values in construction products.

Recycling concrete, masonry, glass and plastic wastes through reprocessing into 3D printing input or robotic fabrication feedstock lowers costs by reducing the need for virgin raw materials, such as river sand and gravel. According to Panda et al., (2017), C&D waste and recycled plastics cost 50% to 80% less than conventional concrete ingredients. Also, significant cost savings follow from mass production or economies of scale. Affordability and access to construction products are enhanced when lower products costs are passed on to consumers in the form of lower prices. Process wise, mass-produced building elements like structural panels, bricks and partition walls printed using recycled concrete and plastics also avoid costs of material wastage and excess inventory build-up common in conventional construction. 3D printing allows just-in-time production with minimal leftovers or offcuts. Dell'Anno et al. (2021) estimate that 3D printing technologies can reduce raw material waste in construction by as much as 30% to 60%, generating substantial savings. Further cost reductions accrue from the elimination of plants and equipment from site and associated costs of transporting materials thereby eliminating carbon emissions and minimising construction carbon footprints (Panda et al., 2017).

However, while additive manufacturing presents numerous opportunities to reuse C&D wastes, and in alignment with circular economy principles, there are factors that should be considered to ascertain if there are net benefits. It is assumed that the functional integrity of manufactured recycled cementitious products will be sustained over the expected product lifecycle. Also not taken into account are the materials that go into producing digitalised additive manufacturing equipment and the energy consumption intensity of cement-based printing machines (Liu et al., 2021). Similarly, wider adoption of additive manufacturing and digitalisation of circular construction products is assumed with little consideration for the challenges that exist, such as high equipment costs and the lack of process standardization. Although these costs are likely to decrease in the future through economies of scale and use of cheaper secondary material inputs, wider innovation of digital manufacturing, hence circular economy into construction industry will depend on the socio-economic and environmental advantages it has over conventional construction method.

Also, it is important to evaluate the disruptive socioeconomic impacts of digital manufacturing for construction employment and built environment

professions. As previously discussed, massive savings accrue from the innovation of digital additive manufacturing into building construction, and for a very labour intensive sector, this means unemployment. However, the net employment effects will depend on whether job displacement is greater or lesser than job creation in the industry. This depends crucially on the production function faced by the construction industry in different countries, which is defined by the relationship between the factors of production. Significant employment will be created in IT applications in construction, and the attendant modern methods of construction will mean that off-site construction will prevail over on-site construction, and this will have a multiplier effect on the rest of the economy, particularly where there is a strong forward and backward linkages between the construction sector and the wider economy (Pheng and Huo, 2019).

A case in point is the UK where it was estimated in 2015 that if a target of 70% recovery rate can be achieved in C&D wastes by 2020, about 6,500 direct jobs would be created in areas of waste management and logistics, with thousands more indirect jobs in haulage, reprocessing, and trading in recycled construction products (Mitchell and Keith, 2015). The 2020 target was exceeded in 2018 when the UK recovered 93.8 of its C&D wastes against the current target of 95%. Estimates show that between 2014 and 2019, about 900,000 additional jobs were created to make a total of 560,000 jobs linked to the circular economy in the UK (WRAP, 2021).

At the same time, 500,000 new jobs were created in EU circular economy, with estimates showing that up to 3.4 million jobs and 240 billion Euros gross values could be added to GDP by 2030 (WRAP, 2021; Mitchell and Keith, 2015). The impact of the circular economy on economic growth is not surprising because, and in addition to reduced input costs, adopting digital fabrication in processing C&D wastes creates avenues for additional revenue streams across the construction value chain. The values of C&D wastes are enhanced as inputs to new construction products manufactures, and prompting new economic activities in collection, sorting, and processing of C&D wastes (Kirchherr et al., 2018). Indeed, World Economic Forum estimates show that over US$100 billion yearly savings from improved productivity are possible by adopting and implementing the circular economy principles in global construction practices (World Economic Forum, 2016).

Huge social effects also accompany the circular economy in the opportunities it provides for reskilling owing to the likely innovations that additive digital construction could attract to the construction industry. Indeed, applying digital additive manufacturing in construction will reimage the industry and makes it attractive to young people, particularly women. As De Jesus et al. (2018) found in their study, the construction systems and value chains could be transformed by circularity implemented through digitalisation. This, they argue, could be profoundly innovative with major economic benefits. This demonstrates that the circular economy approach to global construction carry significant net gains environmentally, economically, and socially.

However, an important key to wider adoption of circular economy driven digitalised additive manufacturing by the construction industry is predicated upon acceptance and uptake of recycled products, hence digitally additive manufactured construction outputs in general. Recycled construction products face many challenges that limit their wider adoption by mainstream construction stakeholders or consumers (Shooshtarian, et al., 2020). It was decided to gauge global opinions and perceptions on the problems facing recycled cementitious products on the market and how they may be resolved (Smith, 2021). It is important to determine stakeholders perspectives and opinions on recycled cementitious products and to understand the challenges and be able to is critical to wider use.

7.1 Market Readiness of Digitally Additive Manufactured Blocks

Historically, some early recycled materials were perceived as inferior in performance to products made from virgin materials (Jones, 2020). This led to enduring belief that recycled alternatives are inferior in quality compared with the original materials. However, technological improvements have enabled manufacturers to create recycled products with equivalent or, in some cases, even superior functionality and durability to conventional items (Jones, 2020; Johnson, 2019). Despite these advances, lingering negative perceptions about quality persist among consumers. This study set out to determine stakeholder opinions and preferences for digitally manufactured recycled building products.

8.0 Global Survey Results

Given the nature of the study and the different stakeholders involved, it was decided to employ a mixed method survey questionnaire to access desired data on stakeholders of interests and be able to make inferences about the broader population of stakeholders (Bhattacherjee, 2012; Fowler, 2013). The questionnaire contained both closed-ended questions that generate quantitative data and open-ended questions that provide qualitative data. This approach is justifiable on grounds of robustness and efficiency, ensures consistency amongst respondents (Rowley, 2014). Similarly, a mixed method is enriching, as the qualitative data will contextualise and afford further insights into quantitative data (Ormston et al., 2013). Thus, the proposed survey questionnaire containing both closed-ended quantitative and open-ended qualitative questions is a suitable method for this study, enabling collection of different types of data from a large sample to address the specified research aims. The survey method with mixed question types is well-established in the literature of this domain (Castro, et al., 2010)

The questionnaire-based field study was conducted through an online survey, which is now commonly used in research, reflecting increased internet penetration and digital literacy globally because of the access it provides to large and diverse samples at low cost (McMaster et al., 2017; Regmi et al., 2016). While the quality of the online survey method is found comparable to conventional survey method (De Bruijne and Wijnant, 2014), the standardised format enables collection of quantitative data for statistical analysis and qualitative open-ended responses, and also makes data administration relatively easier than conventional paper survey (Ward et al., 2018).

The questionnaire was sent electronically to contacts in Saudi Arabia, Bahrain, Jordan, South Africa, Nigeria, Kenya, Chile, Brazil, Portugal, Germany, Netherlands, India, Bangladesh, Florida, Lebanon. And the UK. Our contacts were required to distribute the questionnaire through their channels to built environment stakeholders, including clients, contractors, academics and policy makers. In this regard, the non-probability purposive sampling method was employed for the survey as the targets were built environment stakeholders involved in materials specifications in built asset construction. given Responses came directly to us and not through the contacts.

Although a greater response would have been ideal, the relatively low response is compensated for by the richness of the returned survey evidenced by the spread of respondents across the different parts of the world, and the diverse sectors of the built environment that respondents represented. In all, 77 responses were received and analysed.

8.1 Analysis of Survey Results

8.1.1 Respondents Background Information
Figure 26 shows more than half of respondents have an academic background (53%); followed by architects (15%), managing directors and executives (12%); project managers (6%); construction managers (4%); while those coming from cost consultancy, civil engineering, and built environment consultancy backgrounds formed 3% respectively. Only 1% of our respondents belong to the real estate profession, but the significance of their participation is reflected by the fact almost all the built environment professions – academic and practice, featured in the survey. This is important for uptake of research findings, as key construction stakeholders from different parts of the world participated in the survey.

Figure 26: What is your role in your organisation?

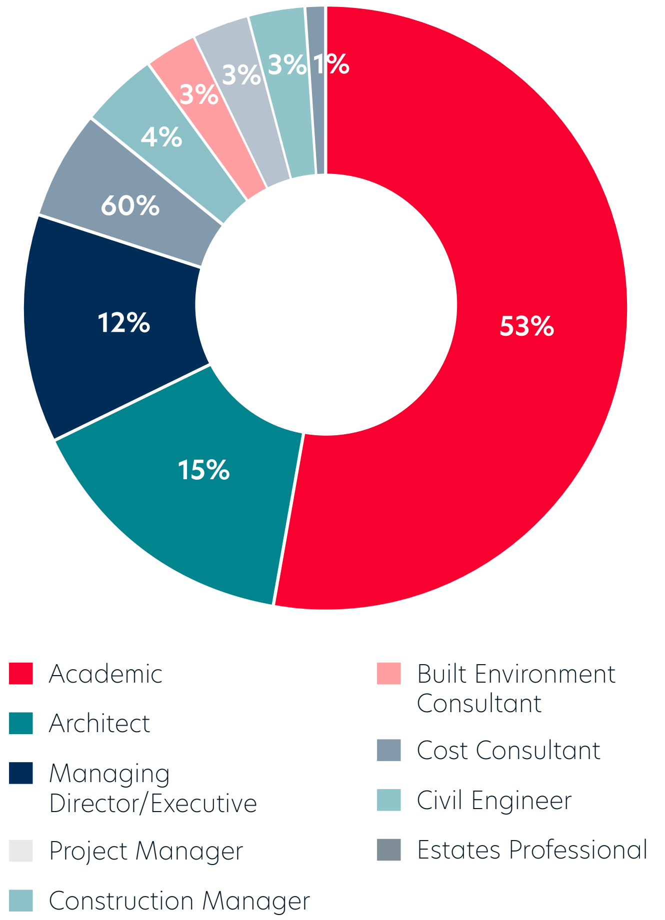
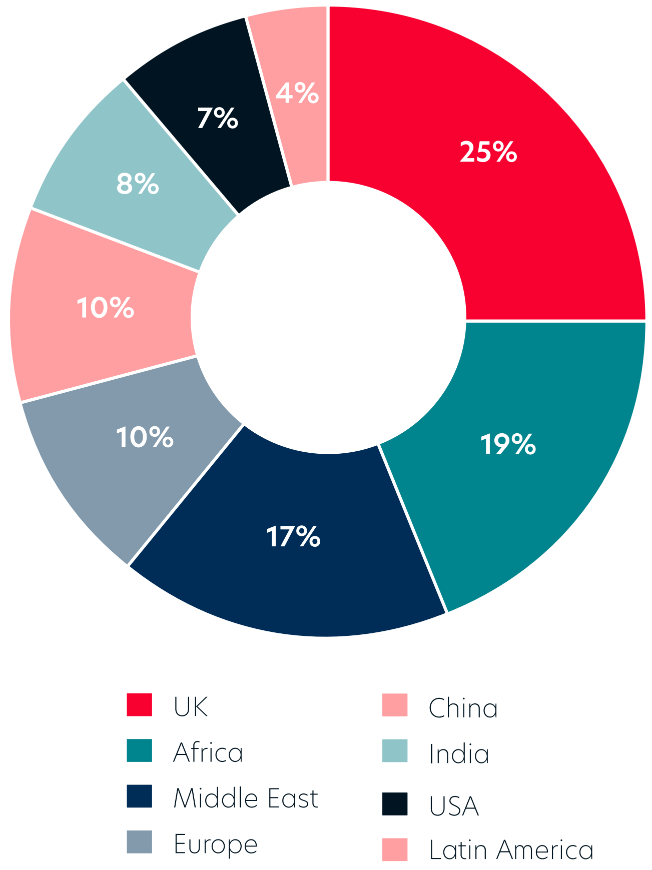


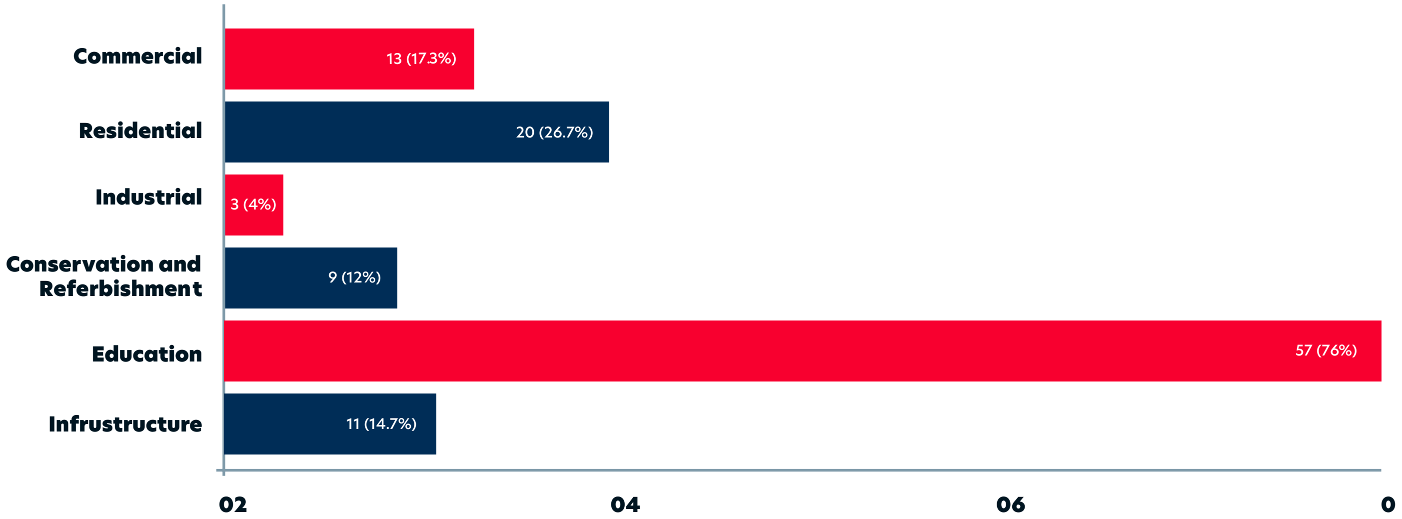
Figure 27: Continent or Country of Participants



There are reasons why the global audience was surveyed for this study. First, C&D wastes is a global problem and so is the impact of the construction industry on the natural environment, and particularly given the transboundary nature of global environmental problems (Divan, et al., 2022), hence the need for collective global solutions (Hormio, 2023). Secondly, H Samuel Foundation and the University of College of Estate Management are international in their external facing, the latter drawing students from all over the world. Finally, As a result, findings from this study are expected to have international influence on policies and measures to decouple growth in construction output from increased raw material inputs. Figure 27 indicates the international spread of survey participants with majority (25%) coming from the UK, 19% from Africa, Middle East accounts for 17%, Europe and China account for 10% each, India and the USA account for 8% and 7% respectively. Thus, findings and policies from this study are globally informed.

Figure 28: Sector of the Construction Represented

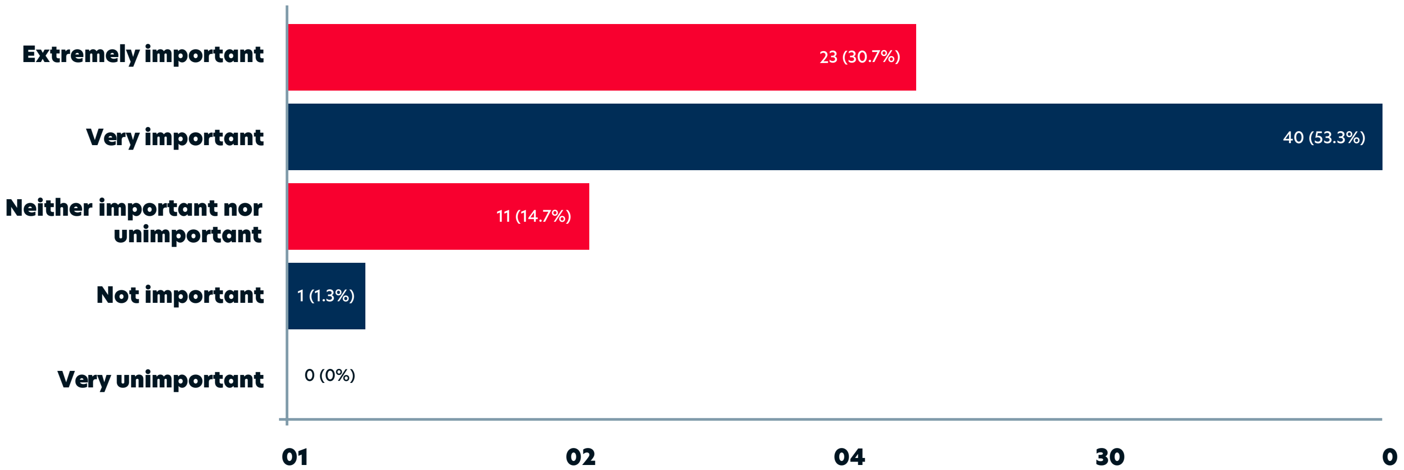
What sector of the construction industry does your organisation represent? (75 responses)



As shown in Figure 28, attempts were made to know the area or sector respondents work in the construction industry. It shows respondents cut across the construction sector right from infrastructure through commercial, residential, industrial, conservation and refurbishment to education. This gives also gives credence to findings from the study.

Figure 29: Importance of Using Recycled Concrete in the Construction Sector

How would you rate the scope for using Recycled Concrete in the construction sector? (75 responses)



The information presented in Figure 29 reveals that 81% of global construction industry stakeholders rated the importance of using recycled concrete in the construction sector extremely important with 15% claiming it is neither important nor unimportant. Only 1.3% believed the use of recycled concrete is unimportant. Evidently, global construction stakeholders are in support of the use of recycled concrete in the industry. This support has not been reflected in practice. As Figure 30 shows, the percentage of recycled products purchased as inputs to final construction outputs is low in the sense that 37% estimated this at between 0 – 10% while between 30 – 40% of respondents were not sure. Only about 15% percent of respondents confirmed more than 40% of purchased inputs to production contain recycled concrete. In particular, the 41.3% of respondents that are not sure indicates huge knowledge gaps even amongst built environment practitioners globally of C&D wastes discourse.

Figure 30: Percentage of Recycled Concrete in Firms Input Purchases

What percentage of products purchased by your firm are made from Recycled Concrete? (77 responses)

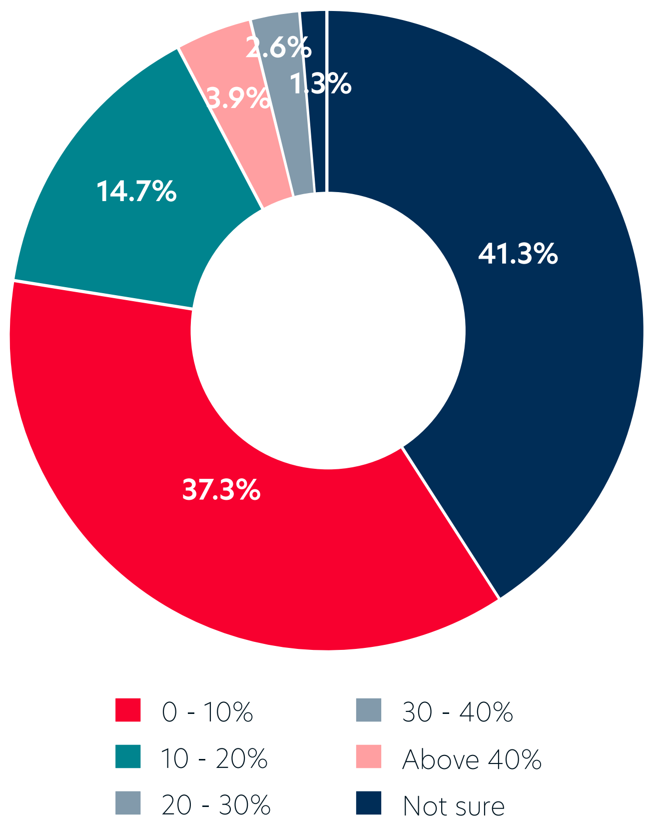
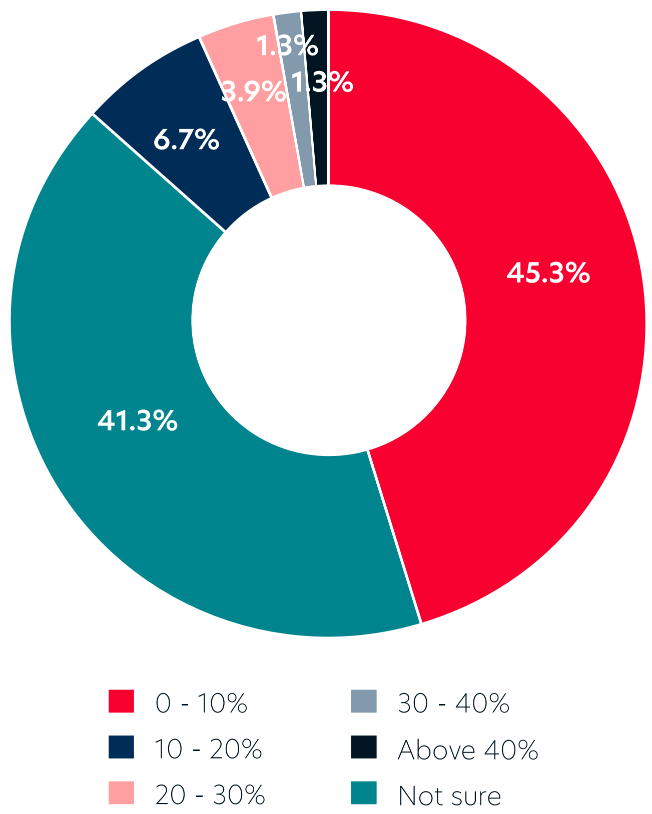


Figure 31: Percentage of Recycled Aggregates in Output Sold

What percentage of the products sold by your firm are made from Recycled Concrete? (77 responses)

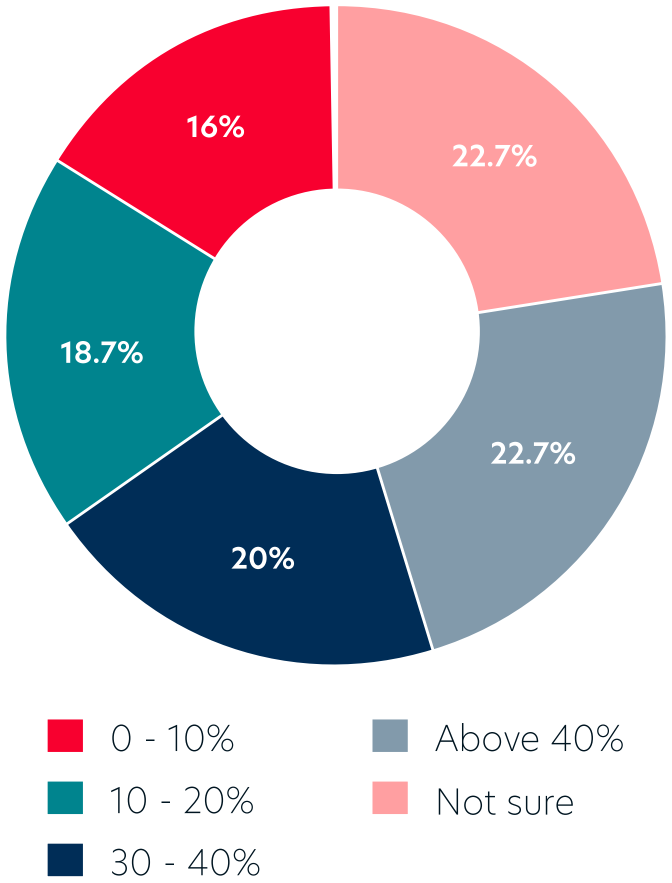


The findings shown in Figure 31 confirm the information presented in Figure 30 where recycled aggregates in input contents were found to be very minimal. The results show that recycled contents in finished products sold by the firms where the respondents work contain very little recycled aggregates. While there appears to be a firm belief amongst respondents of the importance of reusing concrete aggregates in construction activities, there is little evidence of this in practice.

The next question examines the ideal percentage recycle aggregates should account in new construction products. This is critical to the implementation of the circular economy in global construction to have increased use of recycled aggregates in newly manufactured construction products. Similarly, as with Figure 30, 41.3% of respondents are not sure about the percentage of recycled products in the final outputs of their firms, indicating again the knowledge gaps even amongst built environment practitioners at the global levels about C&D wastes issues.

Figure 32: Percentage of Recycled Aggregates in New Construction Products

In your experience, what percentage of the products manufactured by firms in the construction industry must come from Recycled Concrete? (77 responses)



Evidently, only 23% percent of respondents agreed that recycled aggregates should be more than 40% of total contents of new construction products, and if those that settled for between 30% to 40% recycled contents are considered, about 70% of respondents shared the opinion that new construction products should contain more than 40% of recycled aggregates. Some 23% of respondents are not sure of the percentage of construction products should be recycled aggregates. Knowledge about possible solutions to rising C&D wastes amongst built environment professionals is critical to successful implementation of circular economy principles in the global construction industry to decouple growth in construction from intense consumption of natural resources.

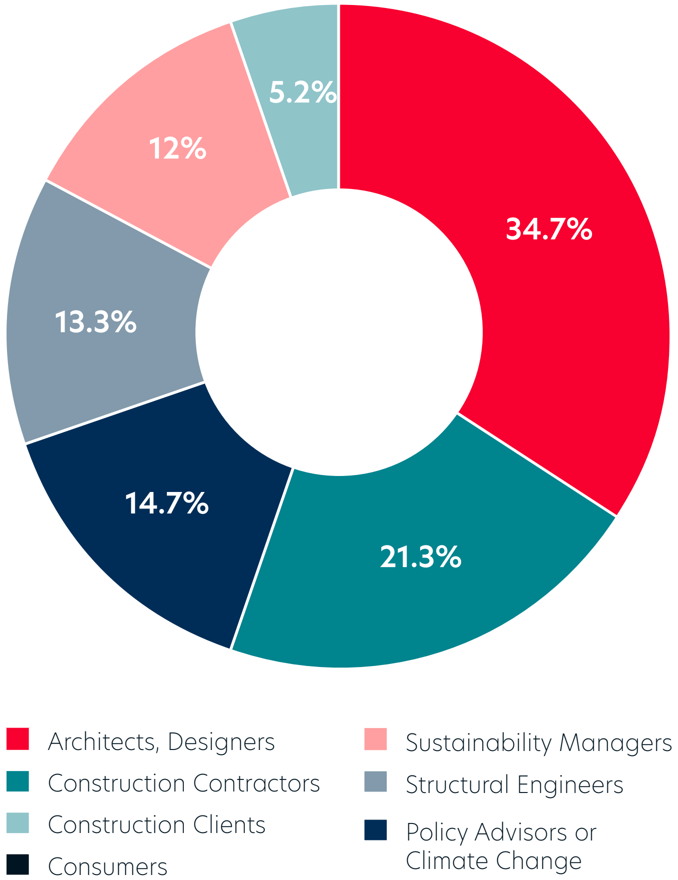
While there is widespread support amongst global built environment stakeholders for reusing recycled aggregates in construction, there is little evidence of implementation in practice, making further investigations on the barriers to the use of recycled aggregates in the industry necessary.

8.1.2 Identification of Critical Roles of Professionals in Closing the Knowledge Gap on the Significance of Wider Adoption of Recycled Concrete Products

Section B explores possible roles built environment professionals could play in raising the profile of recycled aggregates and their increased use in global construction in effect to reduce the growing volumes of C&D wastes and attendant pollution effects. The rationale here is that wastes can be designed out of built assets, but this should not be an afterthought, but it has to be considered at the preconstruction stage. In this regard, built assets can be designed to support adaptation, disassembly and reuse, which will limit waste and extend both the physical and economic lives of built assets, reducing exerted pressures on natural materials. This is unlikely where built environment professionals do not apply the principles of circular economic principles at the project conception phase. Only then can built environment practitioners find new opportunities early in the design process to reduce the ecological footprints of built assets, conserve resources, and reduce costs (Rahla, et. al, 2021).

Figure 33: Built Environment Professionals Best Placed to Influence Usage of Recycled Products

In your experience, which of the following professionals are best placed to influence use of products from Recycled Concrete? (77 responses)

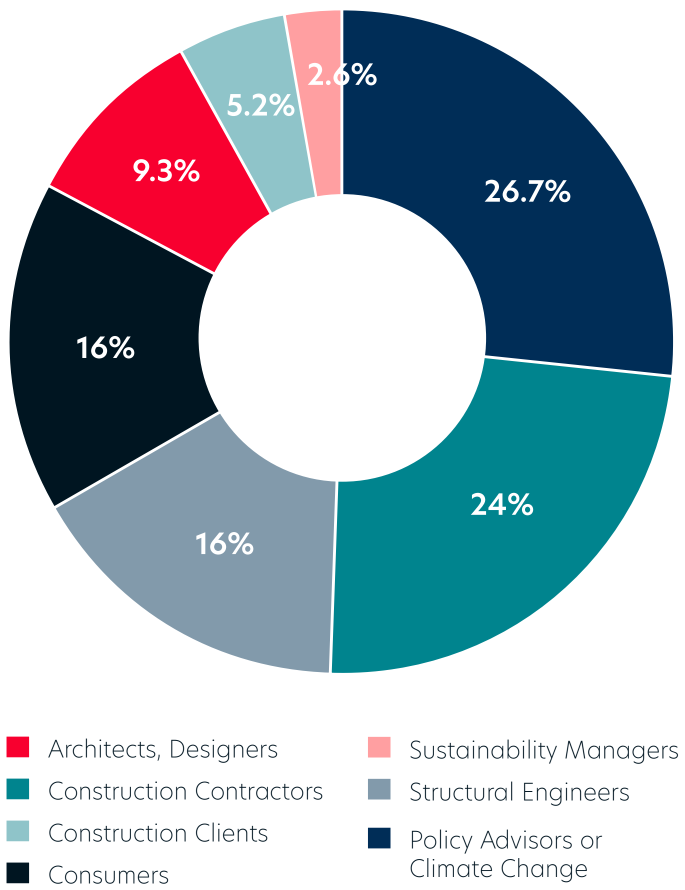


When asked which of the built environment professionals was in the best position to influence the use of recycled aggregates, 35% of respondents identified the architects, and 21% chose construction managers. This reflects the significance of the roles that these two professions play, right from the preconstruction to construction and delivery stages of built assets design, construction, and delivery. Designing to local climate and sites specificity, as well as to the local economy can significantly impact on the ecological footprints of the construction industry and reduce the intensity of raw materials consumption (Munn and Soebarto, 2004; Kozminska, 2019). In addition to the importance given to structural engineers, which is hardly surprising given that most steel used in construction are recycled, the recognition of policy makers and sustainability managers having a role in embedding circular economy in global construction practice is significant.

Identifying which amongst the global built environment professions are most likely to resist the use of recycled aggregates in construction is important for policy formulation, implementation and targeting (Balawejder and Monahan, 2020; Eberhardt, 2019).

Figure 34: Built Environment Professionals Most Resistant to Reuse of Recycled Concretes

In your experience, which of the following professionals are most resistant to the use of Recycled Concrete in the construction industry? (77 responses)

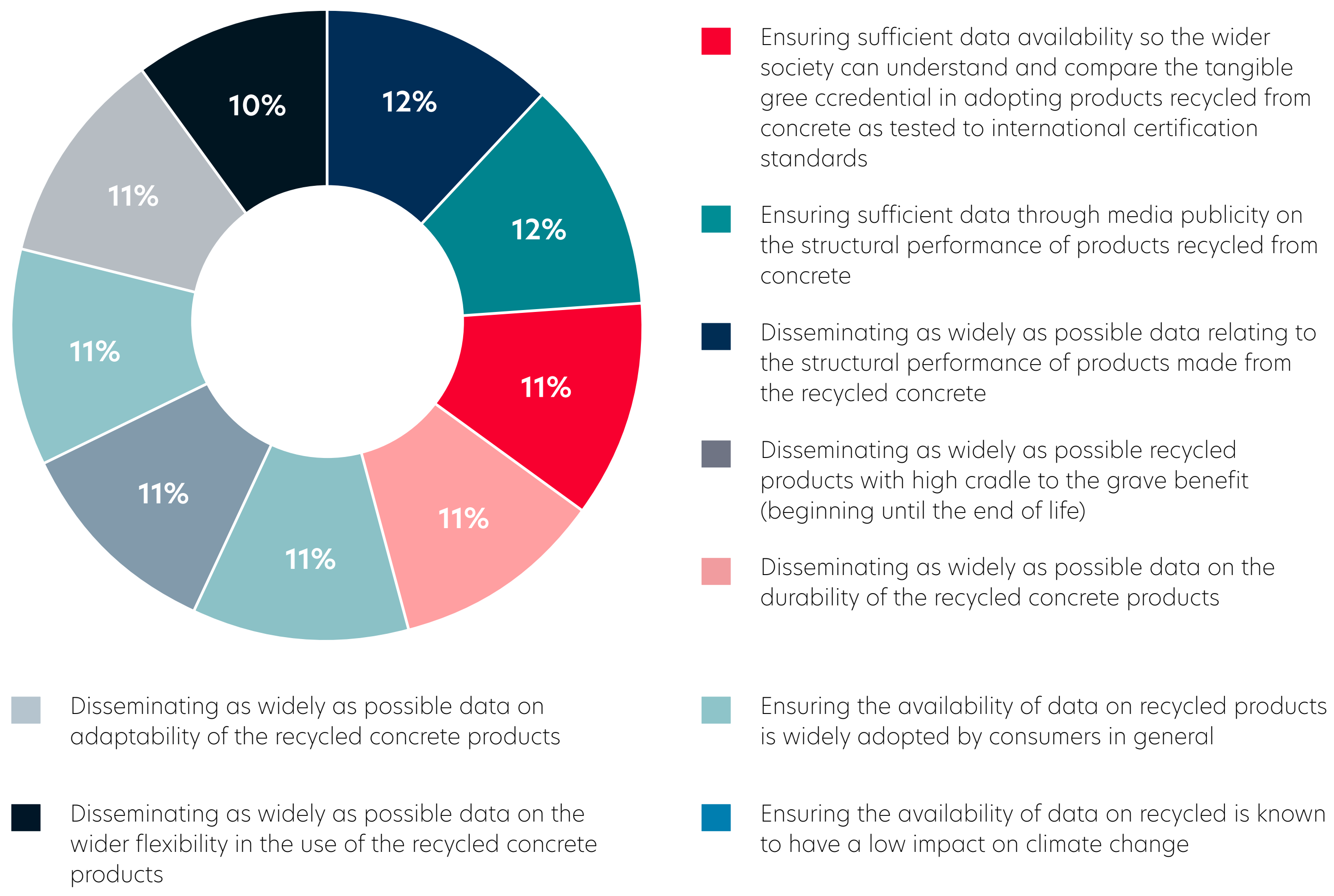


The information in Figure 34 is instructive for anyone contending with the implementation of the circular economy in the global construction industry. Construction clients with a score of 28% and construction contractors with a score of 24% are found to be the construction stakeholders most likely to resist the use of recycled aggregates in global construction industry. This scenario may arise where contractors and clients resist the use of recycled aggregates for the perceived risks associated with the structural integrity of recycled cementitious products, particularly where there are no standards currently available to determine quality compared to conventional construction materials. This is why it was necessary to derive an optimum or right mixes that will produce cementitious materials with the same quality and performance as natural materials. It also explains why it was necessary to further explore the possibility of using the right mixes derived as part of this study for additive manufacturing of cementitious products.

8.1.3 Dissemination and Knowledge Gap for Recycled Concrete Products

One of the many factors hindering the use of recycled aggregates is lack of sufficient information necessary to build consumer confidence (Smith, 2021). Section C seeks to determine the kind of messages that global construction stakeholders believe will enhance awareness of the quality possessed by recycled aggregates. Figure 35 presents the opinions of respondents, and it indicates the importance of making information on the quality as well as sustainability attributes of recycled aggregates available. The nature of information considered to enhance acceptance and wider usage of recycled cementitious products include their durability, adaptability, their green attributes for comparisons with conventional products amongst others.

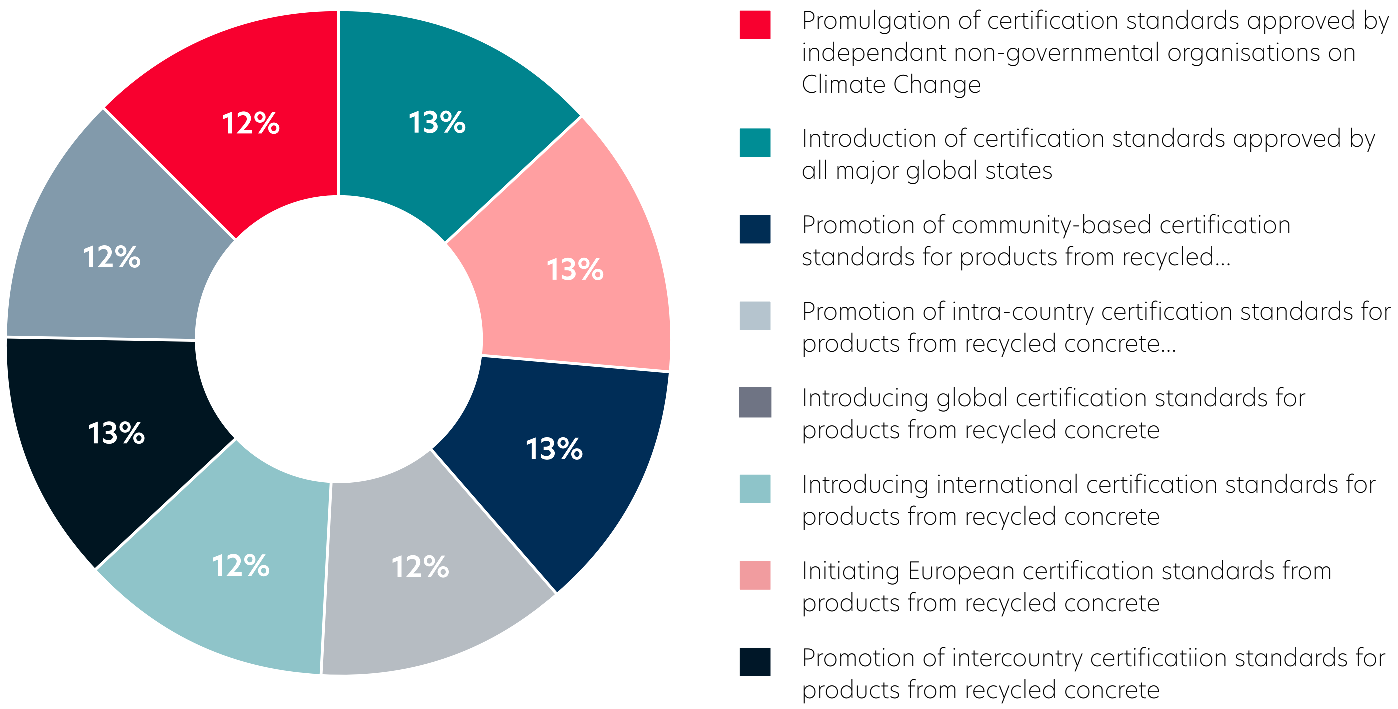
Figure 35: Factors to Enhance Society's Acceptance Recycled Aggregates



8.1.4 Certification Gap for Recycled Concrete Products

One of the reasons advanced in the literature for the limited use of recycled aggregates in construction is the lack of standards and certification. Opinions of stakeholders were sought on the nature and format of certification to use in the promotion of recycled aggregates, and the responses are as presented in Figure 36.

Figure 36: Measures to Promote Wider Use of Recycled Aggregates (Certification)



8.1.5Functional efficiency of recycled concrete products (suitability)

This section further ascertains from global construction stakeholders their awareness of the functional efficiency of recycled concrete products.

As Figure 37 indicates, only 15% of global construction stakeholders are exceptionally informed about the benefits of using recycled concrete in the industry, while 39% and 37% are very well informed and fairly informed respectively. In all, 90% of the respondents are fully aware of the advantages of using recycled concrete yet lacking full knowledge of the quality and sustainability attributes of recycled concrete, as revealed in Figure 34, and suggesting the kind of information that may lead to wider usage in Figures 35 and 36 respectively. The explanation for this could be found in the responses presented in Figure 39, which show that, until recently, as many as 36% of global stakeholders knew very little about the benefits offered by recycled concretes. The implication of this finding is the need to make adequate and quality information about the benefits of the circular economy available to construction industry stakeholders, particularly contractors and clients.

Generally, more work is required to produce and enhance information available to built environment professionals as well as the public domain about the advantages of using recycled products in global construction and the opportunities presented to built environment professionals for innovations and creativity. Section E probes attitudes to, and perceptions of stakeholders, on the reuse of recycled cementitious products in construction.

Figure 37: Stakeholders Awareness of the Benefits of Using Recycled Concrete Products

How informed are you of the benefits of using recycled concrete products? (77 responses)

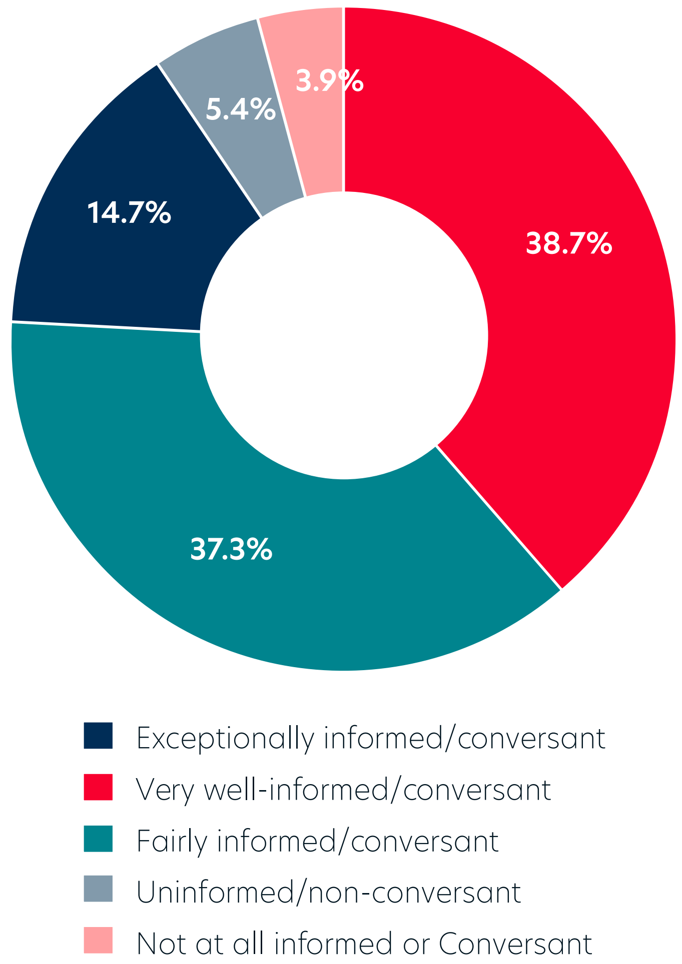
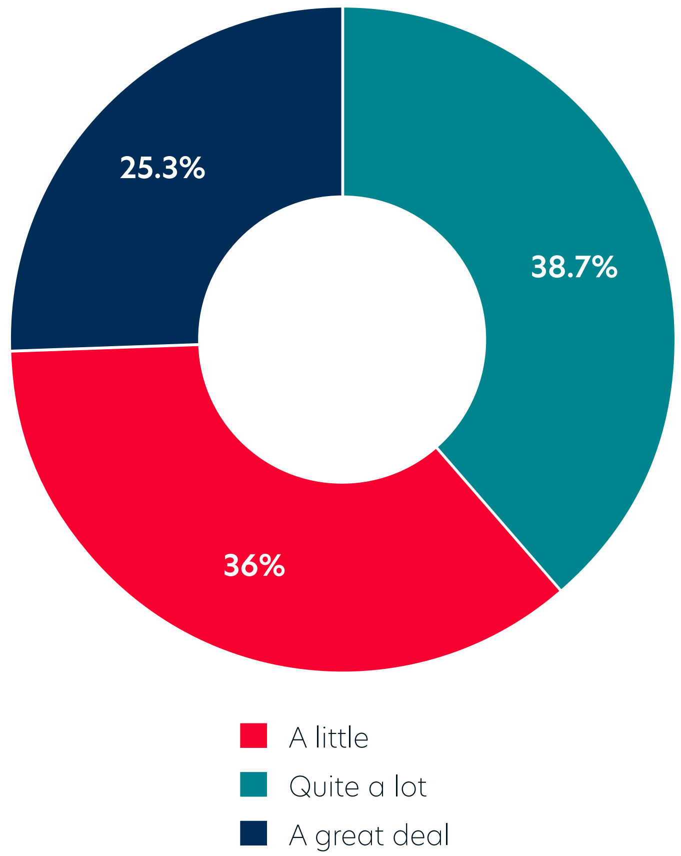


Figure 38: Temporal Awareness of the Benefits of Recycled Products

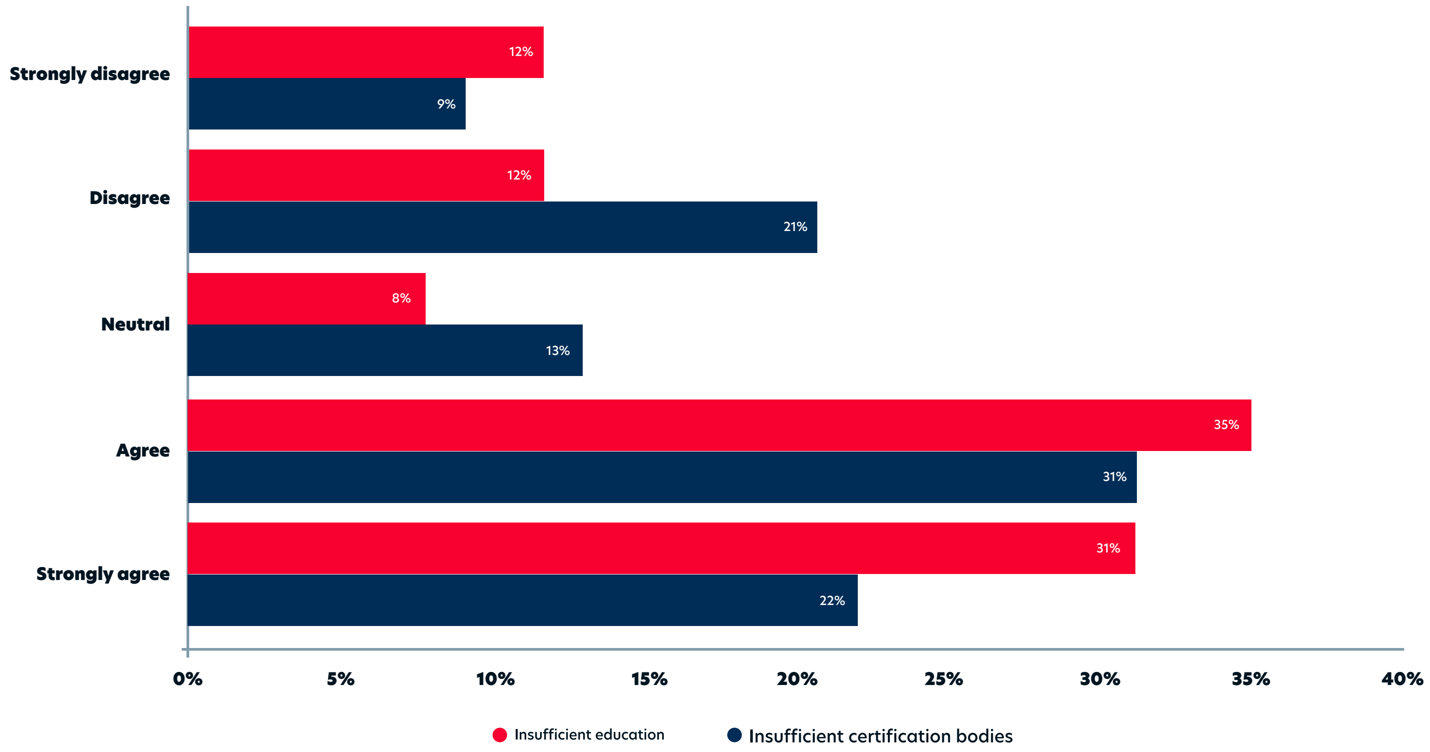
How much would you say, until now you know about the benefits of recycled concrete products? (77 responses)



8.1.6 Attitudes & Perceptions of Recycled Concrete Products (suitability)

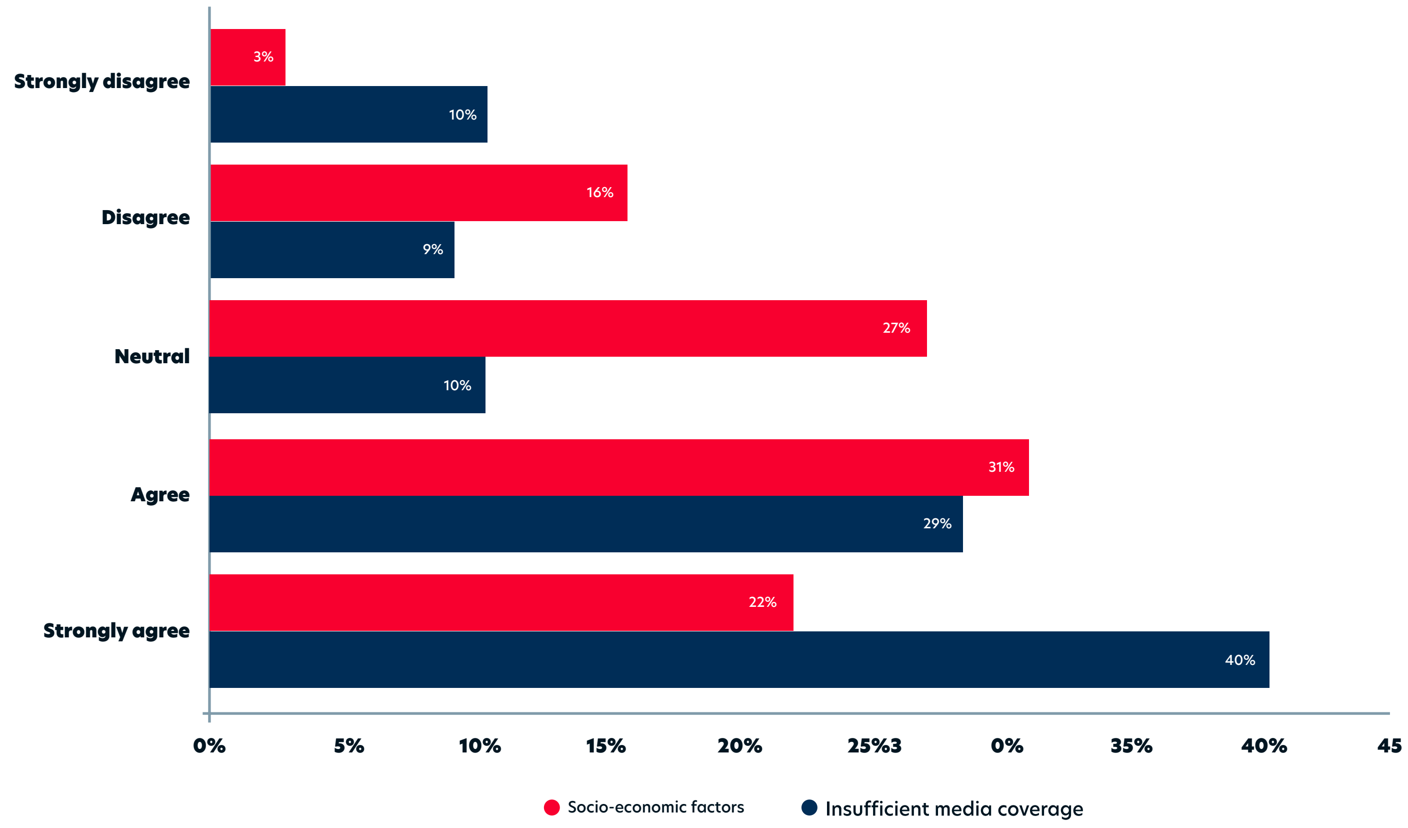
Series of questions were posed to global construction stakeholders interrogating their attitudes to, and perceptions of, recycled concrete products. If the circular economy is to take hold in the construction industry, current attitudes and perceptions of stakeholders underpinning the current low level of usage of recycled products must change (Lee, et. al. 2019). Effecting such changes requires consideration of wider views and perspectives on probable underpinnings to current attitudes and perceptions. Also, changing attitudes requires robust information because any information gap around recycled concrete prevents innovations to drive efficiency and expand applications. With more research information put at the disposal of the industry and the public, new technologies and uses would emerge, benefitting stakeholders across the supply chain and beyond (Jones, 2020). The current knowledge limitations close off possibilities to develop higher-grade aggregates, enhanced mixing methods, and novel products.

Figure 39: Factors Explaining Lack of Information on the Benefits of Recycled Concretes (Insufficient Education and Certification Bodies).



As Figure 39 highlights, insufficient education on the performance and benefits associating with the use of recycled concrete products as the reason for the negative attitudes and perceptions by construction stakeholders of recycled concretes. Few certifying institutional bodies endorsing the attributes of recycled cementitious products is also seen as a problem. Endorsements by reputable certifying bodies will assure confidence in the use of cementitious products and provide the much needed popularity and visibility. and help to mitigate the negative perceptions and risks associated with using recycled products. As Figure 40 indicates, the lack of media coverage of the attributes of recycled concretes is one of the reasons for lack of wider reuse in global construction.

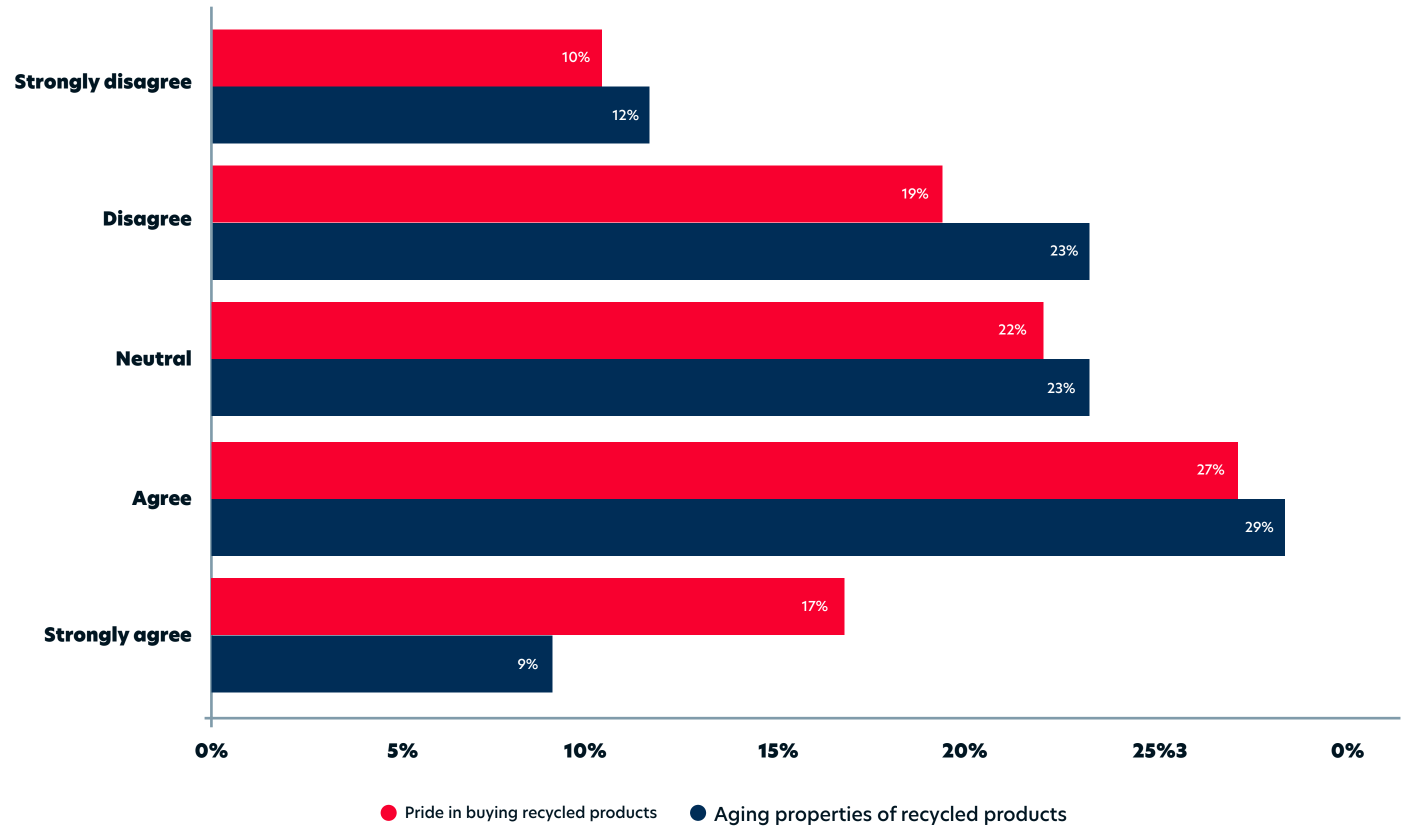
Figure 40: Factors Explaining Lack of Information on the Benefits of Recycled Concretes (Socioeconomic Factors and Insufficient Media Coverage)



Insufficient media coverage is seen as the main reason for lack of information about the benefits of using recycled aggregates in construction activities, which is evident when those who strongly agreed are added to those who agreed, making 69% of respondents. For those who agreed, socio-economic factors were ranked higher than lack of media coverage, and when those who agreed and strongly agreed are combined, socio-economic factors rank second as the reason for lack of information on the benefits of recycled concrete products. Several socioeconomic factors contribute to the construction industry's reluctance to adopt recycled concrete materials. A major barrier is the lack of large-scale production and distribution networks, which limits consistent supply and keeps costs high (Lee et al., 2019).

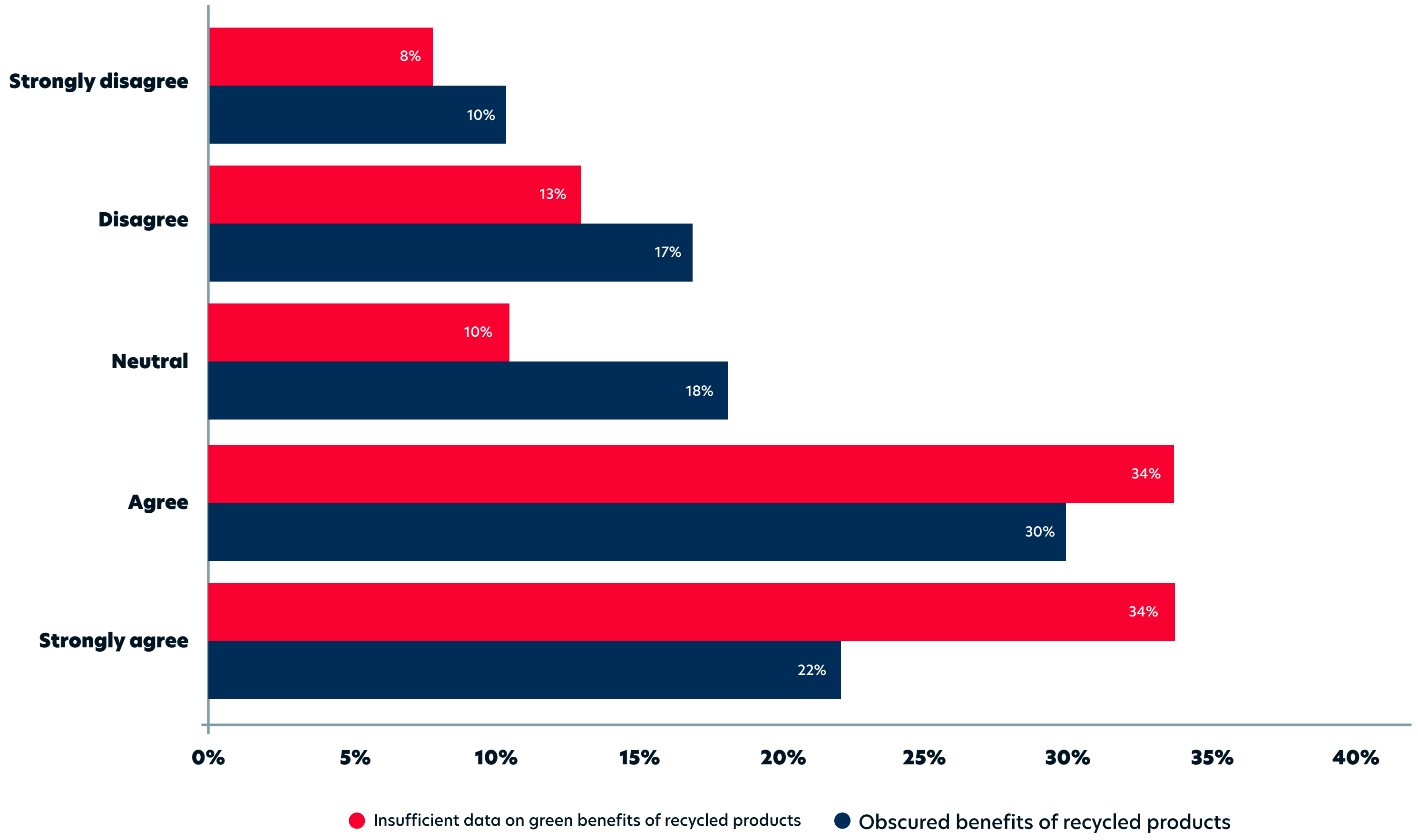
Figure 41 throws further light onto the socio-economic factors inhibiting information on the benefits of recycled concrete aggregates. With 9% of respondents strongly agreeing and 29% agreeing, while 12% strongly disagreed and 23% disagreed, there is no decisive agreement on the aging properties of built assets as being a major barrier to information on the quality of recycled concrete products. However, lack of pride in using recycled concrete products was flagged as a reason for lack of information on the benefits of using recycled concretes.

Figure 41: Factors Explaining Lack of Information on the Benefits of Recycled Concretes (Pride in Using Recycled Products and Aging Properties).



As earlier indicated, the information gap around recycled concrete adversely affects innovations and diminishes opportunities to expand applications (Jones, 2020). This is particularly the case where information about the environmental merits of recycled concrete is unavailable, reducing its use and slowing progress towards sustainability and circularity in global construction practice. As Figure 42 shows, lack of data on the green benefits and the fact that these benefits associating with recycled aggregates and cementitious products are hidden constitute a major hindrance to information availability. In particular, where information about the environmental benefits of using recycled concrete products is not available or where there are no visible examples of iconic built assets that contain the use of recycled cementitious materials, there will be no valuable information to alleviate the fears of critical stakeholders such as contractors and built asset clients (Lee, et al., 2019). It can be observed that 64% of the respondents either agreed or strongly agreed that insufficient data makes information about the benefits associated with recycled products difficult. Also, 52% of respondents pointed to the hidden nature of the benefits of recycled wastes. In general, the current limitations to knowledge will continue to hinder the full benefits of the circular economy in the construction industry.

Figure 42: Factors Explaining Lack of Information on the Benefits of Recycled Concretes (Insufficient Data on Green Attributes and Obscured Benefits of Recycled Products)



8.1.7 Consumer Attitudes & Perceptions of Local Recycled Products

Consumer awareness and perceptions pose a major obstacle to the uptake of locally recycled construction materials like concrete aggregates. Consumers of built assets often have doubts about structural integrity, durability, and quality of concrete with recycled aggregates (Lee et al., 2019). It is often argued that because less is seen of recycled cementitious products used in iconic buildings, preference goes automatically to conventional building materials. Questions were posed to respondents to gauge their opinions on why consumers are not consuming recycled concrete products.

Distance to and from recycling centres where products are sold was seen as a major disincentive. As Figure 43 shows, 59% of the respondents either agreed (43%) or strongly agreed (16%) that location of recycled centres for recycled cementitious materials is a problem. Also, the view that recycling is tagged with substandard products also featured prominently with those who strongly agreed (16%) and those who agreed (45%), making a total of 61% who believed that the association of recycled products with poor quality is a major reason why recycled cementitious products are not adequately consumed. As Figure 44 indicates, this situation can be reversed by relaying tangible benefits of cementitious products to the public with active support from the local authorities.

Figure 43: Factors Explaining Lack of Use of Recycled Concretes (Distance to Recycle Products Centres and Negative Stigma for Recycled Products)

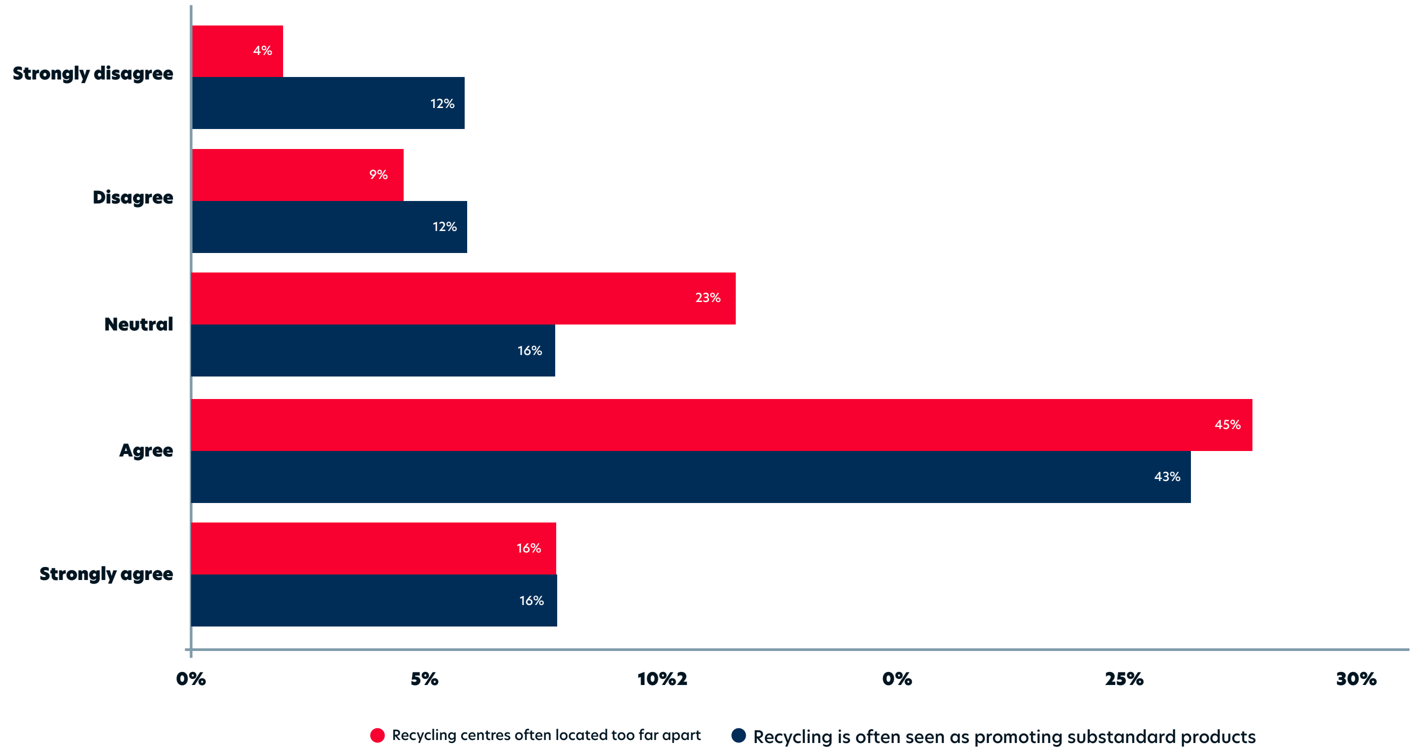
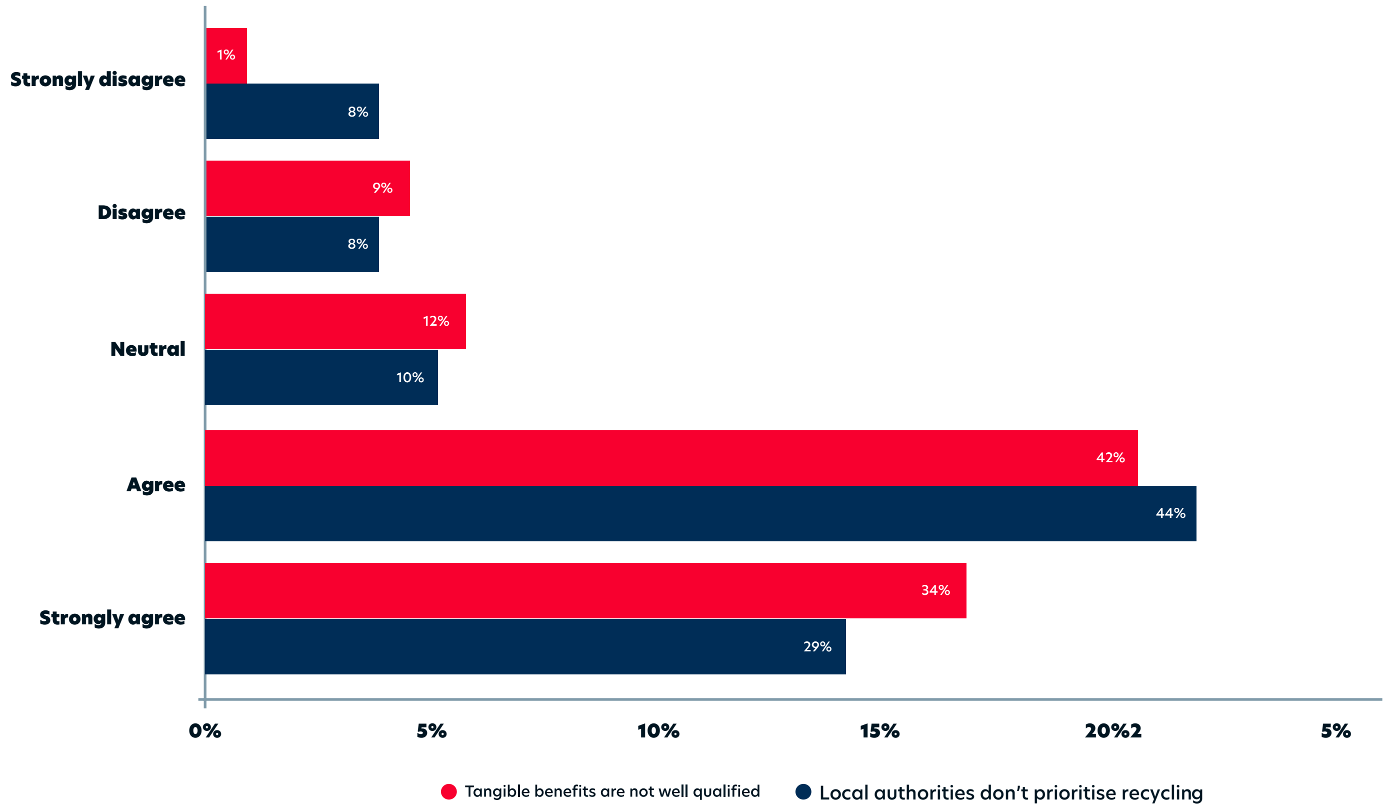
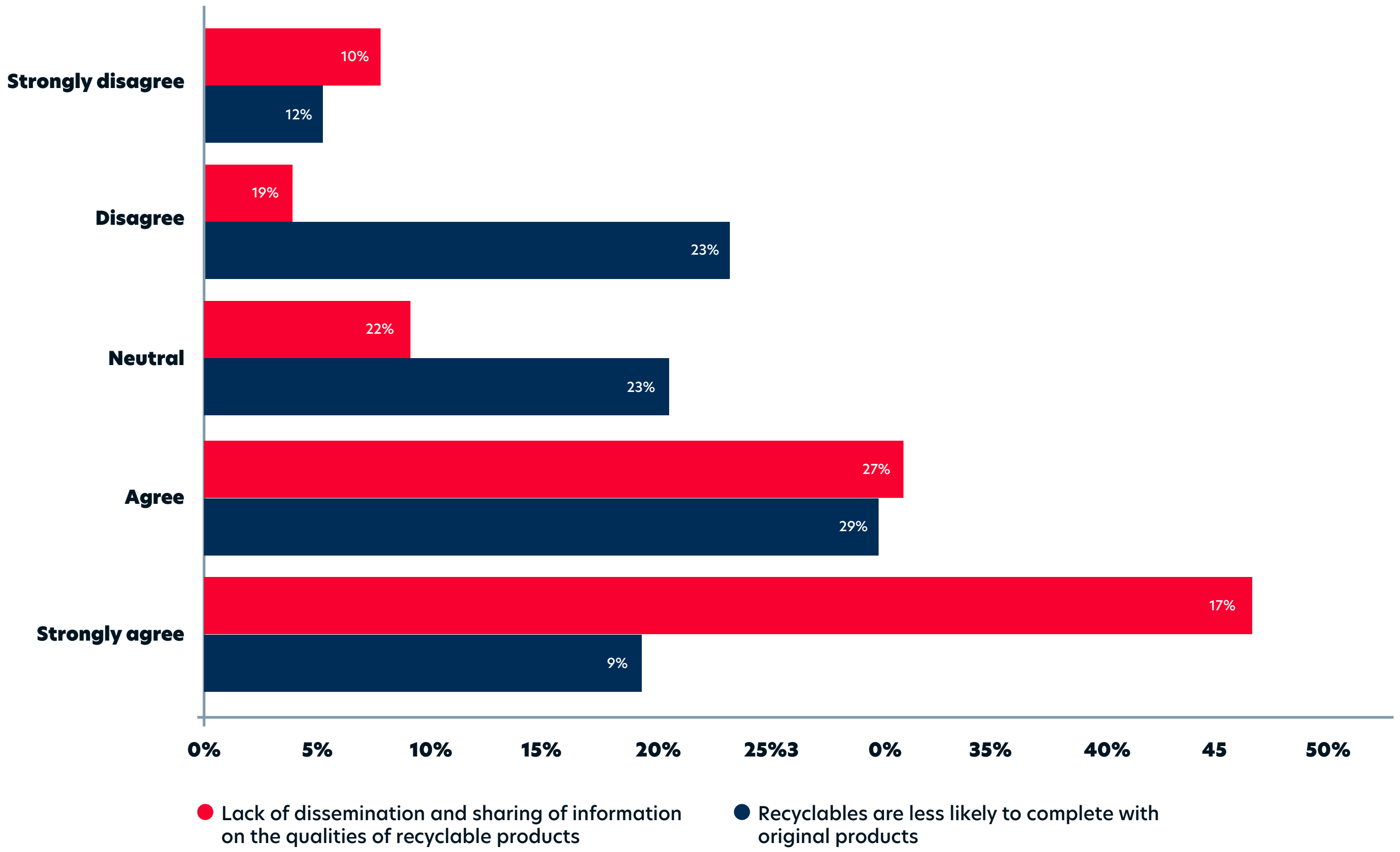


Figure 44: Factors Explaining Lack of Use of Recycled Concretes (Obscured Tangible Benefits and Lack of Support from Local Authorities)



Unavailability of information about the quality and wider sustainability benefits of recycled aggregate cementitious products makes it difficult to compare them with construction products from virgin materials, rendering them uncompetitive (Taylor, 2022). This is seen as one of the reasons explaining the lack of use of recycled concrete products in global construction, and as Figure 45 shows, the respondents agreed.

Figure 45: Factors Explaining Lack of Use of Recycled Concretes (Poor Information Dissemination and Recycled Products Uncompetitive)

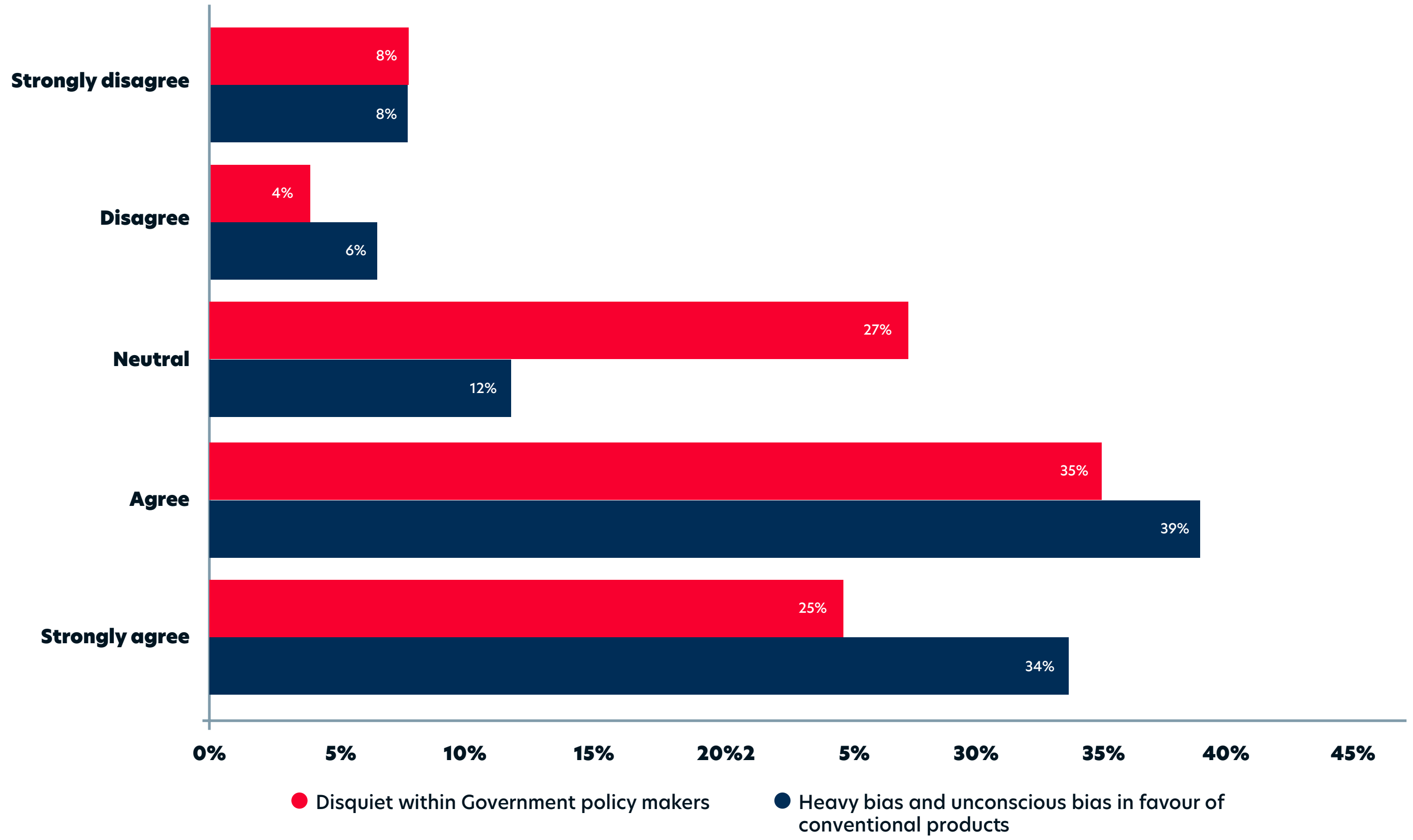


If the proportion of those who strongly agreed (47%) is added to those who agreed (31%), a total of 78% of respondents agreed that lack of dissemination is a hindrance to the use of recycled cementitious products, and hence, a major setback to the practice of a circular economy in global construction. Put against uncompetitiveness of recycled products, respondents see the lack of dissemination as having more negative impact on the use of cementitious products. Developers, designers, and contractors remain cautious about the use of recycled concrete in the absence of sufficient evidence-based information relating to quality, particularly on the structural integrity of cementitious products. Such evidence could come in the form of demonstration projects, particularly by local authorities that preside over a significant amount of outdoor leisure infrastructure where recycled cementitious products could be largely used. This is why respondents were asked about their opinions on the impact of lack of government support on the use of recycled cementitious materials.

Figure 46 presents the opinions of the respondents. Those who strongly agreed (34%) and those who agreed (39%) that there is heavy bias in favour of conventional materials make 73% of the total respondents. This ranks higher than respondents whose opinions point to the lack of government support for recycled cementitious products as one of the reasons for their low usage in construction activities. Respondents who strongly agreed (25%)

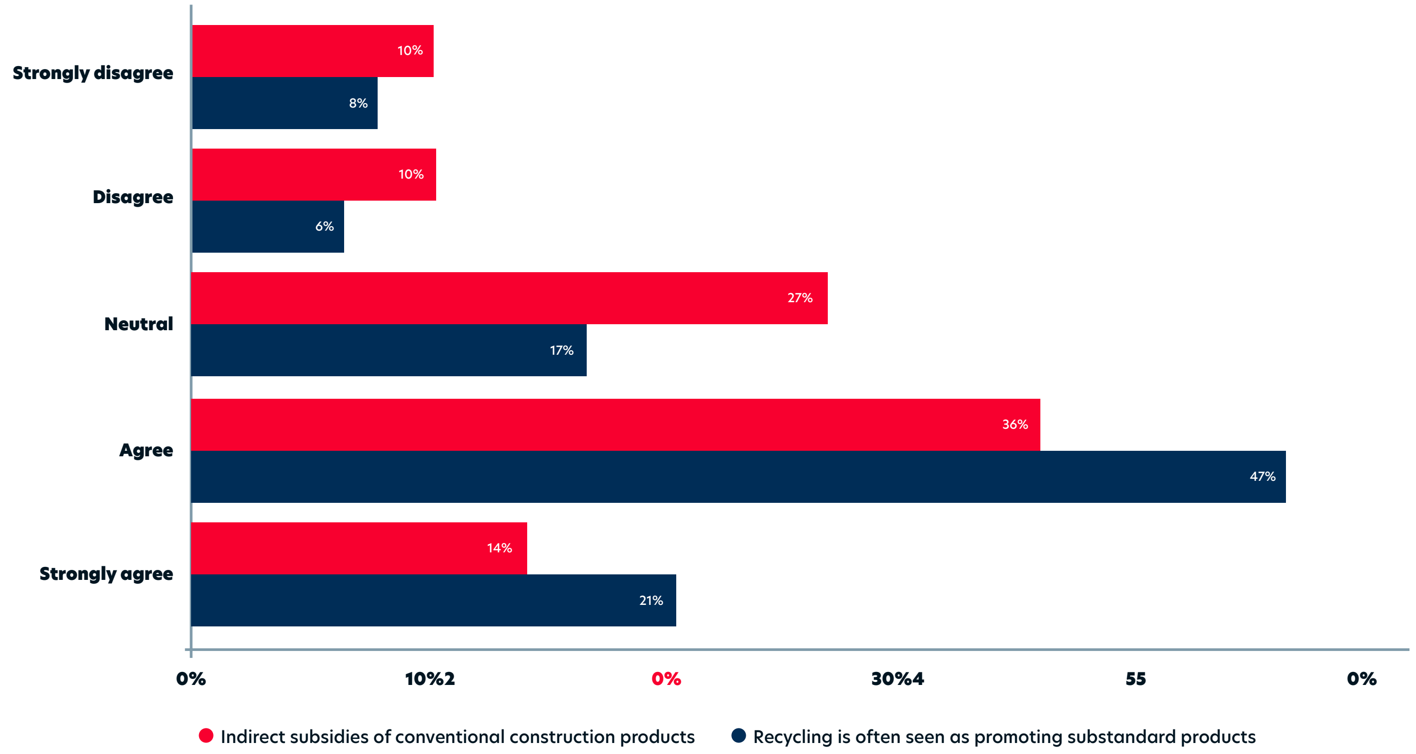
or agreed (35%) that lack of government support hinders the use of recycled cementitious products amount to 60%. Inadequate government backing sends wrong signals to the market in favour of conventional building materials, explaining the distance from recycled cementitious products by consumers. Local governments are best placed to promote recycled cementitious materials through appropriate building regulations.

Figure 46: Factors Explaining Lack of Use of Recycled Concretes (Lack of Government Support and Bias Towards Conventional Materials)



Finally, respondents were asked to consider the impact of indirect subsidies for virgin materials and the lack of local demand for cementitious products as one of the issues to be addressed to enhance its increased use in construction activities. As Figure 47 shows, respondents who strongly agreed (21%) or agreed (47%) that lack of use of recycled cementitious products owes to lack of local demand were 68% of total respondents. Similarly, those who strongly agreed (14%) or agreed (36%) that indirect subsidies for conventional materials explains the low reuse of cementitious products were 50% of the total. Indeed, incorporating natural capital and environmental impacts in national accounting has been recommended (ONS, 2019; Fletcher, et. al., 2019). Such measures would help to reflect the true costs of resource depletion and waste compared to economic benefits of reuse, refurbishment and recycling. In other words, evidence of strong local use of recycled cementitious materials in, say, local public buildings will convince developers and contractors in the private sector about the sustainability attributes of recycled cementitious products developers.

Figure 47: Factors Explaining Lack of Use of Recycled Concretes (Indirect Subsidies for Conventional Materials and Lack of Local Support)



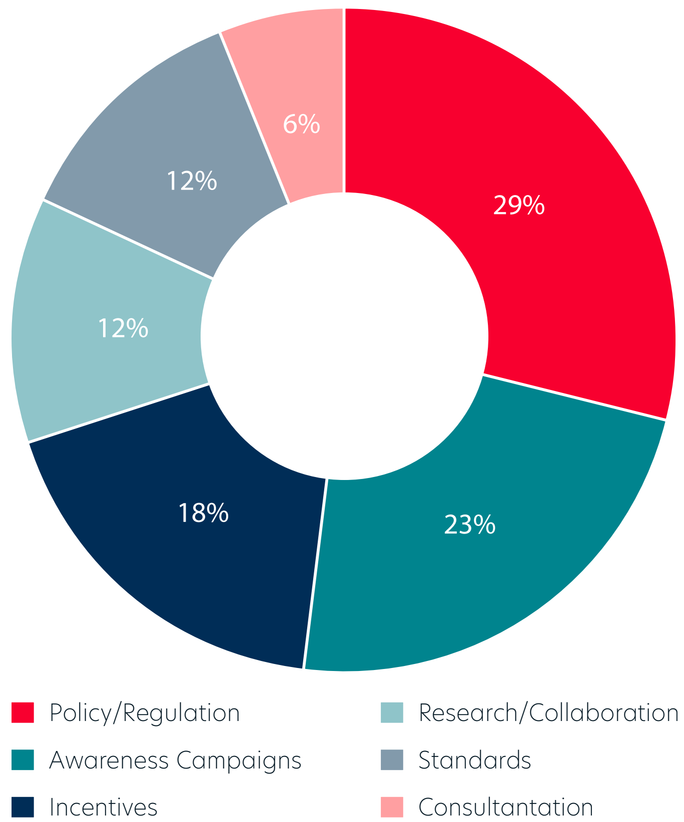
Generally, it is important to interrogate consumer attitudes and perceptions, as a necessary precondition to finding solutions to the low uptake of recycled cementitious products in global construction practice. As evidenced, such an understanding is what it will take to embed circular economy practices in the construction industry, and it also presents an important strategy that can be used to decouple growth in the construction industry's outputs from intensive consumption of raw materials. Other than the importance of doing so with regard to sustainability, it also for an existential reason for global construction industry owing the rapid rates of depletion in natural resources that underpin construction. The policies to drive circular economy practices in global construction and how the policies are to be implemented are seen as important to mitigating climate change and the attendant effects. In section J of the questionnaire, global construction stakeholders were posed a series of questions to throw light on the way forward.

8.1.8 Role of Policymakers in Improving Recyclability of Concrete Products

Policymakers have a crucial role to play in driving the adoption of recycled concrete materials through regulation, incentives, and public procurement. Various initiatives have been discussed in the literature (Smith, 2021), and the views and opinions of respondents were sought to see where they complement or depart from existing findings. For example, Smith (2021) argued that to increase practices of reduce, recycling, and reuse in the global construction industry, it is important that governments revisit building codes, and mandate the use of recycled cementitious materials (Smith, 2021). Other initiatives include the use of fiscal measures such as tax rebates to render recycled cementitious products competitive with the indirectly subsidised products made from conventional virgin materials. Governments should also lead by example by requiring the use of recycled concrete in public projects and infrastructure (Jones, 2020).

Figure 48: Role of Policy Makers in Enhancing Use of Recycled Concrete Products

What do you think could be done by the policymakers to encourage more use of recycled concrete products?

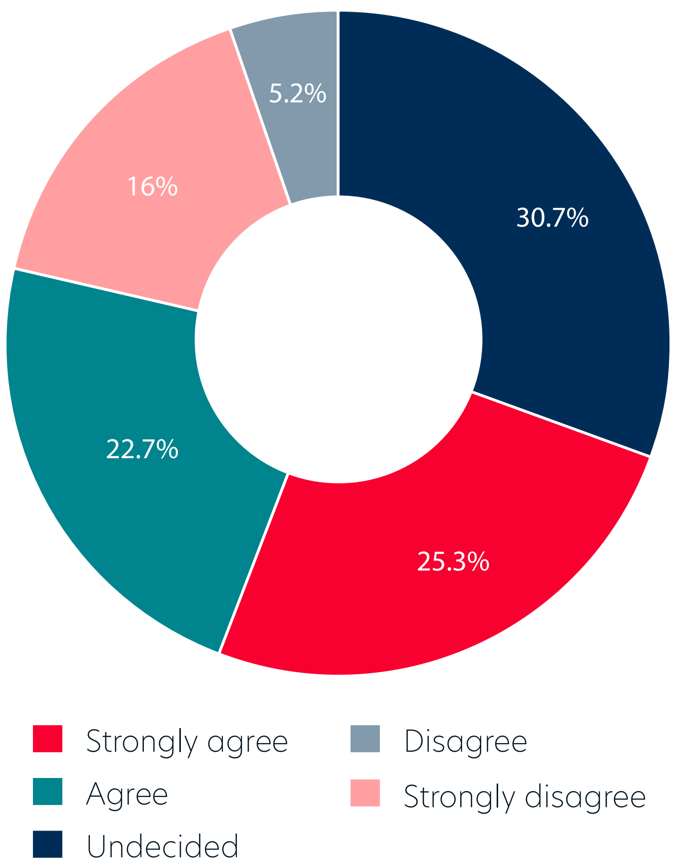


As Figure 48 shows, policy regulation ranks highest amongst areas the respondents believed policy makers could influence the uptake of circular economy practices in the construction industry through policy initiatives. Presently, there are many regulatory limitations to the use of recycled concretes in some areas of the construction sector. For example, the use of recycled concrete items is banned in areas where earthquakes are common, and as shown in this study, no structural weakness is inherent in recycled aggregates, and with the right mixes, recycled concretes can possess the same structural strength as concretes from virgin materials. Fiscal measures could be used to encourage the use of recycled aggregates, and this can be done by exempting built assets with, say, 50% recycled concrete content from property tax, and 18% of the respondents identified economic incentives as important to promoting the use of recycled concrete products in the construction industry.

Other critical areas where policy makers can promote the use of recycled concrete included awareness campaigns (23%), standards (12%), and research collaboration (12%). The government, as the institution that concentrates in itself powers to regulate construction industry activities, can insist on all government projects containing a given percentage of recycled aggregates. One would have thought that standards would rank higher with our stakeholders given that the lack of standards to which recycled aggregates should conform is a major barrier to its reuse in construction products manufacture (Katerusha, 2021).

To further drive home the point about the role of policy makers and noting in particular that local authorities preside over building control in most parts of the world, global construction stakeholders were asked about the assertiveness of their local authorities in promoting reuse of recycling aggregates. As Figure 49 shows, only 21.3% of the respondents either agreed or strongly agreed that their local authorities are doing enough to promote recycling of demolition wastes and reuse of recycled concrete products. Those who disagreed (30.7%) or strongly disagreed 22.7% constitute 56% of total respondents while a significant 25.3% were undecided. This points to one area where policy is required because local authorities are seen as critical to the promotion of circular infrastructure because of their roles in urban design and transition (Preuss, 2007). Local governments have different avenues to push the use of recycled concrete aggregate in construction projects. Local authorities can influence the use of recycled concrete aggregate through building codes, and in so doing create demand and accelerate its use, attracting entrepreneurs into the market for recycled aggregates (Smith, 2021). In particular, local authorities could form partnerships with research institutions, including the universities, to conduct research to dispel some of the misconceptions around the quality of recycled aggregates.

Figure 49: **Role of Local Authorities in Enhancing the Use of Recycled Concrete Products**
Does your local authority do enough to promote the recycling of construction and demolition waste, particularly concrete products? (77 responses)



The literature suggests that standards constitute a major hindrance to the use of recycled aggregates and the respondents were asked about the roles certifying bodies could play in facilitating wider acceptance and use of recycled aggregates in the construction industry (Silva, et. al. 2017). In particular, more contractors and clients would be more willing to use recycled aggregates and related products if they become mandatory requirements as part of green building certification initiatives (Smith, 2021). In Figure 50, the likely roles certification institutions could play to enhance acceptability and use of recycled concretes is made clear by our global respondents. Evidently, 57% of them hold the opinion that awarding points for the extent that recycled aggregates and products are used will incentivise clients and contractors both of whom are likely to take pride in constructing and owning green and sustainable built assets with minimal ecological footprints. Similarly, 38% of respondents believed that education by the certifying institutional bodies will enhance acceptance and use of recycled aggregates and cementitious products. Thus, through public education about successful projects utilizing recycled concrete, the current negative perceptions held of recycled cementitious products can be changed.

Finally, respondents were asked for additional recommendations they believe could help in disseminating and publicising the benefits of recycled cementitious products. As Figure 49 reveals, the overwhelming majority of 60% recommended placing the circular economy in the curriculum of construction education while 21% believed continuing professional development provides a platform where the benefits of using recycled cementitious products could be disseminated. Direct marketing is favoured by 17% of respondents; they believed that the visibility that accompanies direct marketing of cementitious products will bring associated benefits vividly to potential end users.

Figure 50: **Role of Certifying Institutions in Enhancing the Use of Recycled Concrete Products**
What role do you think a certifying institution could play in encouraging wider acceptance and use adoption of recycled concrete products?

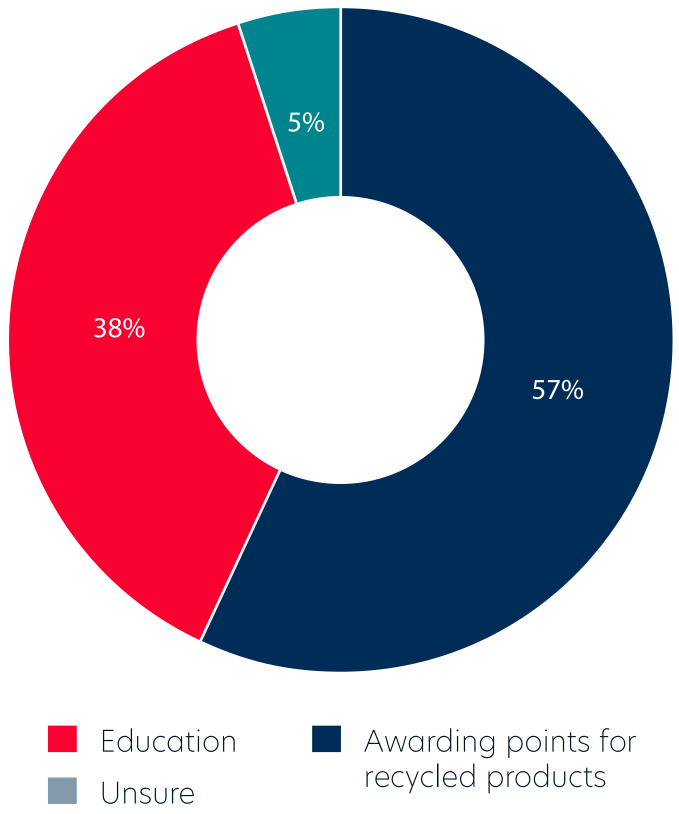
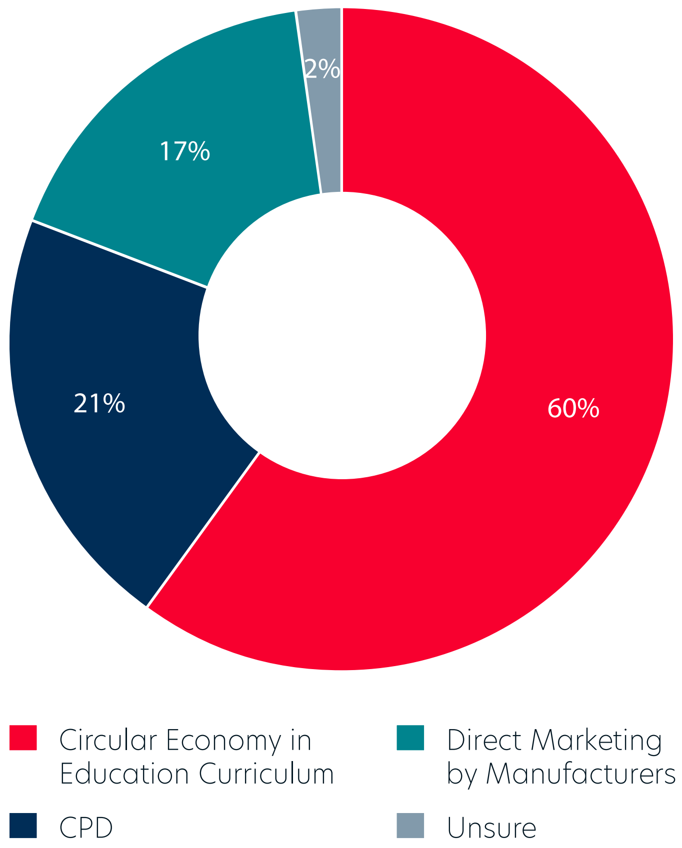


Figure 51: **Additional Measures To Enhance Dissemination of Benefits of Recycled Concrete Products**
In your view, what additional recommendations would you make for disseminating the benefits asscoaited with Recycled Concrete?



8.2 Exploratory Factor Analysis (EFA)

As a statistical analysis, factor analysis is a method employed to identify underlying factors or constructs that explain the correlations among a set of observed variables (Costello and Osborne, 2005; Taherdoost, 2014). This process enables researchers to determine the number of latent factors influencing a set of responses and which variables are reasonable indicators of each underlying factor. According to Osborne (2015), this data determination or reduction method is commonly used in social science research where various traits are measured, using multiple items or questions.

In the present study, a factor analysis was conducted on the survey data to identify the fundamental factors being measured by the questionnaire, which is to determine the validity of the questionnaire survey instrument that was used to evaluate the perceptions of stakeholders on adopting digital manufacturing for circularity in cementitious products. Although all the relevant questions were asked in the survey questionnaire; factor analysis not only allows any hidden factors to be made known, but it also informs on which questions appear to be grouping under the same underlying dimensions, reducing complex variables into a few important dimensions. This technique conforms to acceptable practices in survey validation and scale development

(Costello & Osborne, 2005; Wang et al., 2008).

The steps conducted in the EFA include the assessment of the suitability of the data collected from the questionnaire-based survey, determining the number of items for factor extraction, retaining and rotation, and interpretation of resulting factors.

To determine the strength of intercorrelation of the measurement scales for the dissemination and knowledge gap, certification gap, attitudes and perceptions of recycled concrete products, and role of policymakers in improving recyclability, the Bartlett's Test of Sphericity and the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy test was used to assess the suitability of the statements measuring each construct, presented to the study respondents for evaluation. A set of factors are deemed to appropriately measure a construct when the value of the Kaiser-Meyer-Olkin, which is a measure of Sampling Adequacy (KMO) is higher than the acceptable minimum limit of 0.6 and a limit of 1 (Tabachnick and Fidell, 2013). The cut-off value of 0.05 for the Bartlett's Test of Sphericity indicates the significance and appropriateness of the measurement scales (Hair et al., 2010). This signifies potential correlation among the factors and therefore indicates a potential for a reasonable cluster of factors to be formed from the items (Field, 2013).

Communalities produced by each factor are used to decide which factors must be finally extracted for improvement and refinement of a constructs scale measure. After extraction, an average communality of a factor should be above 0.30 to support that the results obtained from the questionnaire survey are reliable. The higher the communality value, the better the fit of that factor for the measurement of a construct. Low communalities (<.030) indicate that the factor is unfit and is a bad measure of a construct. Values with very low communalities may indicate that the factors are unrelated to the other items in sub-scale (Pallant, 2011). Therefore, excluding factors with low communalities from further analysis tends to create a balance between the total variance that occur between factors.

The significance of factors was determined using Principal component analysis. As each factor is extracted, the principal component analysis statistically tests the significance. The Kaiser's criterion or the eigenvalue rule was adopted to determine the number of factors to retain (Tabachnick and Fidell, 2013). The eigenvalue was used to determine the extent of variance between a factor and other factors measuring a construct. Eigenvalues greater than 1 are considered to be significant and used to explain the variance obtained by a factor.

The corrected item-total correlation values were calculated, and values above the cut-off value of 0.3 were considered to be multicollinear (Tabachnick and Fidell, 2013). Multicollinearity identifies factors of a construct that are very highly correlated (>0.90) with each other. Checking for multicollinearity helps to eliminate factors that are redundant and may not be needed in the analysis. By conducting a correlation analysis, relationships between an item and another were measured. The correlation co-efficient values range from -1.00 to +1.00. A coefficient of 0 indicates the non-existence of a relationship between the variable in question. The closer the coefficient is to 1.00 (positive or negative), the stronger the relationship.

8.2.1 Dissemination And Knowledge Gap for Recycled Concrete Products

Eight items measuring the dissemination and knowledge gap for recycled products were analysed. Inspection of the corrected item-total correlation values were above 0.3 (see Table 2), the factors presented adequately measured respondents perceptions of the role these factors play in the wider acceptance of products manufactured from recycled concrete. To determine the strength of the item's intercorrelations, the Kaiser-Meyer-Olkin (KMO) was 0.904 and a Bartlett's test of Sphericity with p<0.001 was obtained as shown in Table 1. This indicated that the KMO value is above the cut-off value of 0.60. The results indicate that the factors adequately measure the dissemination and knowledge gap for recycled concrete products.

Table 1: KMO and Bartlett's Test for Dissemination and Knowledge Gap for Recycled Concrete Products

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.904
Bartlett's Test of Sphericity	Approx. Chi-Square	742.162
	df	36
	Sig.	<.001

Table 2: Dissemination and Knowledge Gap Factor Statistics

		Factor Loading	Corrected item-total correlation	Initial	Extraction
DKG1	Introducing global certification standards for products from recycled concrete.	.699	.621	.312	.818
DKG2	Introducing international certification standards for products from recycled concrete	.742	.325	.855	.857
DKG3	Initiating European certification standards for products from recycled concrete	.841	.533	.574	.830
DKG3	Initiating European certification standards for products from recycled concrete	.841	.533	.574	.830
DKG4	Promotion of intercountry certification standards for products from recycled concrete	.734	.324	.678	.879
DKG5	Promotion of intra-country certification standards for products from recycled concrete	.705	.422	.606	.902
DKG6	Promotion of community-based certification standards for products from recycled concrete	.742	.625	.717	.796
DKG7	Introduction of certification standards approved by all major global states	.823	.631	.671	.848
DKG8	Promulgation of certification standards approved by independent non-governmental organisations on Climate Change	.774	.427	.647	.784
Extraction Method: Principal Component Analysis.					

From the results presented in Table 3, one factor with an eigenvalue of 6.905 accounted for 76% of the variance. The total variance explained is above the recommended cut-off value of 50%. Since only one factor was extracted, it was unnecessary to rotate the solution. The solution was, therefore, considered unidimensional and as providing evidence that all the factors should be retained.

Table 3: Initial Eigenvalues for Dissemination and Knowledge Gap

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	6.905	76.726	76.726
2	.681	7.563	84.289
3	.382	4.249	88.538
4	.272	3.018	91.556
5	.229	2.542	94.098
6	.182	2.024	96.122
7	.146	1.621	97.743
8	.120	1.336	99.080
9	.083	.920	100.000

Table 4 presents bivariate correlation analysis results for the eight items in the scale. Correlation values ranged from 0.606 to 0.855, indicating that the factors were related to each other.

Table 4: Correlation Coefficient for Dissemination and Knowledge Gap

Correlation Matrix										
		DK1	DK2	DK3	DK4	DK5	DK6	DK7	DK8	DK9
Correlation	DKG1	1.000								
	DKG2	.855	1.000							
	DKG3	.748	.772	1.000						
	DKG4	.574	.671	.806	1.000					
	DKG5	.590	.647	.743	.795	1.000				
	DKG6	.612	.628	.708	.784	.770	1.000			
	DK7	.711	.741	.814	.704	.717	.806	1.000		
	DK8	.750	.741	.783	.678	.606	.725	.827	1.000	
	DK9	.757	.740	.839	.746	.760	.758	.817	.813	1.000

8.2.2 Certification Gap for Recycled Concrete Products

Eight items measuring the certification gap for recycled concrete products were analysed, and revealed a KMO of 0.889, and a Bartlett's test of Sphericity with p<0.001 was obtained, as shown in Table 5. The corrected item-total correlation values were greater than the recommended cut-off value of 0.3, indicating that the items measured the certification gap for recycled concrete products adequately. Results from the analysis of communalities in Table 6 showed that the communalities for the items were all acceptable.

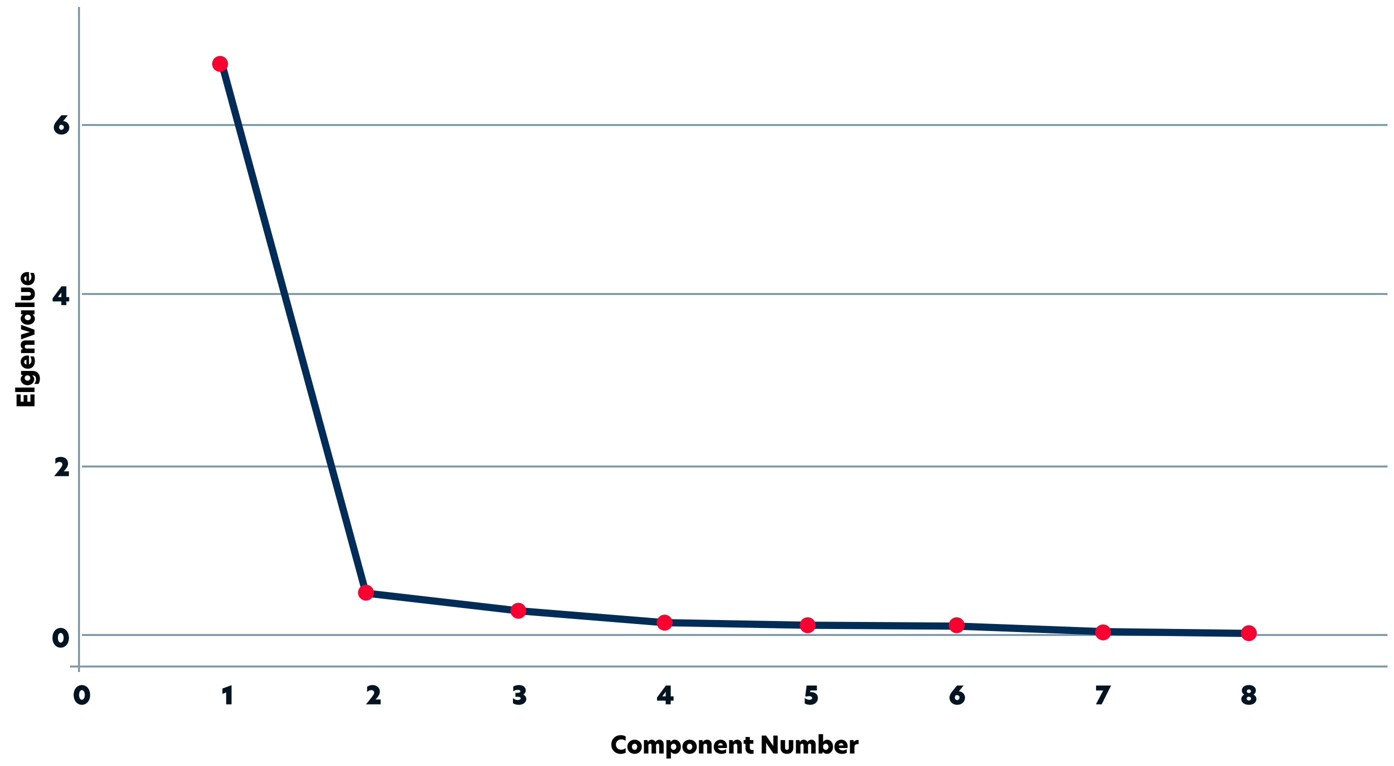
Table 5: KMO and Bartlett's Test for Certification Gap for Recycled Concrete Products

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.889
Bartlett's Test of Sphericity	Approx. Chi-Square	921.327
	df	28
	Sig.	<.001

Table 6: Certification Gap Factor Statistics

		Factor Loading	Corrected item-total correlation	Initial	Extraction
CG1	Introducing global certification standards for products from recycled concrete.	.905	.435	.773	.818
CG2	Introducing international certification standards for products from recycled concrete	.926	.738	.840	.857
CG3	Initiating European certification standards for products from recycled concrete	.911	.336	.651	.830
CG4	Promotion of intercountry certification standards for products from recycled concrete	.938	.640	.540	.879
CG5	Promotion of intra-country certification standards for products from recycled concrete	.950	.841	.534	.902
CG6	Promotion of community-based certification standards for products from recycled concrete	.892	.433	.615	.796
CG7	Introduction of certification standards approved by all major global states	.921	.437	.407	.848
CG8	Promulgation of certification standards approved by independent non-governmental organisations on Climate Change	.886	.532	.333	.784
Extraction Method: Principal Component Analysis.					

Figure 52: Scree Plot for Certification Gap



From the results presented in Figure 1 and Table 7, one factor with an eigenvalue of 6.715 accounted for 83% of the variance. The solution was to provide adequate evidence of validity of the factors.

Table 7: Initial Eigenvalues for Certification Gap

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	6.715	83.935	83.935
2	.506	6.328	90.263
3	.278	3.479	93.742
4	.169	2.114	95.857
5	.146	1.826	97.683
6	.111	1.391	99.073
7	.052	.645	99.718
8	.023	.282	100.000

All the correlation values showed a positive and high correlation between the eight items in the scale (see Table 8). All the correlation values were above 0.30 and less than 0.90, indicating a strong relationship between the items measuring factors known to promote the wider use of recycled concrete.

Table 8: Correlation Coefficient for Certification Gap

Correlation Matrix										
		CG1	CG2	CG3	CG4	CG5	CG6	CG7	CG8	DK9
Correlation	CG1	1.000								
	CG2	.973	1.000							
	CG3	.840	.860	1.000						
	CG4	.803	.831	.861	1.000					
	CG5	.804	.834	.836	.921	1.000				
	CG6	.685	.738	.751	.842	.887	1.000			
	CG7	.799	.803	.788	.815	.870	.807	1.000		
	CG8	.722	.742	.739	.793	.801	.833	.868	1.000	

Section H: Attitudes and Perceptions of Recycled Concrete Products (Suitability)

The KMO for attitudes and perceptions of recycled concrete products was 0.857, and Bartlett's test of Sphericity with $p<0.001$ was obtained (see Table 9). The results showed that strong intercorrelations exist between the factors used to measure the extent of knowledge on the benefits of recycled concrete products. The corrected item-total correlation values for the subscales were greater than the recommended cut-off value of 0.3, indicating that the items adequately measured the attitudes towards, and perceptions of, recycled concrete products. The results show that the data meet the criteria for factor analysability. As shown in Table 10, the analysis of communalities revealed that item AP9 (Conscious or unconscious bias towards original unrecycled products) was problematic due to a low community value. This is indicative of the unsuitability of the factor to measure the attitudes towards, and perceptions of, recycled concrete products. The resulting solution needs to be interpreted with caution.

Table 9: KMO and Bartlett's Test for Attitudes and Perceptions of Recycled Concrete

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.857
Bartlett's Test of Sphericity	Approx. Chi-Square	512.988
	df	91
	Sig.	<.001

Table 10: Attitudes and Perceptions Factor Statistics

		Factor Loading	Corrected item-total correlation	Initial	Extraction
AP1	Insufficient certification bodies	.905	.435	.773	.818
AP2	Insufficient education	.926	.738	.840	.857
AP3	Insufficient media coverage	.911	.336	.651	.830
AP4	Socio-economic factors	.938	.640	.540	.879
AP5	Aging properties of recycled products	.950	.841	.534	.902
AP6	Pride in buying recycled products	.892	.433	.615	.796
AP7	Hidden benefits of recycled products	.921	.437	.407	.848
AP8	Promulgation of certification standards approved by independent non-governmental organisations on Climate Change	.886	.532	.333	.784
AP9	Conscious or unconscious bias towards original unrecycled products	.849	.756	.759	.128
AP10	A wider shift in recognition of the benefits towards recyclability of concrete products	.760	.679	.746	.691
AP11	Dissemination of well-tested concrete products	.786	.337	.848	.658
AP12	Wider adoption by designers/architects	.792	.380	.304	.682
AP13	Clients must be convinced of utility-value	.877	.371	.356	.778
AP14	Consumers must be convinced of utility-value	.870	.649	.797	.780
Extraction Method: Principal Component Analysis.					

Table 11 shows that four factors emerged with eigenvalues greater than 1, explaining 66.9% of the variance. This result suggests the likelihood of multidimensionality of the sub-scale. To obtain a clear factor solution of the attitudes and perceptions construct, item AP9 (Conscious or unconscious bias towards original unrecycled products) was deleted, and the EFA was reiterated.

Table 11: Initial Eigenvalues for Attitudes and Perceptions

Total Variance Explained						
Component	**Initial Eigenvalues**		**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loadings**
	Total	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**	**Total**
1	5.961	42.577	5.961	42.577	42.577	5.829
2	1.284	51.746	1.284	9.169	51.746	1.749
3	1.103	59.626	1.103	7.880	59.626	1.400
4	1.025	66.950	1.025	7.324	66.950	1.473
5	.905	73.412				
6	.771	78.921				
7	.673	83.725				
8	.527	87.488				
9	.481	90.920				
10	.383	93.655				
11	.346	96.126				
12	.259	97.976				
13	.163	99.141				
14	.120	100.000				
Extraction Method: Principal Component Analysis.						

Table 12 shows that after the elimination of item AP9, the KMO was 0.853, and the Bartlett's test of Sphericity was achieved with a significance of $p<0.001$. Results from the analysis of communalities showed that the communalities for the items were all acceptable, indicating that the items were a good measure of the attitudes to, and perceptions of, recycled concrete products (see Table 13).

Table 12: KMO and Bartlett's Test for Attitudes and Perceptions after the deletion of item AP9

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.853
Bartlett's Test of Sphericity	Approx. Chi-Square	421.289
	df	78
	Sig.	<.001

Table 13: Factor Statistics after the deletion of item AP9

		Factor Loading	Corrected item-total correlation	Initial	Extraction
AP1	Insufficient certification bodies	.314	.450	.645	.735
AP2	Insufficient education	.727	.770	.638	.585
AP3	Insufficient media coverage	.722	.340	.338	.600
AP4	Socio-economic factors	.707	.440	.565	.769
AP5	Aging properties of recycled products	.471	.717	.554	.624
AP6	Pride in buying recycled products	.369	.563	.324	.618
AP7	Hidden benefits of recycled products	.694	.332	.889	.563
AP8	Insufficient data on Green benefits of recycled products	.717	.323	.570	.596
AP10	A wider shift in recognition of the benefits towards recyclability of concrete products	.741	.777	.434	.661
AP11	Dissemination of well-tested concrete products	.793	.527	.312	.674
AP12	Wider adoption by designers/architects	.809	.665	.724	.702
AP13	Clients must be convinced of utility-value	.880	.661	.446	.781
AP14	Consumers must be convinced of utility-value	.868	.442	.335	.776
Extraction Method: Principal Component Analysis.					

Results presented in Table 14 show the emergence of 1 factor with an eigenvalue of 1.002, which accounted for 61% of the variance. The solution was, therefore considered unidimensional and provided evidence that all the factors should be retained.

Table 14: Initial Eigenvalues after deletion of item AP9

Total Variance Explained		
Component	**Initial Eigenvalues**	
	Total	**Cumulative %**
1	1.002	61.944
2	.916	63.458
3	.800	65.652
4	.804	66.813
5	.894	73.765
6	.766	79.659
7	.623	84.454
8	.517	88.431
9	.467	92.025
10	.369	94.866
11	.311	97.255
12	.235	99.064
13	.122	100.000

As indicated in Table 15, all the correlation values showed a positive and high correlation between the thirteen items measuring the attitudes and perceptions of the suitability of recycled concrete. All correlation values were above 0.30 and less than 0.90, indicating a significant relationship between all the factors.

Table 15: Correlation Coefficient for attitude and perceptions

Correlation Matrix														
	AP1	AP2	AP3	AP4	AP5	AP6	AP7	AP8	AP9	AP10	AP11	AP12	AP13	AP14
AP1	1.000													
AP2	.566	1.000												
AP3	.676	.887	1.000											
AP4	.889	.554	.327	1.000		.								
AP5	.883	.351	.312	.075	1.000									
AP6	.838	.319	.812	.311	.309	1.000								
AP7	.542	.318	.382	.615	.430	.689	1.000							
AP8	.353	.424	.529	.329	.757	.521	.441	.821	1.000					
AP10	.370	.715	.411	.696	.308	.483	.474	.422	.733	1.000				
AP11	.662	.512	.543	.331	.332	.666	.574	.511	.608	.573	1.000			
AP12	.711	.618	.488	.812	.484	.300	.513	.632	.553	.537	.647	1.000		
AP13	.412	.332	.627	.420	.584	.318	.548	.542	.707	.625	.634	.651	1.000	
AP14	.320	.601	.666	.348	.557	.345	.498	.571	.725	.604	.569	.658	.854	1.000

8.2.3 Role of policymakers in improving recyclability of concrete products.

Ten items were used to examine the role of policy makers in improving the recyclability of concrete products. The Kaiser-Meyer-Olkin (KMO) and Bartlett's test of Sphericity were used to test the strength of item intercorrelations and revealed a KMO of 0.829 with the Bartlett's being $p<0.001$, indicating the suitability of the factors to measure policymakers' role in improving the recyclability of concrete products(See Table 16).

Inspection of the corrected item-total correlation values were above 0.3, indicating that the items adequately measured the role of policymakers in improving recyclability of concrete products (see Table 17).

Table 16: KMO and Bartlett's Test for Role of Policymakers

KMO and Bartlett's Test		
KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.829
Bartlett's Test of Sphericity	Approx. Chi-Square	304.410
	df	45
	Sig.	<.001

Table 17: Role of Policymakers Factor Statistics

		Factor Loading	Corrected item-total correlation	Initial	Extraction
RP1	Recycling is often seen as promoting substandard	.438	.581	.576	.557
RP2	Recycling centres are often located too far apart	.413	.445	.818	.385
RP3	Local authorities don't prioritise recycling	.681	.485	.714	.555
RP4	Tangible benefits are not well quantified	.518	.399	.778	.819
RP5	Recyclables are less likely to compete with original products	.452	.433	.690	.611
RP6	Lack of dissemination and sharing of information on the qualities of recyclable products	.728	.404	.631	.568
RP7	Heavy bias and unconscious bias in favour of conventional products	.872	.372	.486	.838
RP8	Disquiet within Government policy makers	.822	.328	.750	.784
RP9	Reluctance at the local level impacts negatively on the wider society.	.775	.424	.743	.809
RP10	Indirect subsidies of conventional construction products	.660	.381	.395	.646
Extraction Method: Principal Component Analysis.					

One factor with an eigenvalue of 4.303 accounted for 65.722% of the variance (see Table 18). The total variance explained is above the recommended cut-off value of 50%. Since only one factor was extracted, it was unnecessary to rotate the solution. The solution therefore revealed that all the ten factors could be retained.

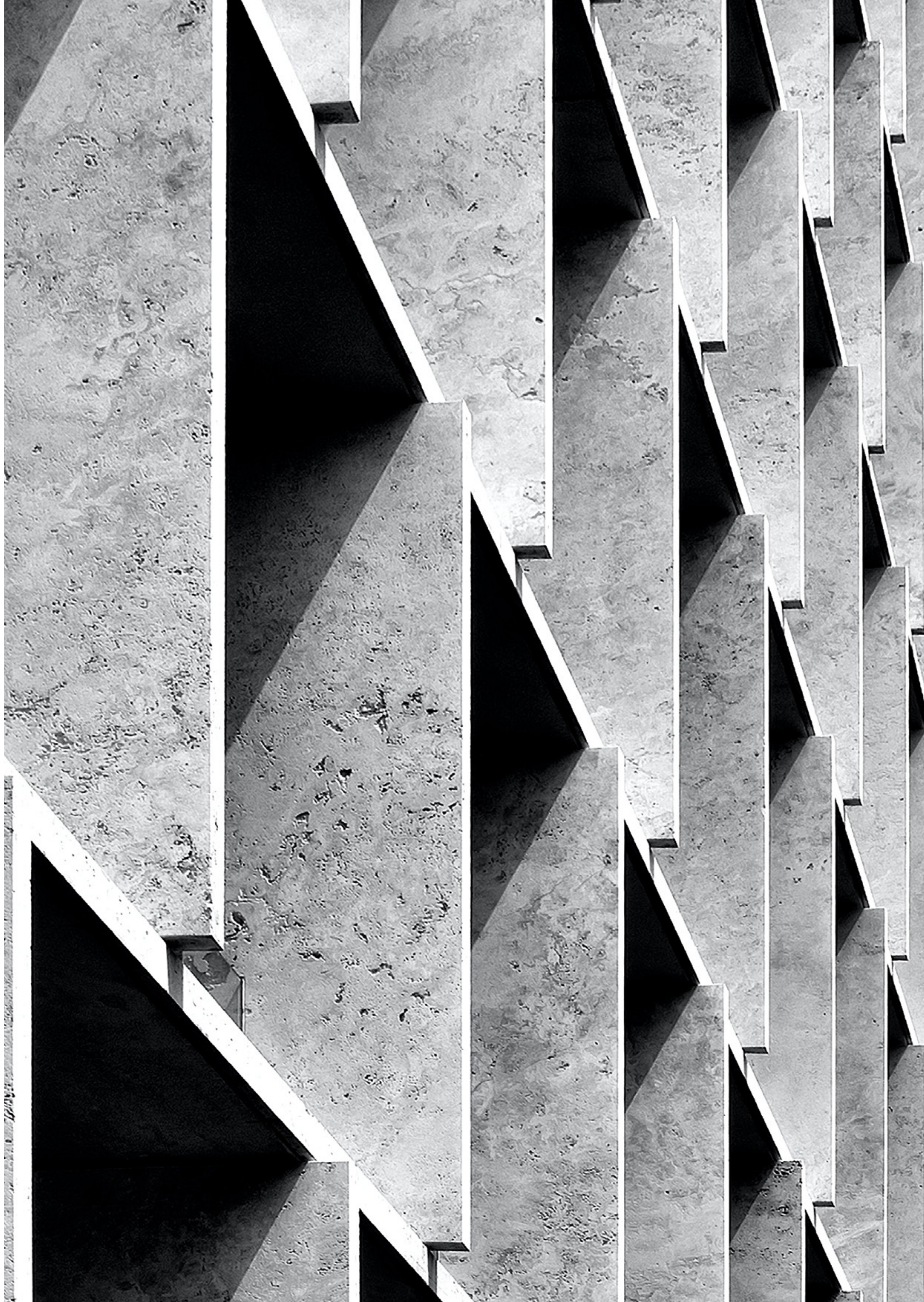
Table 18: Initial Eigenvalues for Role of Policymakers

Total Variance Explained		
Component	Initial Eigenvalues	
	Total	Cumulative %
1	4.303	65.722
2	.920	77.923
3	.949	88.415
4	.856	74.284
5	.712	81.406
6	.603	87.432
7	.502	92.453
8	.351	95.963
9	.218	98.143
10	.186	100.000

Table 19 presents bivariate correlation analysis result for the measurement scale. Correlation values ranged from 0.303 to 0.786, indicating that the factors measuring the role of policymakers in improving recyclability of concrete products were related to each other.

Table 19: Correlation Coefficient for Role of Policymakers

Correlation Matrix										
	RP1	RP2	RP3	RP4	RP5	RP6	RP7	RP8	RP9	RP10
RP1	1.000									
RP2	.341	1.000								
RP3	.328	.344	1.000							
RP4	.550	.397	.391	1.000						
RP5	.398	.458	.339	.477	1.000					
RP6	.344	.331	.366	.482	.346	1.000				
RP7	.362	.341	.494	.425	.447	.582	1.000			
RP8	.365	.355	.493	.371	.447	.447	.786	1.000		
RP9	.318	.350	.331	.317	.401	.497	.744	.732	1.000	
RP10	.494	.418	.378	.303	.303	.367	.533	.486	.549	1.000



9.0 Discussion of Findings

Implementing circular economy principles such as reuse, refurbishment and high-value recycling of materials and buildings enables the construction industry to reduce its environmental impacts. This study has demonstrated the potential that exists for achieving substantial reductions in the demand for raw materials, carbon emissions and waste generation, and deliver significant sustainability gains. As shown in the case of China, the use of recycled demolition waste reduces the use of carbon-intensive virgin materials, such as cement, sand, and gravels. It is clear that repurposing global construction from its current linear model towards a circular system presents the global construction industry with huge opportunities to reduce its enormous ecological footprints.

This study shows that the wider environmental benefits of recycling C&D wastes transcend waste prevention and pollution abatement; they also include those associated with enhancements in the regenerative capacity of the ecosystem following reductions in natural resource depletions.

Similarly, findings from this study should dispel the conventional belief that recycled cementitious products are of low quality, and inferior to those derived from virgin materials. The study shows that given the right and appropriate mixes; recycled aggregates compete favourably to cementitious products from virgin materials and do perform better in some instances, albeit under laboratory conditions. It is further evident that the right mixes identified in this study can be digitally manufactured into cementitious products with comparable qualities quality and attributes comparable to products made from virgin materials. Given that there are no moulds in digital manufacturing, a series of experiments was carried out to see if the mixes produced in the study could be formed into different shapes. This was achieved as shown in Figures 20 - 25.

Higher value recycling, which is what digital cementitious manufacturing is, has numerous environmental and socio-economic advantages which were critically evaluated. The high volume recycling possibilities under digital manufacturing can eliminate more than 50% of current global C&D wates. The environmental benefits are significant given the amount of raw materials, carbon emissions, and wastes that would be avoided by transiting from conventional linear to circular economy practices across construction value chains. This is the transformative change the industry needs to make in order to address its huge environmental burdens and be sustainable.

It is also clear from the study that significant socio-economic benefits can be derived from the digital cementitious manufacturing process. Circular economy strategies of 'cradle to death' sustainable design, reuse, refurbishment and high-value recycling of buildings require new skills in design for disassembly, digitalisation, material recovery and logistics (Huang et al., 2018; Schut et al., 2015). The industry would find it challenging to retrain existing workers for reasons of an aging workforce, low literacy rate in the sector, and costs of training. Nonetheless, through partnerships between the construction industry, its clients, and the government, these challenges are solvable. Various governments across the world have a vital role to play in supporting construction industry transformative agendas, not just in seeing the industry as a key partner in the pursuit of national carbon emissions targets, but also, because of the fundamental role the construction industry plays in economic development (Giang, et. al. 2011; Ofori, 1988).

Significant social benefits accruing from digital cementitious manufacturing can be derived from the economic benefits of employment and income earning opportunities, as well as the benefits from economies of scale, filtering down in terms of lower product prices and enhancing affordability. The transformation of the construction workplace environment in the enhancing of health safety and widening of access to the industry by women remains a significant benefit amongst others, deriving from digital cementitious manufacturing.

It is made clear from the study that for circularity to take a hold in the construction industry and facilitate digital manufacturing of cementitious products, the negative perceptions of construction stakeholders, mainly contractors, and clients and developers should be allayed. It is evident from this study that recycled products face serious competition in the marketplace because consumers still prefer conventional building products that are considered superior to recycled products. Thus, it will require concerted efforts by all construction stakeholders to create an enabling framework of appropriate economic conditions and incentives to drive the circular economy transition in the construction industry. Governments at all levels have a critical role to play in driving the transition using enabling policy instruments, to ensure increased use of recycled cementitious products in construction.

Some measures the governments could take, according to our survey respondents must begin with an end to indirect subsidies enjoyed by conventional building materials where the full economic costs are not internalised within their price structure. For example, virgin materials such as concrete sand and gravel receive indirect government subsidies, and this presents a barrier to uptake of recycled concrete aggregates. This is why conventional concrete would be less expensive relative to recycled cementitious products; by excluding the social costs of extraction and disposal. Revenues realised from taxing the extraction of sand and gravel could be used to subsidise the recycling process, including the digital manufacturing of cementitious products.

Also, improving visibility and making it less arduous to access recycled cementitious products are critical to driving acceptance by mainstream construction industry practitioners. For example, retailers devoted to selling recycled products could be exempted from certain corporation taxes. Similarly, there is the issue of uncertainty of supply, which contractors and developers consider a major risk to specifications of recycled products. Subsidies and soft loans to offset the high upfront costs of C&D wastes processing machines and digital manufacturing equipment for manufacturing products could increase availability of recycled products and ensure supply on demand. With advancing technology and growing eco-awareness, significant opportunities exist to increase adoption through consumer education and improved retail accessibility. This can accelerate the market viability and consumption of recycled goods as ethical and environmentally conscious choices.

The role of education across the construction supply chain, including consumers is important to enhancing the use of recycled concrete and digitally manufactured construction products. Circular economy principles must be embedded into architecture engineering and construction (AEC) educational curricula to focus on design for deconstruction practices that facilitate recycling, covering utilization of recycled aggregates in concrete while quantifying attendant sustainability benefits. Student must be exposed and schooled on installation and workings of digital manufacturing equipment and manufactured 3D printed recycled concrete products. Huge opportunity exists in the educational sector to accelerate progress on recycling and digital manufacturing of cementitious projects. Given that construction students of today are the construction industry practitioners of tomorrow, weaning them on the principles of circular economy advances recycling of concrete, through digital manufacturing, into recycled cementitious products. However, it will take some concerted efforts by all the construction stakeholders to develop the employment and training needs of global construction industry to be able to take advantage that digital manufacturing offers. While general construction skills development initiative is necessary, a targeted initiative directed at the circular economy and the attendant digital cementitious product manufacturing is what global construction requires to transform itself and transit from the wasteful linearised operational mode to the sustainable circularity mode of operation and practice.

Appendices

List of References

- Alabi, B., Fapohunda, J. (2021) 'Effects of Increase in the Cost of Building Materials on the Delivery of Affordable Housing in South Africa', Sustainability, 13(4), p. 1772. https://doi.org/103390/su13041772
- Agustí-Juan, I. and Habert, G. (2017) 'Environmentally friendly design and digital fabrication methods versus traditional construction techniques', Smart and Sustainable Built Environment.
- Alsheyab, M. A. T (2021). Recycling of construction and demolition waste and its impact on climate change and sustainable development. International journal of Environmental Science and Technology. 19(3). DOI:10.1007/s13762-021-03217-1.
- Arzoumanidis, I.; Walker, A.M.; Petti, L.; Raggi, A. (2021) 'Life Cycle-Based Sustainability and Circularity Indicators for the Tourism Industry: A Literature Review', Sustainability, 13(11), p. 1853. https:// doi.org/10.3390/su132111853
- Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., Bertram, N. and Brown, S. (2017) Reinventing construction: a route to higher productivity. McKinsey Global Institute.
- Balawejder, F. and Monahan, E. (2020) "Effective Policy Approaches to Sectoral Issues." Industrial Strategy Council Research Paper. Available at https://industrialstrategycouncil.org/effectivepolicy-approaches-sectoral-issues
- Batayneh, M., Marie, I. and Asi, I. (2007) 'Use of selected waste materials in concrete mixes', Waste Management, 27(12), pp. 1870-1876.
- Behera, B., Rahut, D. B., & Sethi, N. (2020). Analysis of household access to drinking water, sanitation, and waste disposal services in urban areas of Nepal. Utilities Policy, 62, 100996. doi: 10.1016/j.jup.2019.100996.
- Beiser, V. (2017) 'He who controls the sand: the mining 'mafias' killing each to build cities', Guardian Newspaper, 28 February. Available at: https://www.theguardian.com/cities/2017/feb/28/sand-mafias-killing-each-other-buildcities#:~:text=In%20India%2C%20%E2%80%9Csand%20mafias%E2%80%9D,run%20over%20by%20sand%20trucks (Accessed: 10 July 2023).
- Bhattacherjee, A. (2012) Social Science Research: Principles, Methods, and Practices. 2nd edn. Global Text Project.
- Bide, T., Balson, P., Mankelow, J., Selby, I. (2016) 'A new sand and gravel map for the UK Continental Shelf to support sustainable planning', Resources Policy, 48, pp. 1-12.
- Bos, F., Wolfs, R., Ahmed, Z., Salet, T. (2016) 'Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing', Virtual and Physical Prototyping, 11(3), pp. 209-225.
- Braimah, N. and Ndekugri, I. (2009) 'Factors influencing the selection of delay analysis methodologies', International Journal of Project Management, 27(8), pp. 779-788.
- Bruce, K., Reyes, K.M.D., Shetranjiwalla, S. (2023) 'Connecting the periodic table to the planet with systems, life cycle and circularity thinking', Sustainable Chemistry and Pharmacy, 32. https://doi.org/10.1016/j.scp.2023.101018
- Bunte, K., Abt, S. R., Potyondy, J. P. and Ryan, S. E. (2007) 'Measurement of coarse gravel and cobble transport using portable bedload traps', Journal of Hydraulic Engineering, 133(8), pp. 879-893.
- Buswell, R.A., Leal de Silva, W.R., Jones, S.Z. and Dirrenberger, J. (2018) '3D printing using concrete extrusion: A roadmap for research', Cement and Concrete Research, 112, pp. 37-49.
- Cao, Y., Shepherd, P., Shercliff, H., Williams, R.J., (2018). Manufacture of novel aviation components using robot-based additive manufacturing in combination with ultrasonic welding. Additive Manufacturing 22, 197-203.
- Castro, F. G., Kellison, J. G., Boyd, S. J. Kopak, A. (2010). A Methodology for Conducting Integrative Mixed Methods Research and Data Analyses. Journal of Mixed Methods Research 4(4) 342 –360.
- CSE (2020) 'India recycles only 1% of its construction and demolition waste: CSE'. Available at: https://www.cseindia.org/india-recycles-only-1percent-of-its-construction-and-demolition-waste-cse-10481 (Accessed: 10 Jul 2023).
- Cook, E., Velis, C. A., Black, L. (2022) 'Construction Demolition Waste Management: A Systematic Scoping Review of Risks to Occupational and Public Health', Frontiers in Sustainability, 30 June.
- Costello, A. B., & Osborne, J. W. (2005). Best practices in exploratory factor analysis: Four recommendations for getting the most from your analysis. Practical Assessment, Research & Evaluation, 10(7), 1-9.
- Giang, D.T.H and Pheng, L. S. (2011). Role of construction in economic development: Review of key concepts in the past 40 years, Habitat International, Volume 35, Issue 1, pp.118-125,
- De Bruijne, M., & Wijnant, A. (2014). Improving Response Rates and Questionnaire Design for Mobile Web Surveys. Public Opinion Quarterly, 78(4), 951–962. https://doi.org/10.1093/poq/nfu046
- De Jesus, A., Hoppe, T., Coelho, D. and Kamer, P.C. (2019) 'Customization and digital fabrication–A survey on opportunities brought by new technologies for personalized product design and production', Procedia CIRP, 84, pp. 257-262.
- Dell'Anno, F., Marandola, M., Hosseini, A., Ricciardi, L. and Zanoni, S. (2021) 'Circular Economy Strategies in the Built Environment: A systematic literature review', Management of Environmental Quality: An International Journal.
- Dellink, R. (2020). The consequences of a more resource efficient and circular economy for international trade patterns: A modelling assessment – Environment Working Paper N°165. OECD Environment Directorate. Available at: https://www.oecd.org/env/waste/the-consequences-of-a-more-resource-efficient-and-circular-economy-for-international-trade-patterns-fa01b672-en.htm [Accessed 4 July 2023].
- Divan, Shyam, and Armin Rosencranz, (2022) 'Transboundary Environmental Issues', Environmental Law and Policy in India: Cases and Materials. 3rd edn. Oxford, online edn, Oxford Academic. https://doi.org/10.1093/oso/9780192865458.003.0018 (Accessed: 30 August 2023).
- Ebohon, O.J. (1996) 'The scope and limits of sustainable development in Africa's built environment sector', International Journal of Sustainable Development and World Ecology, 3, pp. 1012, ISSN: 1350-4509.
- Ebohon, O.J. (2022) 'Sustainability Economics and the Construction Industry', in Ofori, G. (ed.) Research

Companion to Construction Economics. Edward Elgar Publishing, Northampton, England.

- Ellen Macarthur Foundation (EMF) (2013) Towards a Circular Economy. Business Rationale for an Accelerated Transition. Ellen Macarthur Foundation, Cowes, UK.
- Fletcher, R., Dressler, W. H., Anderson, Z. R., and Büscher, B. (2019) Natural capital must be defended: green growth as neoliberal biopolitics, The Journal of Peasant Studies, 46:5, 1068-1095, DOI: 10.1080/03066150.2018.1428953
- Fowler Jr, F. J. (2013) Survey Research Methods. Sage Publications.
- Greenpeace International. (2012). Sand depletion - Rex Weyler - Greenpeace International. Retrieved July 10, 2023, from https://www.greenpeace.org/international/story/19351/sand-depletion/.
- Guerra, B.C., Shahi, S., Mollaei, A., Skaf, N. Weber, O., Leite, F., Haas, C. (2021) 'Circular economy applications in the construction industry: A global scan of trends and opportunities', Journal of Cleaner Production, 324.
- Guo, H., Shi, C., Guan, X., Zhu, J., Ding, Y., Ling, T. C., Zhang, H., Wang, Y. (2018). Durability of recycled aggregate concrete–A review. Cement and Concrete Composites, 89, pp. 251-259
- Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M. (2015) 'How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005', Journal of Industrial Ecology, 19(5), pp. 765-777.
- Hackney, C.R., Darby, S.E., Parsons, D.R. et al. River bank instability from unsustainable sand mining in the lower Mekong River. Nature Sustainability, 3, 217–225 (2020). https://doi.org/10.1038/s41893-019-0455-3
- Hair, J. F., Black, W. C., Babin, B. J., Anderson, R. E., & Tatham, R. L. (2006). Multivariate Data Analysis. New Jersey: Pearson University Press.
- Hormio, S. (2023) 'Collective responsibility for climate change', WIREs Climate Change, 14(4), p. e830. https://doi.org/10.1002/wcc.830
- Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., Ren, J. (2018) 'Construction and demolition waste management in China through the 3R principle', Resources, Conservation & Recycling, 129, pp. 36-44.
- Huang, B., Gao, X., Xu, X., Song, J., Geng, Y., Sarkis, J., Fishman, T., Kua, H., Nakatani, J. (2020). A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials, One Earth, Volume 3, Issue 5, Pages 564-573.
- Jiseon Lee, J., Perera, D, Glickman, T, Taing, L. (2020). Water-related disasters and their health impacts: A global review. Progress in Disaster Science, Volume 8, pp. 14-17.
- Johnson, A. (2019) 'Assessing the Viability of Recycled Plastic Lumber', Journal of Materials Science, 12(3), pp. 201-213.
- Jones, B. (2020). Pathways to Mass Adoption of Recycled Products. Sustainable Production and Consumption, 22(1), 192-201.
- Jones, B. (2020). Research and development priorities in the construction sector. Journal of Construction Innovation, 23(3), 210-223.
- Jones, B. (2020). The role of public procurement in transitioning to sustainable construction. Architectural Engineering and Sustainable Infrastructure, 22(1), 12-24
- Kalmykova, Y., Sadagopan, M., Rosado, L. (2018) 'Circular economy – from review of theories and practices to development of implementation tools', Resource, Conservation and Recycling, 135 (October), pp. 190–201.
- Katerusha, D. (2021). Barriers to the use of recycled concrete from the perspective of executing companies and possible solution approaches - case study Germany and Switzerland. Resources Policy, Volume 73, ISSN 0301-4207, https://doi.org/10.1016/j.resourpol.2021.102212.
- Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. Cement and concrete research, 33(5), 703-711.
- Kazemian, A., Yuan, X., Cochran, E., & Khoshnevis, B. (2017). Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture. In Construction Research Congress (pp. 21-30).
- Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the Circular Economy: Evidence From the European Union (EU). Ecological Economics, 150, 264-272. ISSN 0921-8009.
- Koehnken, L., Rintoul, M. S., Goichot, M, Tickner, D., Loftus, Anne-Claire, and Acreman, M.C (2019) 'Impacts of riverine sand mining on freshwater ecosystems', Rivers Research Applications, 36, pp. 362-370.
- Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q. and Hotchkiss, R. (2014) 'Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents', Earth's Future, 2(5), pp.256-280.
- Kozminska, U. (2019). Circular design: reused materials and the future reuse of building elements in architecture. Process, challenges and case studies. IOP Conference Series: Earth and Environmental Science. 225 012033. DOI 10.1088/1755-1315/225/1/012033.
- Kresojević, M., Vakanjac R. V., Trifković, D., Nikolić, J., Vakanjac, B., Polomčić, D., Bajić, D. (2023). The Effect of Gravel and Sand Mining on Groundwater and Surface Water Regimes—A Case Study of the Velika Morava River, Serbia. Water. 2023; 15(14):2654. https://doi.org/10.3390/w15142654
- Kusimi, J. M., Amisigo, B. A., & Banoeng-Yakubo, B. K. (2014). Sediment yield of a forest river basin in Ghana. CATENA 123, 225-235. https://doi.org/10.1016/j.catena.2014.08.001
- Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G. F., & Thorpe, T. (2012). Mix design and fresh properties for high-performance printed concrete. Materials and Structures, 53(8), 1-12.
- Lee, J., Park, J., & Kim, J. (2019). Perceptions and barriers to recycled concrete usage in the construction industry. Sustainable Materials and Technologies, 22, 45-51.
- Lee, J., Perera, D, Glickman, T, Taing, L. (2020) 'Water-related disasters and their health impacts: A global review', Progress in Disaster Science, 8, pp. 14-17.
- Lee, M. (2022). Retail Trends in Recycled Goods from 2017-2021. Journal of Retail Analytics, 14(2), 59-71.
- Lenz, N. V., Skender, H.P, Mirković, P.A. (2018) 'The macroeconomic effects of transport infrastructure on economic growth: the case of Central and Eastern E.U. member states', Economic Research-Ekonomska Istraživanja, 31(1), pp. 1953-1964.
- Liu, L. and Ramakrishna, S. (eds.) (2021) An Introduction to Circular Economy. Springer Nature Singapore. https://doi.org/10.1007/978-981-15-8510-4
- Llatas, C. (2011) A model for quantifying construction waste in projects according to the European waste list. Waste Management, 31, ppb 1261-1276.
- Mahadevan, P. (2019). Sand mafias in India: Disorganised crime in growing economy. 2019 Global Initiative Against Transnational Organized Crime. https://globalinitiative.net/wp-content/

uploads/2019/07/Sand-Mining-in-India-Report-17Jul1045-Web.pdf
- McMaster, H.S., LeardMann, C.A., Speigle, S., Dillman, D.A. (2017) 'An experimental comparison of web-push vs. paper-only survey procedures for conducting an in-depth health survey of military spouses', BMC Medical Research Methodology, 17(1), pp. 1-12.
- Mitchell, P. and James, K. (2015) Economic Growth Potential of More Circular Economies. WRAP, London.
- Munn, S and Soebarto, V. (2004). The issues of using recycled materials in architecture. The 38th International Conference of Architectural Science Association ANZAScA "Contexts of architecture", Launceston, Tasmania, 10–12 November 2004.
- Murray A., Skene K., Haynes K. (2017) 'The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context', Journal of Business Ethics, 140, pp. 369–380.
- Nagapan, S., Rahman, I.A. and Asmi, A. (2012) 'Factors contributing to physical and chemical waste generation in high-rise residential buildings', International Journal of Advances in Applied Sciences, 1(4), pp.153-161.
- Ormston, R., Spencer, L., Barnard, M., Snape, D. (2013) 'The foundations of qualitative research', in Qualitative Research Practice: A Guide for Social Science Students and Researchers. pp. 52-55.
- Office of National Statistics (2019). Estimates of the financial and societal value of natural resources to people in the UK. UK natural capital accounts: 2019.
- Ofori, G. (1988). Construction industry and economic growth in Singapore. Construction Management and Economics, 6 (1988), pp. 57-70.
- Osborne, J. W. (2015). What is rotating in exploratory factor analysis. Practical Assessment, Research & Evaluation, 20(2), 1-7.
- Panda, B., Paul, C.P., Hui, L.J., Tay, Y.W.D., Tan, M.J (2017) 'Additive manufacturing of geopolymer for sustainable built environment', Journal of Cleaner Production, 167, pp. 281-288.
- Pandey, B., Brelsford, C., Seto, K. C. (2021). Infrastructure inequality is a characteristic of urbanization. PNAS, Research: Sustainability. P. 119 (15)
- https://doi.org/10.1073/pnas.2119890119.
- Pallant, J. (2011). SPSS survival manual: A step by step guide to data analysis using the SPSS program. 4th Edition, Allen & Unwin, Berkshire.
- Patel, V. (2020). Pricing as a Barrier to Recycled Product Adoption. Journal of Consumer Behavior, 18(4), 301-309.
- Preuss, L. (2007). Buying into our Future: Sustainability Initiatives in Local Government Procurement. Business Strategy and the Environment, 16, pp. 354–365.
- Rahla, K. M., Mateus, R., Braganca, L. (2021) 'Implementing Circular Economy Strategies in Buildings - From Theory to Practice', Applied Systems Innovation, 4(2).
- Rees W.E. (1999) 'The built environment and the ecosphere: A global perspective', Building Research and Information, 27, pp. 206–220.
- Regmi, P.R., Waithaka, E., Paudyal, A., Simkhada, P., Teijlingen, V. E. (2016) 'Guide to the design and application of online questionnaire surveys', Nepal Journal of Epidemiology, 6(4), p. 640.
- Saez, P. V., & Osmani, M. (2019) 'A Diagnosis of Construction and Demolition Waste Generation and Recovery Practice in the European Union', Journal of Cleaner Production, 241.
- Saez, P.V., Porras-Amores, C. and del Río Merino, M. (2013) 'Sustainable demolition waste management: Organization, technology and management of demolition projects', Sustainability, 6(1), pp. 94-114.
- Sanjayan, J. G., Nematollahi, B., Xia, M., & Marchment, T. (2018). Effect of surface moisture on interfacial transition zone and compressive strength of concrete containing recycled concrete aggregate. Cement and Concrete Composites, 92, 1-13.
- Schiller, G. and Roscher, J. (2023). Impact of urbanisation on construction material consumption: A global analysis. Journal of Industrial Ecology, Volume 27, Issue 3, pp. 1021-1036.
- Schut, E., Crielaard, M., Mesman, M. (2015) Circular Economy in the Dutch Construction Sector: A Perspective for the Market and Government. National Institute for Public Health and the Environment (RIVM). https://rivm.openrepository.com/handle/10029/595297
- Shahparvari, M., Robinson, H., Fong, D. and Ebohon, O. (2019) 'Improving affordable housing delivery through the reduction of rework in the supply chain. The case of affordable housing: a global perspective on financing and institutional ownership', University College London, London 12-12 September 2019 UCL.
- Shooshtarian, S.; Caldera, S.; Maqsood, T.; Ryley, T. (2020) 'Using Recycled Construction and Demolition Waste Products: A Review of Stakeholders' Perceptions, Decisions, and Motivations', Recycling, 5(4), p. 31. https://doi.org/10.3390/recycling5040031
- Singh, V. (2022) "Unaccounted deaths lay bare the dark side of sand mining", 7 June 2022, https://india.mongabay.com/2022/06/unaccounted-deaths-lay-bare-the-dark-side-of-sand-mining/ (Accessed: 10 July 2023).
- Silva, J. R.V., de Brito, J., Dhir, R.K. (2017). Availability and processing of recycled aggregates within the construction and demolition supply chain: A review, Journal of Cleaner Production, Volume 143, pp. 598-614.
- Smith, A. (2021). Closing the information gap around recycled concrete aggregates. Construction Research, 14(2), 154-167.
- Smith, A. (2021). Policy opportunities to advance recycled concrete aggregates. Sustainable Construction Policy, 14(3), 195-205.
- Smith, J. (2021) 'Negative Perceptions of Recycled Product Quality: Causes and Solutions', Journal of Consumer Marketing, 19(2), pp. 121-138.
- Sreebha, S., & Padmalal, D. (2011). Environmental impact assessment of sand mining from the small catchment rivers in the southwestern coast of India: a case study. Environmental Management, 47(1), 130-140. doi: 10.1007/s00267-010-9571-6
- Tabachnick, B., and Fidell, L. (2013). Using Multivariate Statistics. Boston, MA: Pearson Education Inc.
- Taherdoost, H., Sahibuddin, H., Jalaliyoon, N. (2014). Exploratory Factor Analysis; Concepts and Theory. In Jerzy Balicki. Advances in Applied and Pure Mathematics, 27, WSEAS, pp.375382, Mathematics and Computers in Science and Engineering Series, 978-960-474-380-3. Hal-02557344
- Tam, V., Tam, C., Ng, W. (2018). Aggregate composition for 3D printable concrete. Materials, 11(10), 1788.
- Torres, A., Brandt, J., Lear, K. & Liu, J. A (2017). Looming tragedy of the sand commons. Science 357, 970–971 (2017).
- Tay, Y.W.D., Panda, B., Paul, S.C., Mohamed, N.A.N., Tan, M.J., Leong, K.F. (2017). 3D printing trends in building and construction industry: a review, Virtual and Physical Prototyping, 12:3, 261-276, DOI:

10.1080/17452759.2017.1326724

- Taylor, M. (2022). Fragmentation as a barrier to circular construction: The case of recycled concrete. Architectural Engineering and Design Management, 18(1), 25-37.
- The Circularity Gap Report. (2023). [PDF] Available at: https://www.circularity-gap.world/2023 [Accessed 10 Jul 2023].
- The Crown Estate-MPA. (2022). The area involved – 24th annual report – Marine aggregate extraction 2021.
- Torres, A. Simoni, M. U., Keiding, J.K, Müller, D.B., zu Ermgassen, S. O.S.E, Liu, J. Jaeger, JAG., Winter, M., Lambin, E. F. (2021). Sustainability of the global sand system in the Anthropocene, One Earth, Volume 4, Issue 5, pages 639-650.
- UN (2018) Revision of World Urbanization Prospects. UN, DESA. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (Accessed: 10 Jul 2023).
- UN DESA, (2018). The 2018 Revision of World Urbanisation Prospects. Population Division, UN Department of Economic and Social Affairs (UNDESA), https://www.un.org/en/desa
- UNEP (2019). Sand and sustainability: Finding new solutions for environmental governance of global sand resources. Global Resources Outlook 2019.
- UN, (2020),"Urbanization: Expanding opportunities but deeper divides" in World Social Report 2020: Inequality in a Rapidly Changing World. United Nations Department of Economic and Social Affairs. pp. 108–126.
- UNEP (2022) Sand and Sustainability: 10 Strategic Recommendations to Avert a Crisis. UNEP, Nairobi. https://wedocs.unep.org/handle/20.500.11822/38362 (Accessed: 10 Jul 2023).
- Urbinati A., Chiaroni D., Chiesa V. (2017) 'Towards a new taxonomy of circular economy business models', Journal of Cleaner Production, 168, pp. 487–498. https://doi.org/10.1016/j.jclepro.2017 (Accessed: 10 Jul 2023).
- USGS (2017) Statement of the U.S. geological survey Before the House Committee on Natural Resources Subcommittee on Energy and Mineral Resources. https://www.usgs.gov/congressional/statement-us-geological-survey (Accessed on 10 Jul 2023).
- Van Der Putten, J.; De Schutter, G.; Van Tittelboom, K. (2019). Surface modification as a technique to improve inter-layer bonding strength in 3D printed cementitious materials. RILEM Tech. Lett. 2019, 4, 33–38.
- Vieira, CS., Pereira, PM., Lopes, MD. (2016) 'Recycled Construction and Demolition Wastes as filling material for geosynthetic reinforced structures. Interface properties', Journal of Cleaner Production, 124, pp. 299-311.
- Wang, J. (2018) 'The relationship between recycling and incineration of construction and demolition waste: The evidence from China', Resources, Conservation and Recycling, 134, pp. 66-74
- Wang, W. C., Zhang, W., McArdle, J. J., & Salthouse, T. A. (2008). Investigating ceiling effects in longitudinal data analysis. Multivariate behavioral research, 43(3), 476-496.
- Ward, M.R., Meade, A.W., Allred, C.M., Pappalardo, G., Stoughton, J.W. (2018) 'Careless response and attrition as sources of bias in online survey assessments of personality traits and performance', Computers in Human Behavior, 76, pp. 417-430.
- Weng, Y., Li, M., Singh, S. P., & Qian, S. (2020). Printability, accuracy and strength of geopolymer made using powder-based 3D printing for construction applications. Automation in Construction, 119, 103334.
- Willis, C.M., and Griggs, G.B., (2003). Reductions in Fluvial Sediment Discharge by Coastal Dams in California and Implications for Beach Sustainability. Journal of Geology 111:167-182.
- World Economic Forum (2016). The Built Environment: from Linear to Circular. @@@
- World Economic Forum (WEF) (2023). Circular economy in action: 9 examples of businesses and policy-makers accelerating the transition. https://www.weforum.org/agenda/2023/03/9-examples-circular-economy-accelerating-transition
- WRAP (2021) Employment and the Circular Economy. https://wrap.org.uk/resources/report/employment-and-circular-economy (Accessed: 10 Jul 2023).
- Yu, F., Chen. Z., Ren, X., Yang, G. (2009) Analysis of historical floods on the Yangtze River, China: characteristics and explanations. Geomorphology, 113(3–4):210–216

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