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Unlocking Resource Efficiency

Phase 1 Cement and Concrete Report

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Expedition UK	Construction
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Mineral Products Association (MPA)	Trade body
Ramboll	Engineering & Architecture Consultancy
UK Quality Ash Association	Trade body
University College London	Research
University of Leeds	Research
Wates	Construction

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Introduction

The Department for Energy Security and Net Zero commissioned a research project to explore the potential benefits from increasing resource efficiency in the UK. This research was carried out in collaboration with the Department for Environment, Food & Rural Affairs. This report outlines the findings for the cement and concrete sector.

For the purposes of this report, resource efficiency is defined as any action that achieves a lower level of resource use for a given level of final consumption. This can occur at any stage of the supply chain including production, consumption, and end-of-life. While material substitution may not always meet the definition of resource efficiency set out above, it is in scope of this research where it reduces whole life carbon.

This research was conducted in the first half of 2023, and reports were written in August 2023. As such, this report does not reflect sector developments beyond that point. The Department for Energy Security and Net Zero has consulted with technical experts as part of research activities for this report. The following report is our understanding of the available evidence and is accurate to the best of our knowledge; however, if any factual errors are encountered, please contact us at Resource_efficiency@energysecurity.gov.uk.

Methodology

This aim of this research was to achieve four key objectives:

1. Identify a comprehensive list of resource efficiency measures for each sector;
2. Identify current and anticipated drivers and barriers which are affecting improvements in the identified resource efficiency measures in each sector, and their relative importance;
3. Build consensus estimates for the current “level of efficiency” and maximum “level of efficiency” in 2035, for each of the identified resource efficiency measures in each sector; and
4. Identify the extent to which industry is currently improving resource efficiency and build consensus estimates for the likely “levels of efficiency” in 2035 given current private sector incentives and the existing policy mix (a “business-as-usual” scenario), for each of the identified resource efficiency measures in each sector.

To achieve these research objectives a mixed-methods methodology was developed. A literature review was conducted for each sector to synthesise evidence from the existing literature relevant to these objectives. The findings from this literature review were presented and tested in facilitated workshops with industry and academic experts. The aim of the workshops was to test the findings of the literature and fill any outstanding evidence gaps. This project did not aim to identify policy recommendations but rather understand the potential for resource efficiency in the UK.

This project has attempted to identify three level of efficiency estimates for each resource efficiency measure:

5. The **current level of efficiency** which is the best estimate for the current level of efficiency of the measure i.e. what is happening in the UK now (in 2023);

6. The **maximum level of efficiency** which is the maximum level of efficiency that is technically possible by 2035 in the UK, without factoring in barriers that could be overcome by 2035 i.e. what is the maximum level that could be achieved; and

7. The **business-as-usual (BAU) scenario** which is the level of efficiency that would be expected in the UK by 2035 with the current policy mix and private sector incentives i.e. what would happen if there were no substantial changes in the policy or private sector environment.

These levels of efficiencies have been identified to understand the potential for resource efficiency and do not represent government targets.

To estimate these levels of efficiency an indicator has been developed for each of the identified measures. These indicators have been chosen based on how well they capture the impact of the relevant measure, and how much data there is available on this basis (both in the literature review and from expert stakeholders).

Note, the purpose of the indicators in this research is so estimates on the current, maximum and BAU level of efficiency can be developed on a consistent basis. They are not intended be used as metrics to monitor the progress of these resource efficiency measures over time, or to be used as metrics for resource efficiency policies.

A high-level overview of the research stages is presented below. A more detailed version of this methodology is presented in the Technical Summary which accompanies this publication.

Literature Review

The literature sources were identified through an online search, and through known sources from Defra, the Department for Energy Security and Net Zero, the research team, and expert stakeholders.

Once literature sources had been identified they were reviewed by the research team and given an Indicative Applicability Score (IAS) ranging from 1 to 5 which indicated the applicability of the sources to the research objectives of this study. This score was based on five key criteria: geography, date of publication, sector applicability, methodologies used and level of peer review.

After the five criteria of the IAS had been evaluated, the overall IAS score was calculated, ranging from 1 to 5, according to the number of criteria scoring ‘high’ and ‘low.’

Table 1: Methodology for the calculation of the IAS

Number of 'high' criteria	Number of 'low' criteria	IAS
Indifferent	3 or more	1
<= 1	2	2
>= 2	2	3
<= 2	1	3
>= 3	1	4
<= 1	None	3
2	None	4
>= 3	None	5

A detailed overview of the parameters used to assess high / medium / low scores for each of the five criteria feeding into the IAS calculation can be found in Appendix A.

The research team drafted literature summaries for each sector which synthesised the best available evidence from the literature for each of the four research objectives. When drafting these summaries, literature sources with a higher IAS score were weighted more than those with lower IAS score.

Facilitated workshops

The findings from these literature summaries were then presented at two half-day facilitated workshops per sector. The workshops were attended by a range of sector experts from both academia and industry (covering different aspects of the value chain). The purpose of these workshops was to test the findings of the literature review against stakeholder expertise, and to fill any evidence gaps from the literature.

The stakeholders contributed through sticky notes in a shared virtual Mural board, by participating in the verbal discussions and by voting on pre-defined ranges on the levels of efficiency and the top drivers & barriers.

Finally, the findings of the literature review and the stakeholder engagement were combined to reach final conclusions against each research objective. For the estimates on the level of efficiency for each measure (Objectives 3 and 4), a five-tier evidence RAG rating was assigned to indicate the level of evidence supporting the proposed figures. Only where the datapoints were supported by literature sources with high IAS and a high degree of consensus amongst experts in the workshops, were the datapoints considered to have a "green" evidence RAG rating. The definitions are as follows:

8. **Red:** Limited evidence available from literature review or stakeholders
9. **Red-amber:** Some evidence available from literature review but it is not relevant/out of date, limited evidence from stakeholders, stakeholders are not experts on this measure

10. **Amber:** High quality evidence from either literature or stakeholders
11. **Amber-green:** High quality evidence from literature or stakeholders, evidence from stakeholders is supported by some information in the literature (or vice versa)
12. **Green:** High quality evidence from literature supported by stakeholder expertise.

It should be noted that the business-as-usual (BAU) level of efficiency was only informed by the stakeholder engagement, so the maximum evidence RAG rating for the BAU is amber.

Sector introduction

Cement and concrete are closely related materials used in construction that play crucial roles in building infrastructure.

Cement is a fine powder made primarily from limestone, clay and other minerals, which undergoes a chemical reaction when mixed with water to form a paste which acts as a binder. The manufacture of cement can be split into two main stages. First, the raw materials are combined and exposed to high temperatures in a rotating kiln. This causes a chemical reaction which produces clinker and directly releases carbon emissions. This is the most emissions intensive part of the process, accounting for 94% of total emissions from cement manufacturing[1]. The clinker is then cooled and ground into a fine powder which is mixed with a small amount of gypsum to form cement. There are different classifications of cement depending on the mix of input materials. A list of cement grades can be found in Appendix E. Cement is mainly used as a binder in concrete but can also be used as a component of mortar, stucco, tile grout or thin-set adhesive.

By contrast, concrete is a composite material formed by mixing cement with aggregates like sand, gravel or crushed stone and water. Clinker is the most emissions intensive ingredient in concrete, accounting for 89% of embedded emissions. The aggregates provide strength and stability to the concrete, while the cement paste acts as a binding agent, holding the aggregates together. Concrete is versatile, durable, and widely used in the construction industry for building foundations, walls, floors and various other structural elements.

Cement and concrete both play a vital role in the UK economy. The construction industry relies heavily on these materials for infrastructure development, including residential, commercial and public projects. In 2021, 15.6 million tonnes of cementitious materials were sold in the UK and over 90 million tonnes of concrete are consumed each year, produced from around 1,000 sites nationwide[2]. Mineral products, including cement and concrete, contribute about £18bn to the UK's GDP, and directly employing 74,000 people while supporting a further 3.5m jobs in 2020.[3] The cement and concrete industries also support a network of related sectors such as mining, transportation, equipment manufacturing and engineering services. These sectors supply raw materials, transport finished products and provide expertise for construction projects, further enhancing economic activity and employment opportunities.

Resource efficiency in the cement and concrete sectors focuses on optimising the use of materials throughout the entire lifecycle of cement and concrete production. Cement production requires significant amounts of raw materials, and these must be carefully selected and proportioned to minimise waste. Additionally, cement and concrete production generate

[1] Material Economics (2019). Industrial Transformation 2050. Accessed at link.
[2] MPA (2021) 'Profile of the UK Mineral Products Industry' supporting statistics workbook
[3] MPA (2020). UK Concrete and Cement Industry Roadmap to Beyond Net Zero.

various waste materials from the cement manufacturing process. Cement also makes up a significant amount of construction and demolition waste. Waste can be managed using effective practices such as recycling and reusing materials. For example, crushed concrete can be used as recycled aggregate in new concrete mixes, reducing the need for virgin aggregates. Additionally, by-products like fly ash and slag from other industries can be utilised as supplementary cementitious materials, further reducing resource consumption outside the sector. Resource efficiency also encompasses optimising the design of concrete products to enhance their durability whilst minimising the use of resources.

Efficient use of resources can also reduce the sectors environmental footprint, reducing raw material consumption, energy consumption and associated greenhouse gas emissions. Cement and concrete manufacturing is currently very carbon intensive, emitting 7.3 $MtCO_2e$ in 2018, approximately 1.5% of the UK's greenhouse gas emissions.[4] The carbon intensity of cement production is due to the chemical reactions required to produce clinker (which emit carbon dioxide directly), and the high temperatures required which is traditionally achieved through the burning of fossil fuels. Resource efficiency measures help reduce the overall environmental impact by optimising material usage, minimising waste generation and conserving energy.

Using resource more efficiently can also results in cost savings through a reduction in raw material use, and a switch to potentially cheaper alternative materials. The cement and concrete sectors are resource-intensive industries, and any wastage or inefficiency in material usage can result in significant financial losses. By adopting resource-efficient practices such as optimising raw material consumption, recycling waste materials and switching to alternative input materials, these sectors can reduce costs and enhance their competitiveness.

Sector scope

The scope of this report covers resource efficiency measures for Portland cement (CEM I) for use as a binder within concrete. This application was selected because the vast majority of cement is used in concrete production, and as a result improvements in cement use within the concrete sector has the largest potential for impact and also the greatest availability of information within the literature.

The following topics are out of scope in this study:

- Non-concrete applications of cement: Although most cement is used in concrete, cement can also be used for other applications such as mortar (which is used for joining bricks, stones and other masonry materials) and grout (used for filling voids, cracks and gaps in structures to provide structural support and prevent water leakage). Cement is also used for soil stabilisation in road construction to enhance the load-bearing capacity and stability of the soil.
- Niche cements: This refers to innovative types of cement that differ from CEM I in terms of their composition or manufacturing process with the aim of addressing specific challenges or offering improved performance. Examples of niche cements not included within this study are cements based on magnesium oxide derived from carbonates or silicates, CSA-belite cements, cement based on municipal solid waste incinerator ash and thermoplastic carbon-based cements. These alternatives occupy

[4] MPA (2020). Net Zero Carbon. Accessed at link.

niche positions in the market, are not yet feasible for use and according to stakeholder comments are unlikely to be ready at scale by 2035.

- Alternative fuels and energy efficiency: The cement industry is energy-intensive, with a significant portion of energy consumption (around 50%) coming from fossil fuels. Some environmental initiatives focus on reducing energy consumption and carbon emissions through alternative fuels such as biomass, waste-derived fuels, or non-recyclable plastics or energy-efficient technologies like advanced kiln designs, waste heat recovery systems, and optimised process control. These are not considered to be resource efficiency measures and so are out of scope of this study. Deep decarbonisation strategies such as carbon capture, utilisation and storage (CCUS) are also considered out of scope.

- Water consumption: Water is a vital resource in cement and concrete production, used for cooling kilns, mixing concrete and curing. Some resource efficiency measures aim to minimise water usage through the adoption of water-efficient technologies, recycling process water, and implementing water management strategies. Techniques like dry process kilns, closed-loop water systems and rainwater harvesting help reduce water consumption and ensure sustainable water use. Water consumption is out of scope as this study focuses only on the efficiency of cement and excludes other resources such as water.

- Concrete durability: Resource efficiency also encompasses optimising the properties and performance of cement and concrete products to enhance their durability and lifespan. Durable concrete structures require fewer repairs and replacements, reducing resource consumption over time. This includes using high-quality materials and considering long-term maintenance and lifecycle costs. Measures that pertain to concrete durability are included in this study but are presented in the Unlocking Resource Efficiency: Phase 1 Construction Report.

Literature review approach

The literature review identified 90 sources that discussed resource efficiency in the cement and concrete sector. These were identified using a range of search strings relating to resource efficiency, the circular economy and the cement and concrete sectors. The search strings are listed in Appendix B. Further sources were identified from sector experts via the workshops and the pre-workshop survey. The full list of sources used are listed in Appendix C.

These 90 sources comprised of:

- 29 industry reports;
- 32 academic papers;
- 1 book chapter;
- 6 technical studies;
- 2 policy documents; and
- 20 website articles.

The sources were considered of generally high applicability and credibility when assessed against the data assessment framework, which recognises the relevance of the sources and the strength of their methodology. The sources had an average IAS of 4.0 (out of 5), with 58 sources exhibiting a score of 4 or above. Twenty-seven sources were specific to the UK market and eleven were specific to Europe. Stakeholder responses to the pre-workshop survey indicated that the initial literature review was reasonably comprehensive, although they also suggested some additional sources which were then incorporated.

More detail on the purpose and approach for these literature reviews can be found in the accompanying Technical Summary.

Workshop approach

There were 12 participants in attendance in the first workshop and 15 participants in the second workshop. The participants broadly represented the cement and concrete sector value chains.

List of resource efficiency measures

The list of resource efficiency measures in the cement and concrete sector identified via the literature review and the facilitated workshops can be found in Table 2. Although there is some vertical integration between the cement and concrete industries, they represent separate markets, so we have differentiated the measures by sub-sector depending on whether they primarily impact the resource efficiency of cement or concrete.

Appendix D contains a list of resource efficiency measures that were discarded from the scope of this study.

As cement and concrete are primarily used as construction materials, resource efficiency measures that impact the construction sector will also impact the cement and concrete sector (e.g., reduction in building overdesign). Measures were assigned to either the cement and concrete sector or the construction sector based on which sector would have the most relevant expertise at the workshops.

A list of construction sector measures is found in Appendix F and further detail of the construction sector measures can be found in the Unlocking Resource Efficiency: Phase 1 Construction Report.

Table 2: List of resource efficiency measures for the cement & concrete sector

#	Lifecycle stage	Strategy	Sub-sector	Measure name	Measure indicator
1	Design	Material substitution	Cement & Concrete	Portland cement (CEM I) intensity in concrete	CEM I-to-concrete ratio
2	Manufacture and assembly	Reducing waste	Cement	Portland Cement (CEM I) manufacturing	% of CKD waste recovered and used as cement manufacturing raw material feedstock

#	Lifecycle stage	Strategy	Sub-sector	Measure name	Measure indicator
				waste recovered as raw material	
3	Design	Use of secondary raw materials	Cement	Use of recycled concrete fines in cement or concrete production	% of concrete fines used in cement or concrete production
4	Design	Light weighting	Concrete	Lean design of concrete structures	% reduction in concrete demand for the same unit throughput relative to 2023
5	Manufacture and assembly	Reducing waste	Concrete	Waste reduction in concrete manufacturing	% of concrete wasted per 100m3 of concrete manufactured
6	Design	Use of secondary raw materials	Concrete	Use of recycled content in concrete	% recycled concrete aggregates used in concrete by mass

The cement and concrete measures are all mapped against either the design or manufacturing & assembly stages of the lifecycle framework. Measures 2 and 3 relate to the cement value chain and Measures 4 to 6 relate to the concrete value chain. Measure 1 looks at the potential resource efficiency savings for cement but involves both the cement and concrete value chains.

No measures have been identified in the later lifecycle stages such as sale & use or end of life; although Measures 2, 3 and 6 deal with the act of recycling (which is an end-of-life activity), the measure is defined as the re-incorporation / use recycled content into the product. As the construction sector is the primary end-user of cement and concrete, measures impacting sale & use and end-of-life of the cement and concrete sector will be covered in the Unlocking Resource Efficiency: Phase 1 Construction Report.

Drivers and Barriers

Drivers and barriers were categorised using two separate systems:

1. The PESTLE framework which is focused on the types of changes: political, economic, social, technological, legal and environmental;

2. The COM-B framework which is focused on behaviour change:
    - **Capability**: can this behaviour be accomplished in practice?
        - Physical Capability – e.g., measure may not be compatible for certain processes
        - Psychological Capability – e.g., lack of knowledge
    - **Opportunity**: is there sufficient opportunity for the behaviour to occur?

    - Physical Opportunity: e.g., bad timing, lack of capital
    - Social Opportunity: e.g., not the norm amongst the competition
- **Motivation**: is there sufficient motivation for the behaviour to occur?
    - Reflective motivation: e.g., inability to understand the costs and benefits,
    - Automatic motivation: e.g., lack of interest from customers, greater priorities

1.0 Measure 1 – Portland Cement (CEM I) intensity in concrete

1.1 Cement resource efficiency measure

1.1.1 Description

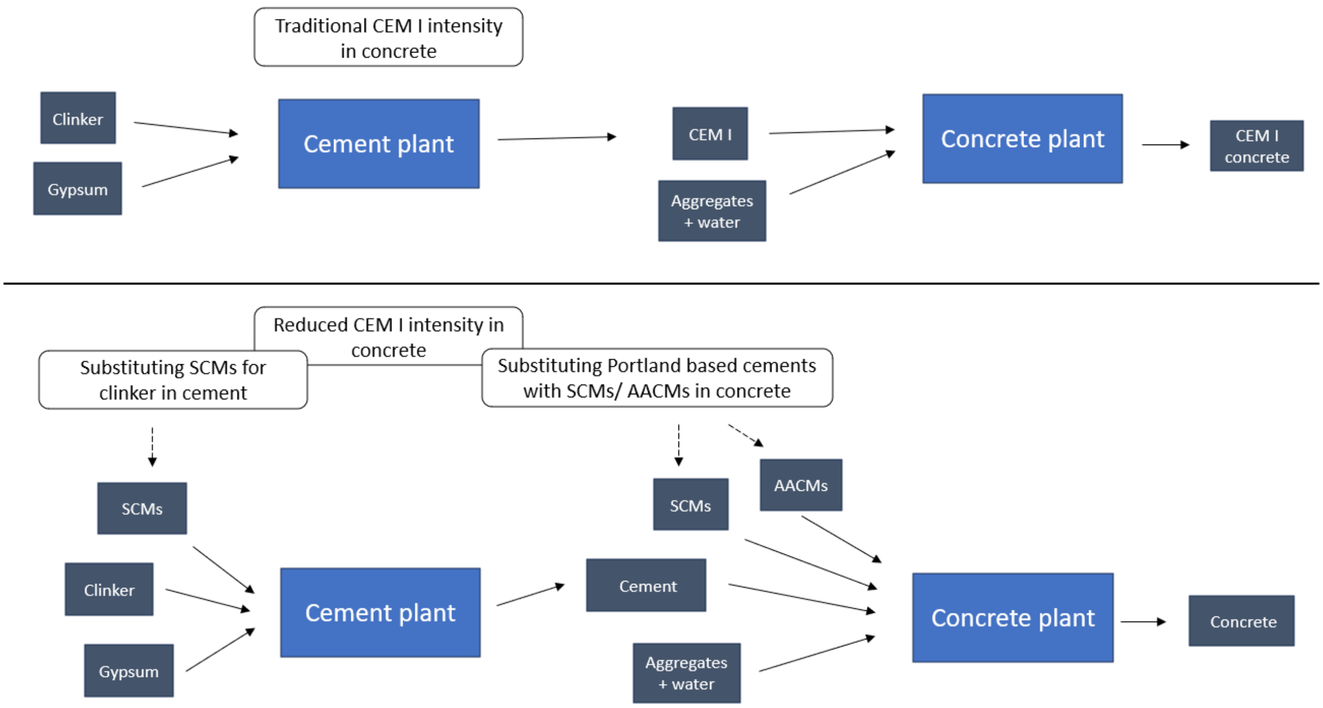
Reduction of the total amount of Portland cement (CEM I) used in the production of concrete.

Portland cement (CEM I) is a traditional cement produced by combining clinker with gypsum. The production of clinker directly releases carbon emissions and requires extremely high temperatures that are generally achieved through burning fossil fuels.

Reducing the total amount of CEM I used in the production of concrete (and subsequently the amount of clinker) is therefore a material substitution measure that reduces the whole life carbon of the resulting concrete. This can be achieved through:

1. Substituting clinker with supplementary cementitious materials (SCMs) during the production of cement;
2. Substituting CEM I with SCMs or alkali activated cementitious materials (AACMs) in the production of concrete; and
3. Avoiding the use of unnecessary cement content in concrete.

Figure 1: Reducing CEM I intensity in concrete



In 2018, about 10 million tonnes, representing 78% of the cement sold in the UK, was Portland cement[5].

Reducing the CEM I intensity in concrete requires the proportion of composite cements used to increase. Because composite cements contain lower proportions of CEM I, it is sometimes possible to raise the total cement content of concrete while lowering overall CEM I intensity when using composite cements.

1.1.2 Measure indicator

The indicator selected to measure the intensity of CEM I in concrete was the '**CEM I-to-concrete ratio**' which is defined as the share of CEM I relative to the total amount of cementitious material in concrete on a mass basis. This is a relative measure with the percentage derived from the mass of CEM I divided by the mass of total binder used in concrete.

Other indicators that were identified but not selected included:

4. Clinker-to-cement ratio
5. Cement-to-concrete ratio; and
6. % SCM by weight in cement.

'Clinker-to-cement ratio' and 'cement-to-concrete ratio' were presented as two separate measures in workshop 1. This was done with the intention of measuring the use of substitute materials during the cement and concrete manufacturing stages separately as it was assumed each industry would carry data for its own process.

However, stakeholder feedback during workshop 1 indicated that these two measures do not capture the overall reduction in use of CEM I very well due to their interdependencies. For example, the resource efficiency benefit of the use of SCMs at the cement plant can be undone with an increase in cement content at the concrete batching stage. Additionally, SCMs in the UK are typically added at the concrete plant instead of at the cement plant.

To capture resource efficiency performance across the full value chain, the measure was therefore amended for workshop 2 to represent the intensity of CEM I in the final concrete product. This provides a picture of the entire value chain and avoids the tension of incentivising a shift in the use of substitute materials between the cement and concrete plants.

1.1.3 Examples in practice

SCMs in use today

In the UK, SCMs are usually added during concrete batching to produce concretes with less CEM I content, while in Europe it is more common to add SCMs during the cement manufacturing stage.[6]

The most promising SCMs for market uptake within the UK are discussed below. Examples of SCMs not included are silica fume, biomass ash, oil shale ash, rice husk ash and quartz due to

[5] MPA (2019). Options for switching UK cement production sites to near zero CO_2 emission fuel: Technical and financial feasibility.
[6] BEIS (2017) Fly ash and blast furnace slag for cement manufacturing. BEIS research paper no. 19

stakeholders' comments on their lack of sufficient availability in the UK. However, these materials would benefit from further research to better understand their full potential.

The SCM currently most used in the UK is ground granulated blast-furnace slag (GGBS). Pulverised fly ash (PFA) is another SCM that is currently used in the UK. GGBS is a by-product of iron production and has been used for many years in combination with CEM I as the cementitious material in concrete. PFA is the by-product from electricity generation sourced from coal-fired power stations and is also used as a cementitious material in concrete.

GGBS and PFA are both limited resources in the UK, with the availability forecast to reduce as steel manufacturing decarbonises and the burning of coal declines. Currently, the global annual production of GGBS makes up only 10% of the total cement use in the world by mass,[7] and the global supply of GGBS is practically fully utilised.

Additionally, use of GGBS and PFA to replace CEM I often requires an increase in the total amount of cement required in concrete, especially in higher strength classes with replacement rates above 50%.[8] Thus, the use of GGBS and PFA can potentially lead to an increase the overall demand of cement, despite lowering the CEM I content for one mix.

BS 8500 defines the percentages of GGBS (6-80%) and PFA (6-55%) allowed in concretes depending on the intended application. However, there is currently a lack of guidance on the most resource-efficient use of GGBS or PFA as an SCM in the UK. In the absence of this guidance, the Low Carbon Concrete Group and the Green Construction Board suggest that increasing the total cement content of any mix by more than 10% to enable a higher percentage of GGBS or PFA may have the adverse effect of increasing the overall use of CEM I globally.[8]

Viable alternative SCMs

Limestone fines are an SCM that are currently widely used in UK cement (CEM II/A-LL).

Calcined clays can also be used as SCMs but they are not currently used in the UK at scale despite their widespread availability, and usability within existing standards.[9] This is primarily due to the lack of research on their impact on performance.

In the medium to long-term, limestone fines and calcined clays could be viable alternative to GGBS and PFA. Research is currently underway to identify suitable clays based in the UK and gain a better understanding of their impact on performance[10]. In addition to their use as primary SCMs, calcined clays can also be used as the SCM in AACMs as a substitute for clinker.

AACMs

AACMs are a type of cement produced without heat via a chemical reaction between an aluminate-rich precursor (e.g., clinker or an SCM) and an alkali-based material (e.g., NaOH). The ratio is typically around 90% precursor to 10% alkali-based material.

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[7] Scrivener, John and Gartner (2018) Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry.
[8] Low Carbon Concrete Group (2022). Low Carbon Concrete Routemap.
[9] Limits defined in BS EN 197-5. Available at link.
[10] Mineral Products Association (2023) Reclaimed calcined clay cements (Re-C3). Available at link

The main benefit associated with AACMs made with SCMs is their lower energy requirement and process emissions, resulting in overall lower associated emissions when compared with CEM I. AACMs have a small amount of activator which may result in slow setting cements. Whilst AACMs can be manufactured in the UK, they are currently not widely used as there is a limited range of applications that they can be used for. Research is still underway to verify that the materials available in the UK can produce consistently high-quality products.

Minimising cement use in concrete

In addition to utilising substitute materials to lower CEM I intensity, it is also important to use the appropriate cement content in the final concrete product. Higher cement content concrete is generally assumed to be stronger. Thus, higher cement contents than are specified in the design calculations are often used. For example, high cement content may be used to reduce time before formwork striking (the removal of formwork once the concrete has achieved the initial recommended strength).

Another reason that high cement content is often used is that there is variation in the strength of concrete between batches. As a result, the mix designer often aims to achieve a target mean strength (TMS) that is higher than the specified strength to allow for the variation between batches. Improvements in quality control, as well as confidence in workmanship onsite, can reduce the variation in strength and permit a reduction of the TMS and therefore possibly the cement content used.[8]

It's worth noting that there is also some doubt about whether higher cement content necessarily results in stronger concrete. For example, one study observed little consistency in the relationship between cement content and compressive strength,[11] and another found that concretes could reduce their cement content by 20% without loss of strength properties and other durability indicators.[12] These results suggest there is potential to reduce the cement use in concrete without adversely impacting concrete strength.

Admixtures

Admixtures are natural or manufactured chemicals that can be added during concrete batching to improve the performance of concrete by increasing workability and reducing the required water-to-cement ratio. This results in an increase in strength and a reduction in the permeability of the hardened concrete without increasing the cement content. The amount of admixture used is small and usually makes up no more than 0.2% of the concrete by mass.[13]

1.2 Available sources

1.2.1 Literature review

This measure is well covered in the literature and reducing the CEM I intensity in concrete is part of multiple net zero roadmaps for the sector.[14,15,16] The literature review identified 47

[11] Obla et al. (2017) Should Minimum Cementitious Contents for Concrete Be Specified?
[12] Wasserman, R. (2009). Minimum cement content requirements: A must or a myth?
[13] MPA (2018) Material Efficiency.
[14] MPA, UK Concrete and Cement Industry Roadmap to Beyond Net Zero
[15] GCCA – Concrete Future Roadmap for Net Zero
[16] CEMBUREAU (2020). Carbon neutrality roadmap.

sources that identified CEM I intensity in concrete as a resource efficiency measure. This comprised of:

- one book chapter;
- fifteen academic papers;
- one policy document;
- three technical studies;
- sixteen industry reports; and
- eleven website articles.

Due to the high number of sources (representing close to half of the available sources), it would be impracticable to list them in this section as footnotes, so the sources are highlighted in Appendix C.

These sources were considered of high applicability and credibility when assessed against the data assessment framework, which recognises the relevance of the sources and the strength of the methodology within each. The sources had an average IAS of 4.2, with 32 sources with a score of 4 or above. Fourteen of the sources were specific to the UK, and 37 of them were from 2016 or later.

Overall, the literature was deemed to be highly applicable to the UK market today. However, only a portion of the literature provided quantitative data relating to this resource efficiency measure. Where data was available it was generally provided for a sub-section of the measure (e.g., the percentage of GGBS that can be used in concrete), rather than for the measure as a whole. As a result, the measure level conclusions are based on the aggregation of multiple data sources, and sources that provided quantitative data for the measure as a whole were relied on more heavily than those that provided only partial data for the measure.

1.2.2 Workshops

As discussed in section 1.1.2, Measure 1 was separated into two measures for the purposes of the first workshop. Specifically, participants were asked about the use of substitute materials during the cement and concrete production stages separately. These measures were combined for the second workshop following stakeholder comments.

Measure 1 received the highest level of engagement in both workshops and the most comments in the pre-workshop survey. However, some stakeholders only felt confident in providing input for sub-sections of this measure (e.g., potential level of substitution for a particular SCM), and did not feel they could provide information at the whole measure level (i.e., the CEM I intensity of concrete across the entire market). Stakeholder views providing quantitative data to a sub-section of the measure were used to validate the assumptions underlying the efficiency calculation for the full measure. The level of engagement in both workshops was as follows:

7. **Workshop 1** – Twelve stakeholders across industry and academia were active on the mural board and ten stakeholders actively contributed to verbal discussion.
8. **Workshop 2** - Ten stakeholders across industry and academia were active on the mural board and nine stakeholders actively contributed to verbal discussion.

1.3 Drivers & Barriers

The drivers and barriers influencing this measure were identified through a combination of the literature review and stakeholder feedback at the workshops.

1.3.1 Drivers

Table 3 shows a list of identified drivers for reducing the CEM I intensity in concrete. The most significant drivers as voted for by workshop participants are highlighted in bold.

Table 3: Drivers for cement & concrete Measure 1

Description	PESTLE	COM-B
Some substitutes are widely available	**Technological**	**Capability – physical**
Some substitutes are cheaper	**Economical**	**Opportunity – social**
Climate policies driving carbon reductions	**Environmental**	**Opportunity – social**
Substitutes produce concrete with good mechanical properties	Technological	Capability – physical
Demand for sustainable products	Social	Opportunity – social
Substitutes can be used in a wide range of applications	Technological	Capability – physical

Some substitutes are widely available

It was determined during the literature review that SCM's such as calcined clays and limestone fines are widely available and so could have the greatest scope to act as an alternative to the most prevalent SCMs in the UK (GGBS and some PFA). This was reinforced during the workshops, with one participant stating that there are already a wide range of available materials that have the appropriate chemical properties, especially limestone and calcined clays – which combined form an SCM known as limestone calcined clay cement, or CEMII/C. This was expanded upon by another stakeholder, who pointed out that cement manufacturers are already exploring a shift from primarily CEM I production, to a mix of CEM I with CEMII/C – which contains 15% limestone and 30% calcined clays (CEM II/C). However this is unlikely to become a new 'standard' of cement produced in the UK until full testing is completed and calcinated clays have been accepted into UK standards. One stakeholder also outlined that the UK cement sector is beginning to shift from CEM I to CEM II/A which involves increasing the limestone fines content from 5% to 20%.

Some substitutes are cheaper

Some SCMs such as GGBS and PFA are cheaper on average than clinker and CEM I (although this is dependent on the standard of cement required), and their use is already providing cost savings to certain manufacturers. Not all substitutes are currently cheaper (see barrier "*Some substitutes are more expensive"* in the following section), however, stakeholders pointed out that additional cost savings might also be realised in the future as alternative substitutes become more readily available, increasing the overall supply of SCM's and driving price reductions. This will be amplified as their effects on concrete quality (strength, durability, etc.) are more extensively researched, bringing the use of CEM I in concrete down. It is worth noting that not all substitutes will become cheaper over time – the price of GGBS and PFA is likely to increase in the long term – this is explained under the barrier "*Some substitutes are more expensive"* for this measure.

Climate policies driving carbon reductions

Reducing the CEM I intensity in concrete generally reduces the carbon intensity of the concrete. A key driver of this measure is therefore the Government's Net Zero commitment, and the widespread push to decarbonise both from industry and from consumers.

Other Drivers

There were other drivers that were also identified through literature or raised by stakeholders, but received fewer votes of significance/engagement from stakeholders during the workshop:

- **Substitutes can produce concrete with good mechanical properties:** The literature shows that concretes produced with cements containing GGBS can actually exhibit a lower early strength when compared to CEM I, and also show higher long-term strength and particularly improved chemical resistance.[17] Linking to the point raised by a stakeholder regarding the increasing use of limestone in CEM I (see driver *"Some substitutes are widely available"* for this measure), the same literature showed that cement made with calcined clays have the potential to produce concretes that are at least as strong as those that use CEM I.

- **Demand for sustainable products:** this driver ties in with climate policy, one stakeholder highlighted that the BAU scenario for the cement/construction sectors is decarbonisation – as the construction sector increasingly calls for more sustainable products, cement manufacturers will be expected to reduce the CEM I intensity of their concrete (e.g., via an increase their use of SCM's) to achieve this.

- **Substitutes can be used for a wide range of applications:** The literature shows that cements with varying quantities/types of SCM content can have a host of different concrete applications, where the quantity or type of SCM used is better suited to that specific application when compared to using primarily CEM I. For example, cements with a higher level of SCM content typically take longer to set, with a greater 28-day-and-beyond strength when compared to traditional CEM I concrete[18] – this is beneficial when speed of construction is not a project bottleneck, as well as during hot months where concrete can set too quickly, reducing its strength. A stakeholder emphasised that this driver would provide cost savings when SCM's are used 'appropriately', which ties in with that corresponding driver, as well as the driver "*substitutes can produce concrete with good mechanical properties.*"

1.3.2 Barriers

Table 4 shows a list of identified barriers to reducing the CEM I intensity in concrete. The most significant barriers as voted for by workshop participants are highlighted in bold.

[17] W. Shanks, et al. (2019) How much cement can we do without? Lessons from cement material flows in the UK
[18] BEIS (2017) Fly ash and blast furnace slag for cement manufacturing. BEIS research paper no. 19

Table 4: Barriers for cement & concrete Measure 1

Description	PESTLE	COM-B
Some substitutes are not widely available	**Technological**	**Capability – physical**
Some substitutes are more expensive	**Economical**	**Opportunity – social**
Lack of testing and industry experience	**Technological**	**Opportunity – social**
Lack of regulation, standards and guidelines for novel SCMs	Technological	Capability - physical
End of life waste for structures produced with new substitutes need to be assessed	Technological	Capability – physical
Substitutes can impact performance of concrete	Technological	Capability – physical
Substitutes may be limited to use in certain applications	Technological	Capability – physical
Substitutes could require change to cement or concrete production processes	Technological	Capability – physical
Limited opportunity to decrease global emissions when using SCMs that are limited resources	Environmental	Opportunity – social
Reluctance from finance / insurance	Legal	Opportunity – social

Some substitutes are not widely available

Substitute availability determines the extent to which SCMs can be utilised at scale. The availability of the SCMs that are currently most widely used in the UK (GGBS and some PFA) are both expected to decrease over time, as the steel industry and the power sector decarbonise.[19] There are also temporal challenges in the availability of some substitutes. For example, the literature shows that certain substitutes such as PFA typically have over-capacity in the winter and under-capacity in the summer, making it difficult to source a consistent substitute.[20]

However limestone and calcined clays are two widely available materials in the UK that can act as SCM's (in place of GGBS and PFA), with one stakeholder stating during the workshop that their use is already increasing.

Some substitutes are more expensive

While the SCMs that are currently used in the UK (GGBS and some PFA) are currently cheaper on average than clinker and CEM I, the price of these is expected to rise in the future as demand for these materials increases. Prices are also expected to rise further as the availability of these substitutes decreases over time (see above). Because of these price rises for the "traditional" SCMs, stakeholders highlighted that alternative SCM's, such as calcined clays, are expected to make up an increasing proportion of SCMs used in the future.

[19] T. Czigler, et al. (2020). Laying the foundation for zero-carbon cement
[20] Dr L. K. A. Sear (2011). Future trends for PFA in cementitious systems. UKQAA

Lack of testing and industry experience of novel SCMs

Strength and durability are key factors in determining the longevity of a structure and in winning the confidence of clients and engineers within the construction sector. Strength is the amount of load the structure will take and durability is how long the structure will keep taking its designed load. While strength is straightforward to test, there is a lack of proven long-term durability for novel SCM-based concretes. This is in part because most durability testing methods were developed with CEM I in mind and do not account for complex systems such as admixtures, limestone additions, SCMs and AACMs. While this does not necessarily mean that these SCM's will not be able to meet required standards, it does mean that buyers may have less confidence in the durability of concrete structures manufactured with more novel SCM's. This is decreasing the size of the customer base in the SCM market, which could also cause the cost of SCM's to rise.

Additionally, there is a lack of knowledge between engineers and contractors around the advantages and practical applications of alternative cements, meaning that the use of certain SCM's can simply be overlooked, with engineers either recommending CEM I unnecessarily, or contractors opting to use CEM I or other more well-established SCM's instead of other recommendations – unaware that they could be missing out on cost-savings and/or environmental benefits.

Lack of regulation, standards and guidelines for novel SCMs

Standards are used widely in the UK as a compliance requirement for construction regulations, and to ensure performance of materials and structures. The most widely accepted technologies in the UK are typically included in the British Standards (BS) and British Standards incorporating a European Standard (BS EN). A list of relevant UK standards and guidance for concrete can be found in Appendix E.

BS 8500 provides the guidance for minimum cement content when designing a suitable concrete mix. While concrete technology has evolved over the years, the prescribed values in BS 8500 have remained static. The cements are categorised into two groups:

- 'General purpose' – those with suitability established in the UK concrete standard BS 8500
- 'Other cements' – those with suitability not yet established in BS 8500

'General purpose' cements can include prescribed quantities of SCMs in place of clinker. If high quantities of SCMs are used then they are classified as 'Other cements' unless they are covered within BS 8500, and their use requires rigorous testing to demonstrate that the cement content is sufficient to meet the performance requirements of the application, such as early strength gain, consistence, water-to-cement ratio and strength required in service. This places an effective ceiling on the amount of SCM that can be substituted for cement without an additional cost burden.

BS8500 already covers Portland based cements which use SCMs (such as Cem II, Cem III and Cem IV). EN 197 which defines 32 cement types that can be specified. However, only 17 BS EN 197 cements are recognised in BS 8500[21]. The absence of the remaining 15 cements is not due to unsuitability, but because more data is required for their use in generic concrete

[21] Low Carbon Concrete Group (2022). Low Carbon Concrete Routemap.

applications. Updating BS 8500 to include more novel cements could drive the increased use of certain SCMs in cement production.

Other Barriers

There were other barriers that were also identified through literature or raised by stakeholders, but received fewer votes of significance/engagement from stakeholders during the workshop:

- **End of life waste for structures produced with new substitutes need to be assessed:** This was highlighted by one stakeholder in the workshop and linked to the barrier “lack of testing and industry experience”. New substitutes not only need to be tested for durability/strength reasons, but also for their end-of-life impact – certain substitutes like metakaolin and bauxite residue contain chemicals such as heavy metals or ones with a high alkali content, and these could potentially have an adverse effect on the environment after demolition occurs. More research is needed in this area to better understand these potential impacts.

- **Substitutes can impact performance of concrete:** As previously stated in the driver’s section for this measure, a large amount of SCMs cause concrete to exhibit longer setting times, which is not feasible for many projects where speed of construction is the priority. This links to the barrier “*lack of testing and industry experience*” – there may be suitable SCMs for contractors to use in many instances, but the lack of knowledge on how particular SCMs may impact concrete performance will slow their uptake.

- **Substitutes may be limited to use in certain applications:** Building standards vary between devolved nations in the UK (and globally) in terms of the type of SCM’s that are permitted for certain construction applications, causing the use of some of them to simply be unviable. Therefore, the use of SCMs is influenced by the performance requirements of the concrete it is intended to be used in relating to the designed use and location of the end product.

- **Substitute requires change to cement or concrete production processes:** One stakeholder highlighted that the UK uses a ‘blend at concrete plant’ model, which suggests that the uptake of SCM’s may be inhibited by concrete blending plants being unable to make the required changes to their production processes to increase the use of SCM’s – this could be due to space or economical constraints at plants, for example. If the UK shifted away from this model, and instead implemented a model where cement plants blended concretes with SCM’s directly on site, it could increase the availability of concretes with certain SCM contents, overcoming this barrier to increasing their uptake. One stakeholder did outline that this shift is potentially not feasible due to the amount of aggregate that would need to be transported around the country for this to happen.

- **Limited opportunity to decrease global emissions when using SCMs that are limited resources:** One stakeholder mentioned that it is important to consider the global impact involved in the use of SCMs. Where an SCM is a limited resource (for example GGBS) then the total global use of this SCM cannot increase (because it is already highly utilised). This means there is limited opportunity to reduce the global emissions associated with using GGBS, because if a UK company were to import GGBS to produce low carbon cement, this would result in GGBS not being used elsewhere resulting in a balancing out of emissions[22]. This highlights the necessity of using SCM's appropriately, which was also pointed out by a stakeholder when discussing the drivers for this measure.

- **Reluctance from finance / insurance:** Similar to the barrier "*lack of regulation, standards and guidelines",* stakeholders pointed out that underwriters and insurance providers are currently reluctant to become involved in certain projects where SCMs are used, causing contractors to avoid them - Again, this limits the size of the customer base for SCM's, compounding the problem and inhibiting their uptake.

1.4 Levels of efficiency

Table 5: Levels of efficiency for cement & concrete Measure 1

Indicator: CEM I-to-concrete ratio			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	70-82%	45 – 55%	50 – 60%
Evidence RAG	Amber-Green	Amber-Green	Amber

1.4.1 Current level of efficiency

Information on the current level of efficiency is available through data collected and managed by the Global Cement and Concrete Association (GCCA)[23] (and previously managed by the Cement Sustainability Initiative through the World Business Council for Sustainable Development). These data are collected in accordance with the CO_2 and Energy Accounting and Reporting Standard for the Cement Industry.

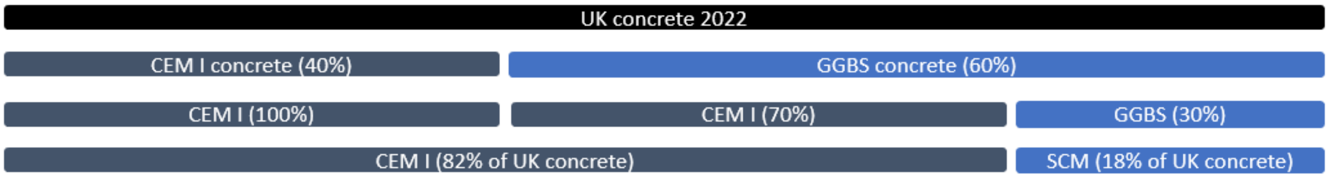
The data from these sources state that the current total level of SCM replacement in concrete in the UK is 18%. A discussion with a stakeholder revealed that for modelling purposes in the Low Carbon Concrete Routemap it is assumed that this replacement stems entirely from GGBS use despite PFA being used in small quantities in the UK. This is due to the lack of available data on the split between GGBS and PFA. The model assumes that CEM I concrete currently makes up 40% of the concrete market and GGBS concrete makes up 60% of the market. Within the GGBS concrete market it is assumed that GGBS replaces 30% of CEM I in concrete on average (Figure 2). As a result, 82% of the binder currently used in concrete is CEM I.

Another stakeholder noted that resource efficiency benefits of AACMs currently on the market are not necessarily additive as their use requires competition for the same precursors (i.e., GGBS) that are used in blended cements. As a result, the use of these AACMs is omitted from the model for the current rate of efficiency. AACMs based on limestone and calcined clay could provide resource efficiency benefits, however these are not currently present at commercial

[22] The Institution of Structural Engineers (2023), The efficient use of GGBS in reducing global emissions. Available at link.
[23] GCCA, GNR 2.0 – GCCA in Numbers. Available at link.

scale in the UK market. These AACMs are instead introduced in the maximum level of efficiency for 2035 under the assumption they will be available then.

Figure 2: Current composition of UK concrete market (data obtained from GCCA model)



One stakeholder pointed out that the 82% level seemed too high, and pointed to MPA data that outlines that in 2022 the overall SCM content of cement in UK was 27%.[24] Given that further SCMs are added at the concrete production stage the stakeholder warns that the CEM I content of concrete could be well below 82%.

Workshop stakeholders' views were broadly consistent with the GCCA model. Five stakeholders voted for a current level of >70% CEM I use across the UK concrete market. Only one participant voted that CEM I represented between 60 – 70% of the binder and one participant voted between 40 – 50% CEM I. Whilst the GCCA model and MPA data differ in their estimates of the current CEM I intensity of concrete, a range of 70-82% has been concluded which is consistent with stakeholder feedback and takes into account the possible lower value suggested by MPA data.

A RAG rating of amber-green has been given because the GCCA model value was validated by the majority of stakeholders whilst also taking into account the possible lower value suggested by MPA data.

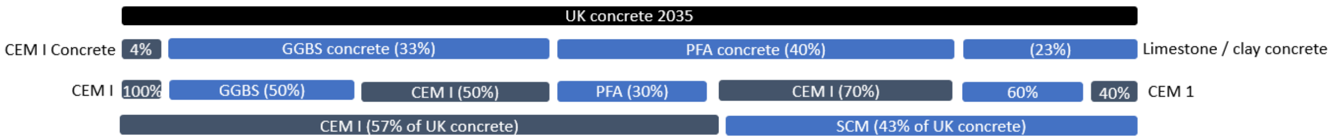
1.4.2 Maximum level of efficiency in 2035

The literature for the maximum level of efficiency also draws from modelling done in the Low Carbon Concrete Routemap.[25] This illustrates the maximum technical potential carbon savings for various interventions across the concrete industry in the UK. A review of model calculations (accessed as a separate spreadsheet to the report) shows an estimate of 43% of UK concrete could be derived from SCMs or AACMs by 2035 (leaving 57% as CEM I).

Specifically, this assumes that in 2035 the UK concrete market will be comprised of 4% CEM I concrete, 33% GGBS concrete, 40% PFA concrete from stockpiles and 23% concrete made with limestone or calcined clay as either the primary SCM or as an AACM. The CEM I replacement rate for each SCM is shown in Figure 3. For example, in CEM I concrete the CEM I content is 100%. However, in GGBS concrete, CEM I is replaced with GGBS at a 50% rate. These figures, however, do not account for savings due to the reduction of the amount of cement used in concrete due to overspecification. Stakeholders commented that this element is difficult to quantify as the resource efficiency benefits from interventions such as reducing the minimum cement content in BS 8500 and the use of admixtures may be negated by the overall increase in average binder content due to increased use of SCMs.

[24] MPA (2022), Annual Cementitious Statistics. Available at link.
[25] Low Carbon Concrete Group (2022). Low Carbon Concrete Routemap.

Figure 3: Maximum CEM I replacement in 2035



These figures from the literature were presented to the stakeholders at the workshop. There was less consensus between workshop stakeholders on the maximum level of efficiency compared with the current level of efficiency, with four participants voting for between 40 – 50% CEM I intensity in concrete, two votes for 50 – 60%, one vote each for 60 – 70% and 30 – 40%. As the stakeholders in the workshop voted for a more ambitious level of replacement than in the literature, we have reconciled the literature data and the workshop outcome to estimate a ratio range of 45 – 55% with an amber-green RAG rating of evidence.

During the discussion, stakeholders commented on the maximum level of efficiency for individual SCMs as some had expertise in some SCMs and not others. Stakeholders noted that GGBS is currently the only SCM that can comfortably exceed a 30% replacement rate but that this is likely to change by 2035 as technologies develop to allow for higher utilisation of other materials. Stakeholders also noted that although standards allow for a 90% replacement rate, this rate will not be achieved as the global supply of GGBS is already fully utilised and the price of the material will likely rise as supply continues to fall. A similar sentiment was expressed towards PFA, with a 60% replacement rate technically feasible but unlikely in practice due to the limited availability associated with the decline of the carbon-intensive coal industry.

1.4.3 Business-as-usual in 2035

The business-as-usual level of efficiency of 50 – 60% was solely informed by stakeholder expertise from the workshops. There was a high level of consensus on the BAU level with five participants voting for between 50 – 60% and one participant voting for 40 – 50%. However, about half of the participants decided not to vote on this measure and stakeholders commented that it is difficult to project the business-as-usual scenario because there is so much activity to decarbonise concrete through alternative specification and manufacture methods. The combination of these along with newly implemented climate policies has already begun to impact companies' business models, so it is almost impossible to take a static approach to conceptualising a business-as-usual scenario. Additionally, although new technologies are being developed, it is difficult to measure consumer uptake of these technologies and consumers often take a conservative approach. For this reason, there is an amber level RAG rating of evidence in the accuracy of this figure.

It was clear from comments in the workshops that the limit for the business-as-usual level of efficiency will be primarily economic rather than technical. There are currently a limited number of SCMs allowed within the standards which has pushed up their price, causing contractors to rely more on resource efficiency gains through mix design rather than through use of SCMs. Another limit in the business-as-usual scenario is the risk burden of failure. Concrete is currently overdesigned with a high cement content by contractors to minimise risk, and this is unlikely to change without a shift in the way responsibility is allocated throughout the supply chain.

It should be noted that the business-as-usual level is quite close to the maximum level of technical efficiency. This is consistent with the workshop participants' beliefs that the cement industry has already started to drive increasing resource efficiency due to the carbon emissions associated with clinker.

2.0 Measure 2 – Portland cement (CEM I) manufacturing waste recovered as a raw material

2.1 Cement resource efficiency measure

2.1.1 Description

The use of waste created during the cement manufacturing process as kiln feedstock onsite, replacing the need for primary raw materials.

Cement kiln dust (CKD) is a bypass dust generated from the burning of raw materials in the rotary kiln during clinker production and is composed of small particles collected in particulate matter control devices such as cyclones and bag filters. This dust can then be separated and returned into the kiln to be used in the production of clinker or recycled/discarded.

In the UK, no CKD has been sent to landfill since 2012. Therefore, this measure is focused on increasing the percentage of CKD returned to the kiln as feedstock (rather than being sold on for other uses), replacing the need for primary raw materials such as limestone, sand, shale, and iron ore in cement production.

Often resource efficiency measures that focus on closed loop recycling of manufacturing wastes back into the original product's manufacturing process are considered the most efficient use of those materials, rather than sending on to secondary applications. However, the literature review and stakeholder workshops did not identify any evidence that CKD return in cement manufacturing was more resource efficient than using it in other secondary applications.

2.1.2 Measure indicator

The indicator selected was '**the percentage of CKD waste recovered and used as cement manufacturing raw material feedstock.**'

The other indicator considered but not selected was 'the percentage of recovered material used per tonne of cement' which was initially used in workshop 1 but changed following the workshop following stakeholder feedback that the indicator is misleading and appears to reward the generation of a large amount of CKD waste to subsequently be used in recycling. Another key limitation of this indicator is that it focuses on the recovery of CKD (which could then be used for multiple uses), rather than the CKD which is used specifically in cement manufacturing.

2.1.3 Examples in practice

The recycling of CKD is commonplace. Some cement manufacturers return a proportion of the CKD to the kiln as a feedstock replacing primary material input, while other facilities sell the dust for numerous secondary applications, such as an agricultural liming agent, soil stabilisation, concrete mix, chemical treatment, and ceramic and brick manufacturing.

Reasons for CKD not being returned to the kiln system include equipment limitations for handling the dust, or if the chemical composition of the dust is such that it would be detrimental to the final cement product. However, stakeholders at the workshop suggested that landfill disposal was unlikely in the UK, with dust that is not returned to the kiln generally being sold for secondary applications. This was supported by MPA data[26] that identified 0% process waste to landfill (which would include CKD) for the cement industry.

2.2 Available sources

2.2.1 Literature review

The literature review identified ten sources that discussed CKD waste recovery and use as feedstock in cement manufacturing, although there was little quantitative evidence on the future levels of resource efficiency that could be achieved through this measure. This comprised of:

- two industry reports;[27] [28]
- four academic papers;[29] [30] [31] [32]
- one policy document;[33] and
- three website articles.[34] [35] [36]

The relevant sources were considered of medium applicability and credibility when assessed against the data assessment framework, which recognises the relevance of the sources and the strength of the methodology within each. The sources exhibited an average IAS of 2.8 (out of 5), with only two sources exhibiting a score of 4 or above. Only two literature sources were UK-specific and four sources were not recent studies. Because of this more emphasis was placed on the findings of the workshop to confirm or counter the literature review findings.

Across the literature there was very little applicable quantitative data relating to methods to improve resource efficiency through the identified process nor in aggregate what this would mean in terms of overall resource efficiency for this measure. The only data found was from a US EPA source with an IAS of 3,[37] which provided 1993 US recovery values.

[26] MPA Cement website sustainability page. Available at link.
[27] Garth J. Hawkins, Javed I. Bhatty, and Andrew T. O'Hare (2003) Everything you need to know about Cement Kiln Dust Generation and Management
[28] Sustainable Development (2014) Waste management solutions by the cement industry
[29] Saleh, H.M., Faheim, A.A., Salman, A.A., El Sayed, A.M. (2021) "A Review on Cement Kiln Dust (CKD), Improvement and Green Sustainable Applications
[30] Ali Albakri (2022) Cement Kiln Dust (CKD): Potential Beneficial Applications and Eco-Sustainable Solutions
[31] Minhye Seo,Soo-Young Lee,Chul Lee andSung-Su Cho (2019) Recycling of Cement Kiln Dust as a Raw Material for Cement
[32] Alastair T.M. Marsh, Anne P.M. Velenturf, Susan A. Bernal (2022) Circular Economy strategies for concrete: implementation and integration
[33] US EPA (1993), Report to Congress on Cement Kiln Dust: Alternative CKD Management.
[34] MPA Cement website sustainability page. Available at link.
[35] Recycled materials resource center (n.d.) Kiln Dusts - Material Description
[36] Engineering and Physical Science Research Council (1998) Value added recycling routes for CKD - summary
[37] US EPA (1993), Report to Congress on Cement Kiln Dust: Alternative CKD Management.

2.2.2 Workshops

This measure was added after the first workshop due to a stakeholder recommendation, and was presented at workshop 2 with the indicator: 'the percentage of recovered material used per tonne of cement.' This was adapted following workshop 2 to 'percentage of CKD waste recovered and used as cement manufacturing raw material feedstock' based on feedback from stakeholders during the workshop to rephrase it and clarify what specific material the indicator was referring to. The initial indicator referred to the recycling of CKD, which is already commonplace according to stakeholders. The indicator was then amended to focus on closed loop recycling of CKD as a feedstock for cement production.

Many workshop participants were familiar with the topic but were not experts. Despite the lack of detailed data present in the literature, the topic of CKD recycling has been on the sustainability agenda for the industry for decades. As a result, stakeholders were aware of the topic but were unable to contribute substantially to identifying quantitative levels of efficiency. The level of engagement in both workshops was as follows:

- **Workshop 1** – No engagement as this measure was newly added after the first workshop.
- **Workshop 2** – Seven stakeholders across industry and academia were active on the mural board and three stakeholders actively contributed to verbal discussion.

2.3 Drivers & Barriers

The drivers and barriers influencing this measure were identified through a combination of the literature review and stakeholder feedback at the workshops.

2.3.1 Drivers

The literature identified drivers focused solely on improved environmental outcomes, and cost savings. The participants in the workshops built on this by framing the improved environmental outcomes as part of the wider drive to decarbonise the sector. The most significant driver is in bold.

Table 6: Drivers for cement & concrete Measure 2

Description	PESTLE	COM-B
Cost savings	**Economic**	**Opportunity – physical**
Climate policy and decarbonisation trend	Social	Opportunity – social

Cost savings

Generally, any reuse of materials that would otherwise be wasted but can be reincorporated into the same manufacturing process, will provide a net cost benefit to the manufacturer and an improvement in resource efficiency. There will be a reduction in the quantity of raw materials required for manufacture, as well as the potential for excess CKD to be sold to other cement manufacturers or even for other uses - CKD is already sold by cement manufacturers, thus they can realise even greater cost savings should they employ the means to recover higher quantities of it during the manufacturing process.

The World Business Council for Sustainable Development reported that extensive testing has proven that cement made with CKD from the manufacturing process can exhibit the same physical and chemical characteristics as cement produced with conventional resources[38]. By increasing the use of CKD, the distances of long-haul waste transport can subsequently be decreased, providing a further cost benefit for manufacturers whilst simultaneously reducing transport emissions[39].

Climate policy and decarbonisation trend

One stakeholder highlighted that aside from cost savings, there is additional carbon benefit from reusing CKD besides from those associated with the reduction in raw material usage - its high alkaline content allows it to capture CO_2 generated inside the kiln during the clinkerisation process. The implementation of climate policies that place limits on carbon emissions will therefore further drive the uptake/research of the recovery and reuse of CKD, as it will encourage manufacturers to fully utilise the potential carbon savings that can be achieved by using it. In one workshop it was stated that the UK cement industry has been undergoing a decarbonisation trend for years, and that this can potentially be a driver for improving resource efficiency in all the measures presented.

2.3.2 Barriers

One literature source[40] identified several barriers to greater recovery and return of CKD into the manufacturing process, although this study is potentially outdated and was published in 2003. The participants in the workshops did not build on these to a great extent.

Table 7 shows a list of identified barriers to recovering cement manufacturing waste and returning it to the manufacturing process. The most significant barriers are highlighted in bold. These barriers are discussed in further detail below.

Table 7: Barriers for cement & concrete Measure 2

Description	PESTLE	COM-B
Market concerns about cement performance	**Technological**	**Capability – physical**
Lack of cost-effective technology to return dust to the kiln system	**Economic**	**Opportunity – social**
Existing secondary markets for CKD may be disrupted	Economical	Opportunity – social

Market concerns about cement performance

Despite extensive testing having shown that cement made with CKD can exhibit the same physical and chemical characteristics as cement produced with conventional resources[38], there are concerns in the market regarding the performance of cement made with CKD as increasing its use would increase alkali content in cement. There is a low market demand for higher alkali

[38] World Business Council for Sustainable Development (2014). Waste Management Solutions by the Cement Industry
[39] Constro Facilitator (2019). Alternative Cement Substitutes

content cement because of concerns for potential alkali-silica reactions, which may impact the long-term performance of the concrete and cause issues such as cracking[40]. One stakeholder at the workshop stated that alkalis are generally removed from cements for quality purposes, suggesting that in some circumstances this may no longer be a barrier, however the literature review did not find any information to support this claim.

Lack of cost-effective technology to return dust to the kiln system

Historically, manufacturing challenges and expenses associated with CKD recycling have been greater than the cost of quarrying and processing raw materials to replace the feed lost by dust removal from the kiln system. As energy and disposal costs have increased, more plants have been evaluating how to optimise the return of CKD to the kiln system while maintaining high product quality[40]. Currently, however, there is no easy way to return CKD to the kiln systems after extraction during the manufacturing process – this is what is currently inhibiting most manufacturers from using CKD as a feedstock.

Existing secondary markets for CKD may be disrupted

Some CKD is recovered offsite with the rest already being returned to the manufacturing process. This means there are existing markets for the material in applications such as agricultural liming agent, soil stabilisation, concrete mix, chemical treatment, and ceramic and brick manufacturing. Alternative materials that can act as substitutes for CKD may have more significant resource or cost impacts.[40]

2.4 Levels of efficiency

Table 8: Levels of efficiency for cement & concrete Measure 2

Indicator: % of CKD waste recovered and used as cement manufacturing raw material feedstock			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	3.7%	60 – 70%	<5%
Evidence RAG	Amber-Green	Red	Red

2.4.1 Current level of efficiency

The current level of efficiency was determined to be 3.7%. The literature for current level of efficiency draws on two sources. The first is the MPA industry sustainability report webpage which reports on resource use metrics within the cement industry between the years of 2016 – 2021[41]. This source is considered of high quality because the MPA is a major trade association for the cement industry in the UK and the data provided is recent. This source states that in 2021 there was zero unrecovered cement process waste from the cement industry (which is assumed to also include CKD), and that 1,152 tonnes of process waste were recovered onsite back into the kiln while 31,095 tonnes were recovered offsite, giving us our current level of efficiency of 3.7%. The second source reviewed was a 1993 study by the US Environment

[40] G.J Hawkins, et al. (2003) Everything you need to know about Cement Kiln Dust Generation and Management
[41] MPA (2022), Sustainability. Access at this link.

Protection Agency[42] which estimated a higher percentage (60–67%) of the total CKD generated being returned to the manufacturing process. However, this figure was not deemed applicable because the source is outdated and not geographically relevant to a UK context.

Workshop stakeholders opted to defer to the MPA data and most declined to vote on the current level of efficiency, only noting that all cement production waste is utilised in some way and that none was sent to landfill. One stakeholder stated that the remaining CKD that is not fed back into the kiln is applied to agricultural land as a means of stabilising and raising soil pH in acidic soils as an agricultural liming substitute and as a fertilising agent due to the presence of typically high concentrations of potassium and sulphur.

The evidence RAG rating is classified as amber-green because there is only one source of data identified in the literature review, however stakeholders did show consensus that this data reliable.

2.4.2 Maximum level of efficiency in 2035

The maximum level of efficiency in 2035 was determined to be 60 - 70%. Only four workshop participants voted on the maximum level of efficiency in 2035. Two voted for >20% while one voted for 15 – 20% and one voted for less than 5%. Notably, the 1993 US study showing a CKD recycling rate of between 60 – 70%[43] demonstrates that the technical level of efficiency is likely to be significantly over 20%. Therefore, this datapoint has a red evidence RAG rating due to the lack of recent literature relevant to the UK and the limited participant input. There is also a possibility that this result may have been skewed by stakeholders who may have interpreted the measure to mean recycling rate of CKD, including both on- and offsite.

During the discussion, stakeholders expressed the belief that cement manufacturing is already a very efficient process and that there have been numerous drivers (e.g., cost and carbon emissions) that have incentivised resource efficiency gains for many years. As a result, the scope for greater efficiency in this part of the process is minimal and the use of CKD in other applications such as fertiliser and soil stabilisation may be just as beneficial as closed loop recycling into the kiln since the material still acts as a direct replacement of raw limestone.

It was therefore concluded that Measure 2 is an appropriate measure but may offer less potential for resource efficiency than some of the other measures due to the high level of recovery that is already happening and the lack of evidence that closed loop recycling into the kiln provides greater resource efficiency than use in secondary applications.

2.4.3 Business-as-usual in 2035

The business-as-usual level of efficiency in 2035 was determined to be <5%. All business-as-usual data came from the stakeholder engagement. Only four workshop participants voted on the business-as-usual level of efficiency in 2035. Two of them voted for <5% while one participant voted for 10 – 14% and one participant voted for greater than 20%. However, given the discussions it is likely that the participant who voted for >20% was under the impression that the vote was for recycling rate of CKD, including both on- and offsite. This large spread in responses and limited participation gives us a red evidence RAG rating for this data point. However, based on comments in the discussion it appears that the barriers and lack of drivers

[42] US EPA (1993), Report to Congress on Cement Kiln Dust: Alternative CKD Management.
[43] US EPA (1993). Report to Congress on Cement Kiln Dust: Alternative CKD Management.

means that closed loop recycling of CKD is not expected to change in the business-as-usual scenario to reach its full technical potential.

3.0 Measure 3 – Use of recycled concrete fines in cement or concrete production

3.1 Cement resource efficiency measure

3.1.1 Description

Recycling of hydrated and unhydrated cement from fine recycled concrete aggregate (FRCA) as a substitute for an SCM or as a clinker substitute in cement production (hydrated cement) or cement in concrete production (unhydrated cement).

When recycled, concrete is typically used as aggregate for use in new concrete, road construction or earthworks. In these applications, concrete waste is crushed into recycled concrete aggregate (RCA). The quality of RCA is generally of lower quality than that of natural aggregates due to contamination from residual mortar. Consequently, RCA is categorised as either coarse or fine recycled concrete aggregate (CRCA / FRCA) depending on the size of the rubble and subsequent level of contamination. CRCA is used more often as a replacement for natural aggregate, but only represents 50 – 60% of concrete demolition waste.[44] FRCA is considered less useful due to the high level of cement paste contamination which may contain chlorides and sulphates that have a negative impact on the durability of new concrete. As a result, the concrete recycling industry currently has limited use for FRCA despite its accounting for about 30 – 50% of waste material.[45] The remaining 10% might be composed of neither CRCA nor FRCA but other building materials such as steel and glass.

This measure looks at the utilisation of FRCA in applications that would provide resource efficiency benefits to the cement sector. The utilisation of CRCA as a replacement for natural aggregate is covered in 'Measure 6 – use of recycled content in concrete.'

3.1.2 Measure indicator

The indicator selected was '**percentage of concrete fines used in cement or concrete production.**' This is a relative measure with the percentage derived by dividing the 'mass of FRCA used in cement or concrete production' by the 'mass of cement produced or utilised in concrete.'

Other indicators that were identified but not selected included:

- % recovered material used per tonne of cement; and
- % reduction in concrete demand.

These were not selected as they were either hard to quantify or associated with a version of the measure that was subsequently discarded.

[44] Yury A. Villagrán-Zaccardi et al. (2022). Complete re-utilization of waste concretes–Valorisation pathways and research needs
[45] D. Gastaldi et al. (2015). An investigation on the recycling of hydrated cement from concrete demolition waste.

3.1.3 Examples in practice

It was highlighted by multiple stakeholders during the workshops that concrete fines are currently not recycled into the cement production process on a regular basis in the UK, or anywhere else globally.

Recovery of unhydrated cement

All concrete contains some amount of residual unhydrated cement. The level of unhydrated cement varies due to factors such as the water-to-cement ratio or how coarse the cement used is. Unhydrated cement can also be found in higher levels in fresh concrete waste that has not yet been cured. A recent study found that the amount of unhydrated cement can range from 6 – 36%[46] depending on the strength of the concrete. Specifically, higher levels of unhydrated cement were found in high strength concretes with low water-to-cement ratios. This indicates that there is scope for this material to be recovered and reused if carefully designed processes are used to separate the unhydrated cement material. Additionally, as the application of high strength concretes has increased over the years, the amount of unhydrated cement potentially available is also increasing. While these findings are promising, further research is needed on methods of extracting this material before it can be considered a commercially viable option.

Recycling of hydrated cement

Extracting cement from concrete once it has been mixed was once considered technically impossible. However, researchers have recently been evaluating the feasibility of extracting hydrated cement waste from FRCA. This material is of interest to the cement industry as it is similar in composition to raw clinker meal and may be used as an SCM or as a clinker substitute.

To extract hydrated cement from FRCA it must first be processed through further grinding to produce a product referred to as recycled concrete powder (RCP). However, the amount of RCP that can be obtained from FRCA is limited to about 10%.[47] This limits the resource efficiency potential of this material.

Research has considered the opportunity for RCP to be used as an SCM. However, the use of RCP as an SCM is repeatedly reported to degrade key mechanical properties of concrete such as compressive strength and durability[48]. RCP has shown greater promise as a feedstock for clinker production. This has been demonstrated to reduce CO_2e emissions of clinker production by 53% while also enhancing the burnability of clinker feedstocks, which decreases the amount of energy required to achieve clinkerisation in the kiln.[47] As a result, use of RCP as a feedstock for clinker production reduces both the need for consumption of raw materials such as limestone and the carbon emissions associated with clinker production.

[46] Daniele Kulisch, et al. (2023) Quantification of Residual Unhydrated Cement Content in Cement Pastes as a Potential for Recovery
[47] Yury A., et al. (2022). Complete re-utilization of waste concretes–Valorisation pathways and research needs.
[48] Yuan Jiang, et al. (2022) Role of recycled concrete powder as sand replacement in the properties of cement mortar

3.2 Available sources

3.2.1 Literature review

The literature review found fourteen sources that identified the use of recycled concrete fines in cement or concrete production as a resource efficiency measure, although there was little quantitative evidence on the current or future levels of resource efficiency that could be achieved through this measure. This comprised of:

- two industry reports;[49] [50]
- nine academic papers; [51] [52] [53] [54] [55] [56] [57] [58] [59] and
- three website articles.[60] [61] [62]

The relevant sources were considered of high applicability and credibility when assessed against the data assessment framework, which recognises the relevance of the sources and the strength of the methodology within each. The sources exhibited an average IAS of 4.1 (out of 5), with nine sources exhibiting a score of 4 or above. It should be noted that none of the data in the literature sources were specific to the UK because FRCA recycling is a novel technology that is currently mostly being explored at lab scale, with only a few commercial examples happening in Europe.

Across the literature there was very little applicable quantitative data relating to methods to improve resource efficiency through the identified processes, nor in aggregate what this would mean in terms of overall resource efficiency for this measure. This is likely because utilisation of FRCA in cement production is a novel technique with a low level of market uptake.

3.2.2 Workshops

Measure 3 was added between the first and second workshop based on feedback from stakeholders during workshop 1 and a stakeholder recommendation via a feedback survey. In workshop 1, the measure was presented as ‘reuse and recycling of concrete’ and the indicator

[49] Energy Transitions Commision (2019) Mission Possible Sectoral Focus: Cement
[50] WBCSD (2009) The Cement Sustainability Initiative - Recycling Concrete
[51] Yury A. Villagrán-Zaccardi et al. (2022). Complete re-utilization of waste concretes–Valorisation pathways and research needs
[52] D. Gastaldi et al. (2015). An investigation on the recycling of hydrated cement from concrete demolition waste.
[53] Daniele Kulisch, et al. (2023) Quantification of Residual Unhydrated Cement Content in Cement Pastes as a Potential for Recovery
[54] Alastair T.M. Marsh, Anne P.M. Velenturf, Susan A. Bernal (2022) Circular Economy strategies for concrete: implementation and integration
[55] Joris Schoon, Klaartje De Buysser, Isabel Van Driessche, Nele De Belie (2015) Fines extracted from recycled concrete as alternative raw material for Portland cement clinker production
[56] Zhutovsky, Shishkin - Israel Institute of Technology (2020) Portland Cement Production from Fine Fractions of Concrete Waste
[57] Somayeh Lotfi, Peter Rem (2016) Recycling of End of Life Concrete Fines into Hardened Cement and Clean Sand
[58] Yuan Jiang, Bo Li, Shu Liu, Jun He, Alvaro Garcia Hernandez (2022) Role of recycled concrete powder as sand replacement in the properties of cement mortar
[59] Romain Trauchessec, Hichem Krour, Cécile Diliberto, André Lecomte - University of Lorraine (2019) Use of recycled aggregates for cement production
[60] Cembureau (n.d.) Alternative Raw Materials Study
[61] Cembureau (n.d.) Concrete Recycling Positioning Paper
[62] Cembureau (n.d.) Recycling concrete

was presented as '% reduction in concrete demand.' Stakeholders during the workshop stated that this measure was not an appropriate measure or indicator for the cement sector as recycled concrete is mainly used as a replacement for sand and/or natural aggregates instead of cement (covered in Measure 6 – use of recycled content in concrete).

In workshop 2, the measure was amended to 'use of recycled concrete fines in clinker production' to ensure that it was properly capturing resource efficiency in the cement sector. This measure was received positively by stakeholders, but it was highlighted that this area of research is very new to the industry and that there is a lack of available data for the maximum technical efficiency. However, following the workshop the measure was amended to refer to 'cement or concrete production' instead of 'clinker production' because it became clear through the literature that the addition of FRCA is a very new technology and it is not yet clear which manufacturing stage it will be used in. The level of engagement in both workshops was as follows:

- **Workshop 1** – No engagement as this measure was newly added after the first workshop.
- **Workshop 2** – Eight stakeholders across industry and academia were active on the mural board and Four stakeholders actively contributed to verbal discussion.

3.3 Drivers & Barriers

The drivers and barriers influencing this measure were identified through a combination of literature review and stakeholder feedback at the workshops.

3.3.1 Drivers

Table 9 shows a list of identified drivers for the use of recycled concrete fines and the most significant drivers are highlighted in bold.

Table 9: Drivers for cement & concrete Measure 3

Description	PESTLE	COM-B
Cost savings	**Economical**	**Opportunity – social**
Decarbonisation potential	Environmental	Motivation – reflective
Economic benefits due to carbon capture and storage	Economic	Motivation – reflective

Cost savings

It was identified through the literature and highlighted by a stakeholder that use of concrete fines as a feedstock in cement production could have the potential to provide massive cost savings for manufacturers, as most of the energy investment into cement kilns goes into decarbonising the limestone (calcination - where CO_2 is released as a by-product of turning limestone into lime by heating it to high temperatures).[44] The same stakeholder expanded on this, stating that the limestone in recycled concrete fines has already undergone calcination, which allows cement to be manufactured with not only less energy, but with fewer carbon emissions, as less clinker will be required. This driver was voted as the most significant driver for this measure by stakeholders but could be challenging until there is a larger network of demolition sites available - concrete fines are currently not widely available, driving up collection costs depending on where they are located (see barrier for this measure: "*cost of collection and demolition").*

Other Drivers

There were other drivers that were also identified through literature or raised by stakeholders, but received fewer votes of significance/engagement from stakeholders during the workshop:

- **Decarbonisation potential:** Both the literature and stakeholders showed that the use of recycled concrete fines in clinker production is an excellent means of decarbonising the industry and reducing both raw material and energy consumption, with one stakeholder stating that it could comfortably reduce the carbon footprint of concrete structures by 10%. Another stakeholder stated that this could act as a driver if policies mandating limits on the carbon footprint of concrete structures were implemented. It is worth noting that another stakeholder highlighted the importance of the industry establishing what the 'best' use of concrete fines is - whether it lies in cement manufacturing, or in concrete manufacturing as an SCM, as this will be critical to enable an increase in the percentage of concrete fines recovered/recycled for cement production.
- **Economic benefits due to carbon capture and storage:** As stated, both literature and stakeholders showed that recycled concrete fines can directly reduce the amount of CO_2 emissions resulting from clinker production when used as a kiln feedstock, as it readily carbonates - acting as a form of carbon capture and storage.[63] A stakeholder highlighted that if recycled concrete fines can act as a good carbon capture and storage option, then the use of recycled concrete fines in clinker production could provide economic benefits to contractors in future. This could be in the form of a reduction in carbon taxation, reduced cost of emission control during the manufacturing process, or even additional business development resulting from an enhanced public image - cement manufacturers can highlight their commitment to environmental stewardship, attracting environmentally conscious customers and investors. However one stakeholder pointed out that these benefits would only occur if the concrete fines were uncarbonated – and given that Portland based cement and concretes carbonate when used in the built environment this may be unlikely.

3.3.2 Barriers

Table 10 shows a list of identified barriers to the use of recycled concrete fines and the most significant barriers are highlighted in bold. These barriers are discussed in further detail below.

Table 10: Barriers for cement & concrete Measure 3

Description	PESTLE	COM-B
Quality of concrete fines and potential contamination	**Technological**	**Capability – physical**
Cost of collection and demolition	**Economical**	**Opportunity – social**
Lack of regulation, standards and guidelines	**Legal**	**Capability - psychological**

[63] S. Lotfi, P. Rem (2016), Recycling of End of Life Concrete Fines into Hardened Cement and Clean Sand, Delt University of Technology. Available at link:

Description	PESTLE	COM-B
Availability of concrete fines	Technological	Capability – physical
Separating fines from impurities and other materials	Technological	Capability – physical
Transport distance	Technological	Capability – physical

Quality of concrete fines and potential contamination

A stakeholder pointed out during the workshops that there are technical limits to the amount of concrete fines that can be fed into clinker production. These technical limits are dependent on contamination levels from compounds such as sulphates or silica, which can have severe effects on the structural integrity of concrete that is subsequently produced from clinker made in this manner.

Cost of collection and demolition

The availability of demolition site waste that is suitable for concrete fine extraction is not yet at a suitable scale to enable this measure to make a meaningful impact on resource efficiency, as concrete structures are also typically not designed to extract these fines, driving up the cost of collection.

Widespread use of recycled concrete fines may also require a centralised network of concrete recycling plants to be set up to reduce transportation distances/costs - although it was mentioned in the workshop that most of the global cement players are currently going through mergers & acquisitions (M&A) of recycling centres, suggesting that they are gearing up to make this part of their portfolio.

Lack of regulation, standards and guidelines

Similar to the issue described in Measure 1, stakeholders highlighted that there are currently no norms for the use of recycled concrete fines, and that they are currently not permitted within certain quality and testing standards in the same way that cement derived from raw materials is. One stakeholder stated that this is a big deterrent for cement manufacturers using them as a feedstock, as recycled fines can have a varying chemical composition, requiring different adjustments to the manufacturing process depending on the origin of the fines used. Similarly, without these standards, buyers of cements/concretes may not feel confident in purchasing them if they contain recycled concrete fines due to contamination concerns.

Other Barriers

There were other barriers that were also identified through literature or raised by stakeholders, but received fewer votes from stakeholders during the workshop, it is worth noting that they are all linked to the barrier *"cost of collection and demolition":*

- **Availability of concrete fines:** The availability of demolition site waste would need to reach a much larger scale, with the establishment of a centralised network required for it to begin to exhibit meaningful resource efficiency gains.
- **Separating fines from impurities and other materials:** One stakeholder pointed out that concrete structures are not designed with extraction of their fines in mind at the demolition stage. Concrete structures may contain impurities or contaminants, such as

plastic and other non-ferrous materials – this can also affect the fines extraction process. Removing these impurities requires additional sorting and cleaning steps to ensure the extracted fines meet the desired quality standards, acting as a barrier to their use. One stakeholder highlighted that higher kiln temperatures in the clinkerisation process may be required to abate the presence of these contaminants – this is the most energy intensive element of the cement manufacturing process, and thus could significantly limit the quantity of concrete fines viable for use in cement production. Another stakeholder expanded on this, stating that there will need to be technological developments made in order to scale their use. One stakeholder indicated that better separating fines from non-ferrous materials is an area of research development that is currently underway.

- **Transport distance:** The lack of a centralised network of available concrete fines increases the transport costs to an extent that is not feasible from a cost perspective (as well as increasing carbon emissions) due to their significant weight. Further collaboration between the cement industry and other uses of concrete fines (such as asphalt) would help overcome this barrier.

3.4 Levels of efficiency

Table 11: Levels of efficiency for cement & concrete Measure 3

Indicator: % recycled concrete fines used in cement or concrete production			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	0 – 1%	16 – 30%	1 – 5%
Evidence RAG	Amber	Red-Amber	Amber

3.4.1 Current level of efficiency

The current level of efficiency for this measure is between 0 – 1%. There was no evidence for the current level of efficiency identified in the literature review. This is not surprising given the novelty of the technology. However, there was a high level of agreement between workshop participants, with most participants (five) voting that the current level is <1% and two voting that the level was between 1 – 5%. Thus, the evidence RAG rating is defined as amber.

One of the participants, who stated on a sticky note that the level is 0% in the UK, is currently working on a project looking at this measure in the EU. Another participant mentioned that this measure was researched during the consultation for BS EN 197-5:2021 which also found that the level is currently 0%.

During the discussion stakeholders commented on the fact that this idea is new to the industry and could have potential for further development in the UK, particularly within companies with vertical integration across the supply chain or who have purchased waste management companies that deal with construction and demolition waste.

3.4.2 Maximum level of efficiency in 2035

The maximum level of efficiency is between 16 – 30%. There is a maximum technical limit to the use of recycled fines due to their negative impacts on the final concrete product. One study found that a 20 – 30% replacement rate of CEM I with a combination of hydrated and unhydrated fines is optimal while limiting the negative impacts of the recycled fines.[64]

Of the workshop participants who voted, three voted that the range was between 16 –25% while one voted that the range was between 6 – 15% and one voted that it was between 1 – 5%. During the discussion one stakeholder commented that the sulphate content of cement fines limits clinkerisation in the kiln which sets the technical limit to about 15%. Another stakeholder commented that reaching maximum technical level of efficiency will require a change in the business model of waste management companies and efficient collection of FRCA.

The range in values and the early stage of the technology gives a red-amber evidence RAG rating in this data point.

3.4.3 Business-as-usual in 2035

The business-as-usual level of efficiency is between 1 – 5%. All business-as-usual data came from the stakeholder engagement. Of the workshop participants who responded, four voted that the range was between 1 – 5% and one voted that it was <1%. There appeared to be a consensus, but the lack of participants with expertise in this area gives us a red-amber evidence RAG rating for this data point.

According to stakeholders, there appears to be interest in FRCA recycling as it is a subject of ongoing research. Additionally, stakeholders noted that the major global cement players are undergoing mergers and acquisitions of recycling businesses. As such, it would appear that the cement sector is gearing up to make this technology a part of their portfolio. However, there are currently limits to the availability of demolition waste at suitable scale to make this endeavour economically worthwhile. Stakeholders claim that there is enough demolition waste overall, but the structures are not in place to centralise and treat all of it for use in recycling. As a result, it is unlikely there will be much change in the business-as-usual scenario despite the technical potential for improvement. Stakeholders also noted that significant financial incentives or a government framework may be necessary to make the process economically viable.

[64] Daniele Kulisch, Amnon Katz and Semion Zhutovsky (2023). Quantification of Residual Unhydrated Cement Content in Cement Pastes as a Potential for Recovery.

4.0 Measure 4 – Lean design of concrete structures

4.1 Concrete resource efficiency measure

4.1.1 Description

Optimising structure design to reduce the unnecessary consumption of concrete.

The use of concrete can be optimised through structural and design decisions that improve resource efficiency by optimising structural performance and utilisation, thus reducing the need for materials.

Designers have a wide variety of structural frame options to choose from, including precast, in-situ and hybrid solutions, which have different material footprints. Additionally, different structural frame components such as flat slab, ribs, band beams and waffle decks impact the type and quantity of materials and reinforcement needed within the structure. Utilising the most appropriate design option for reducing material use while avoiding over-specification can help to improve resource efficiency.

4.1.2 Measure indicator

The indicator selected to measure the lean design of concrete structures was '**percentage reduction in concrete demand for the same unit throughput relative to 2023'** which is defined as the percentage reduction in concrete produced in the sector overall as a result of lean design. This was the only indicator that was identified for this measure.

4.1.3 Examples in practice

Structures that are both optimised and fully utilised make the most efficient use of materials. 'Optimisation' refers to how efficiently material is used throughout the structure. 'Utilisation' refers to how hard a structure works to resist the load it is under.

Optimisation - Post-tensioning

Post-tensioned slabs are a form of flat slab construction that provides key strength benefits. Concrete has low tensile strength but is strong under compression. Post-tensioning is the stressing of the steel reinforcements in concrete slabs before external loads are applied, which increases the proportion of concrete under compression (and so increasing concrete strength). This allows for a more efficient design structure to be achieved and reduces the of concrete needed in floor slabs. This also minimises floor thickness which reduces the total height of buildings and provides concrete savings elsewhere through shorter flights of stairs, walls and cores.

As a result, post-tensioning can reduce the total concrete volume used by 10%,[65] or as much as 20% in non-residential applications where spans are typically greater than 6m.[66]

[65] MPA (2019) Concrete Quarterly, Return of the Rib.
[66] Shanks et al (2019). How much cement can we do without? Lessons from cement material flows in the UK

Optimisation - Voids, coffers & non-structural fill

It is sometimes possible to omit some of the concrete in a structure without impacting its performance. This can reduce the volume of concrete used by more than 50%.[67] For example, voided slabs incorporate air voids into the thickness of the slab, which reduces the amount of concrete used and the overall weight of the slab. Additionally, precast hollowcore floor units can provide an efficient flooring system that reduces the design load of a building and saves material and costs associated with foundations.

Optimisation - Ribbed and waffle slabs

Ribbed and waffle slabs provide a lighter, stiffer slab than a traditional flat slab, which reduces the size of the foundations. This results in savings of about 20% in the volume of concrete used compared to flat slabs.[68] Ribbed slabs are typically constructed using forms of glass reinforced plastic or polystyrene. For large, two-way spans this type of design gives a material-efficient option for supporting high loads.

Utilisation

A structure with low utilisation has the capacity to bear higher loads than it is currently bearing. Efficient structures should have utilisation of close to 100%. In this case, the load on the structure matches the maximum load permitted. Note that failure is unlikely to occur unless the load exceeds the specified maximum load by a substantial amount. Recent reports have shown that the utilisation of most structures often falls below 60%[69] leaving significant room for improvement.

4.2 Available sources

4.2.1 Literature review

The literature review identified 22 sources that identified lean design of concrete structures as a resource efficiency measure, although there was little quantitative evidence on the current or future levels of resource efficiency that could be achieved through this measure. This comprised of:

[67] Drewniok, M. (2021) Relationships between building structural parameters and embodied carbon Part 1: Reinforced concrete floors solutions (ENG-TR.013): www.doi.org/10.17863/CAM.75783
[68] Shanks et al (2019). How much cement can we do without? Lessons from cement material flows in the UK
[69] Low Carbon Concrete Group (2022). Low Carbon Concrete Routemap.

- one book chapter;[70]
- eight academic papers;[71] [72] [73] [74] [75] [76] [77] [78]
- two technical studies;[79] [80]
- nine industry reports; [81] [82] [83] [84] [85] [86] [87] [88] [89] and
- two website articles.[90] [91]

The relevant sources were considered of high applicability and credibility when assessed against the data assessment framework, which recognises the relevance of the sources and the strength of the methodology within each. The sources exhibited an average IAS of 4.6 (out of 5), with only one source exhibiting a score of 3 or below. A little less than half (nine) of the sources were UK specific, and sixteen of them were from 2016 or later. Overall, the literature was deemed to be highly applicable to the UK market today. However, only a portion of the literature provided quantitative data relating to the methods to improve resource efficiency. In many cases this data was provided at the intervention level (e.g., post-tensioned floors) as opposed to measure level. Some of the literature covered both quantitative and qualitative data while some of it covered qualitative information on the measure only.

4.2.2 Workshops

Measure 4 was amended between the workshops based on feedback from stakeholders in the pre-workshop survey. In workshop 1, measure 4 was captured as ‘post-tensioning of concrete floor slabs’. Feedback stated that this method was very niche and specific and suggested it would be better to widen the measure to apply to all design techniques that improve resource efficiency. In workshop 2 the measure was therefore broadened to include all lean design and

[70] Allwood J.M. & Cullen, J. M. (2012) Sustainable Materials: With Both Eyes Open
[71] Alastair T.M. Marsh, Anne P.M. Velenturf, Susan A. Bernal (2022) Circular Economy strategies for concrete: implementation and integration
[72] Drewniok, M. (2021) Relationships between building structural parameters and embodied carbon Part 1: Reinforced concrete floors solutions (ENG-TR.013): www.doi.org/10.17863/CAM.75783
[73] Shanks et al (2019). How much cement can we do without? Lessons from cement material flows in the UK
[74] Cyrille F Dunant et al. (2021). Good early stage design decisions can halve embodied CO_2 and lower structural frames’ cost.
[75] López-Mesa, B., Pitarch, A., Tomas, A., Gallego, T. (2009) Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors
[76] Giesekam, J., Barrett, J. R. and Taylor, P. (2016) Construction sector views on low carbon building materials
[77] Miller, D., Doh, J., Guan, H., Mulvey, M., Fragomeni, S., McCarthy, T., Peters, T. (2013) Environmental impact assessment of post tensioned and reinforced concrete slab
[78] Firehiwot Kedir, Daniel M. Hall (2021) Resource efficiency in industrialized housing construction: A systematic review of current performance and future opportunities
[79] Bison Precast Ltd. (2007) Precast concrete flooring
[80] The Post-Tensioning Association (2011) Sustainable Construction with Post-Tensioned Slabs
[81] MPA (2022) Comparison of embodied carbon in concrete structural systems
[82] MPA (2020) Concrete Quarterly Application: Collected Technical Articles 2020-21
[83] MPA (2019) Concrete Quarterly, summer 2019: Return of the Rib
[84] MPA (2020) High tension: An introduction to specifying post-tensioned slabs
[85] Andrew Mullholland et al. – Low Carbon Conrete Group – The Green Construction Board (2022) Low Carbon Concrete Routemap
[86] MPA (2018) Material Efficiency
[87] Energy Transition Commission (2019) Mission Possible Sectoral Focus: Cement
[88] MPA (2017) Post-tensioned Concrete Floors
[89] Michael Lord (2017) Rethinking Cement
[90] ConstructionOR (2021) ConstructionOR
[91] Post Tensioning Association (2018) Post Tensioning Benefits for Developers

specification optimisation techniques that reduce the amount of concrete required such as lightweighting and alternative reinforcement. This was received positively by stakeholders.

The level of engagement in both workshops was as follows:

- **Workshop 1** – No measurable engagement as this measure was changed after the first workshop.
- **Workshop 2** – Seven stakeholders from industry were active on the mural board and three stakeholders actively contributed to verbal discussion.

4.3 Drivers & Barriers

The drivers and barriers influencing this measure were identified through a combination of literature review and stakeholder feedback at the workshops.

4.3.1 Drivers

Table 12 shows a list of identified drivers for the lean design of concrete structures and the most significant drivers are highlighted in bold. These drivers are discussed in further detail below.

Table 12: Drivers for cement & concrete Measure 4

Description	PESTLE	COM-B
Climate policy	**Environmental**	**Opportunity – social**
Increased cost of cement	Economical	Opportunity – social
Societal pressure	Social	Opportunity – social

Climate policy

It was noted in the workshop that optimisation/lean design of concrete structures has potential to make huge carbon emission savings, and that societal pressure for carbon reduction is already driving some change. Carbon emission savings that could be made are a result of reduced consumption of raw materials and material transportation requirements, and a potentially faster/easier demolition process at the end of a structure's life - due to a lower total volume of concrete that needs to be demolished and collected/recycled. Future net-zero targets/roadmaps, coupled with the implementation of climate policies that place limits on carbon emissions, will make this a significant driver for the lean design of concrete structures in the future.

Other Drivers

There were other drivers that were also identified through literature or raised by stakeholders, but received fewer votes of significance/engagement from stakeholders during the workshop:

- **Increased cost of cement:** The cost of cement (along with many other construction materials) has already experienced an unprecedented increase in recent years, due to supply chain issues and soaring energy prices arising from the Covid-19 pandemic and

Russia's invasion of Ukraine. This will cause contractors to place a greater value on materials and encourage the leaner design of concrete structures.

- **Societal pressure:** Stakeholders pointed out during the workshop that societal pressure for greener structures is already driving change within the sector and acting as a driver for leaner concrete structures; however, the extent to which this occurs is dependent on who chooses to 'react' to this influence.

4.3.2 Barriers

Table 13 shows a list of identified barriers to the lean design of concrete structures and the most significant barriers are highlighted in bold. These barriers are discussed in further detail below.

Table 13: Barriers for cement & concrete Measure 4

Description	PESTLE	COM-B
Cost of construction for lean design	**Economical**	**Opportunity – social**
Industry culture	**Social**	**Opportunity – social**
Lack of testing / industry experience	Technological	Capability - psychological
Lack of collaboration across the value chain	Social	Opportunity - social

Cost of construction for lean design

Cost is one of the most significant barriers to this measure – this was reinforced by almost all the stakeholders during the workshops, who highlighted that there is currently no financial incentive to build with less concrete, because the material cost is almost always smaller than the construction/programme implications of having to spend more time in the design phase.

For example, the technology exists to use structures such as voids and coffers, however, the cost premium from the use of more complex formwork exceeds the financial savings achieved by reducing the volume of concrete. Additionally, reinforcements for waffle slabs are difficult to prefabricate and may be slow and costly to fix.

Industry culture

A barrier identified in both the literature and stakeholder workshops was the unwillingness of practitioners to adopt unfamiliar materials in a notoriously litigious and risk-averse industry. There is a willingness to adopt new products where liability rests with another party or where innovations are seen as otherwise convenient. However, this is considered uncommon due to current contract structures and procurement routes, with one stakeholder highlighting that it can also be extremely difficult to get backing from insurance companies for structures that use novel concepts/designs. This is compounded by a reluctance to discuss failures across the industry, owing to a fear of reputational damage. As a result, learning transfer tends to be slow between firms. This barrier could be challenged if contract structures were to move away from the typical competitive tender route based solely on price.

Other Barriers

There were other barriers that were also identified through literature or raised by stakeholders, but received fewer votes of significance/engagement from stakeholders during the workshop:

- **Lack of testing / industry experience:** Similar to Measure 1, strength and durability are key factors in determining the longevity of a structure and in winning the confidence of clients and engineers within the construction sector. Because of this, proposals that contain leaner concrete structures may give rise to strength and durability concerns that cause designers/engineers to subsequently to change their designs to contain more concrete - this is common practise in the construction industry and a change in the current industry practice will be required to overcome this barrier.
- **Lack of collaboration across the value chain:** Highlighted by multiple stakeholders when discussing not just this measure but others (e.g., Measure 5), the lack of collaboration across the value chain is a barrier as cement manufacturers have little to no bearing over how their cement is used in concrete production. This makes it challenging for the cement industry to contribute to the development of leaner concrete structures. This is particularly important in the UK, which currently uses a ‘blend at concrete plant’ model – cement is typically blended with the other constituents of concrete *at* concrete blending plants, not necessarily at the cement plants. A shift away from this model could help overcome this barrier.

4.4 Levels of efficiency

Table 14: Levels of efficiency for cement & concrete Measure 4

Indicator: % reduction in concrete demand for the same unit throughput relative to 2023			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	0%	26 – 35%	5 – 15%
Evidence RAG	N/A	Amber	Red-Amber

4.4.1 Current level of efficiency

The current level of efficiency for this measure is 0% because the current level is considered the baseline against which future reductions will be made.

4.4.2 Maximum level of efficiency in 2035

The maximum level of efficiency was determined to be between 26 – 35%. A key source identified in the literature was the modelling done for the Low Carbon Concrete Routemap[92] which illustrates the potential carbon savings for various interventions across the concrete industry in the UK. The model analysis assumes that form optimisation and use of voids can offer a 20% reduction by 2035[93] and design optimisation can offer a further 15% reduction by

[92] Low Carbon Concrete Group (2022). Low Carbon Concrete Routemap.
[93] Drewniok, M. (2021). Relationships between building structural parameters and embodied carbon Part 1: Reinforced concrete floors solutions

2035.[94] This provides an overall concrete demand reduction of 32% by 2035. This assumption was also consistent with the other literature reviewed, which provided similar figures (e.g., 23% total reduction in demand possible from post-tensioning[95]).

Workshop stakeholders had less expertise in Measure 4 as the panel was weighted towards the cement industry and Measure 4 primarily concerns the concrete industry. As a result, engagement in this measure was lower compared to others. While there was expertise on the topic represented in the workshop, especially between participants who work in academia, it would be useful to validate these results with concrete experts who work in industry.

Two stakeholders voted consistently with the literature, stating that the maximum level of efficiency was between 26 – 35%. One stakeholder voted for 16 – 25% and one voted >35%. Although stakeholder engagement within the workshop was low, the robust nature of the modelling done in the literature gives an amber evidence RAG rating for this measure.

4.4.3 Business-as-usual in 2035

The business-as-usual level of efficiency was determined to be between 5 – 15%. The literature review did not aim to find evidence for the business-as-usual level of efficiency in 2035, so all data came from the workshops. Of the workshop participants who responded, three voted that the range was between 6 – 15% and one voted between 1 – 5%. However, multiple stakeholders commented that they don't believe there will be meaningful change in this measure without the proper incentives. One stakeholder disagreed, citing the desire to reduce embodied carbon as something that will likely change a business-as-usual scenario. As such, the level of efficiency was lowered slightly to 5 – 15%. There appeared to be a consensus, but the lack of participants with expertise in this area gives a red-amber evidence level in this data point.

The main barrier discussed by stakeholders in the business-as-usual scenario is economic rather than technical, as many elements of lean design are tried and tested. Whilst the business-as-usual level is higher than the current level of efficiency due to carbon reduction incentives, it is still well below the maximum technical level efficiency due to economic factors. For example, the materials are cheap compared to the construction costs to implement these designs. As a result, a clear financial incentive to use less materials is required to achieve the maximum technical level of efficiency. Cement and concrete are materials with a high level of embedded emissions, so this incentive could be driven by climate policy.

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[94] Cyrille F Dunant et al. (2021). Good early stage design decisions can halve embodied CO_2 and lower structural frames' cost.
[95] W. Shanks, et al. (2019). How much cement can we do without? Lessons from cement material flows in the UK

5.0 Measure 5 – Waste reduction in concrete manufacturing

5.1 Concrete resource efficiency measure

5.1.1 Description

Improving in-situ concrete manufacturing and use efficiency to reduce the amount of raw materials required to meet concrete demand.

Reduction of concrete construction waste is key to reducing cost and improving resource efficiency for cement. Concrete waste can include fresh concrete that is returned to a concrete plant, residues left inside concrete truck drums or mixers and hardened concrete not used for the intended application. Over-ordering of concrete is the main cause of in-situ concrete wastage.[96] In addition to over-ordering, concrete can be wasted because of planning errors requiring structural amendments or demolition.

5.1.2 Measure indicator

The indicator selected for this measure was '**percentage of concrete wasted per 100m^3 of concrete manufactured'** which is a relative measure defined as the mass of concrete that goes unused divided by the mass of concrete that is manufactured each year.

Other indicators that were identified but not selected included:

- Concrete wastage per 100m^2 and
- Concrete wastage per £100,000 of cost.

These were not selected as m^2 is not a suitable unit for a three-dimensional structure and cost fluctuates depending on multiple factors and is thus not a reliable way to measure material efficiency.

5.1.3 Examples in practice

Ready-mixed concrete

Reducing wasted concrete requires accurate calculations and estimates of material required for construction. Ready-mixed concrete is unique in that the raw materials are stored at nearby batching plants until required, then mixed for specific orders and delivered directly to site. Local ready-mixed concretes allow for additional materials to be readily available and obtained quickly, which promotes efficient ordering practices by reducing over-ordering. Under circumstances when over-ordering is likely, contractors can have a contingency plan in place for using excess concrete on site and reduce the amount ordered in the future. Ready-mixed concrete suppliers can also offer take-back schemes to reduce waste.

[96] Kazaz, A. et al (2016) Identification of waste sources in ready-mixed concrete plants, European Journal of Engineering and Natural Sciences 1, 1, 9-14

Prefabrication

Use of prefabricated elements can help reduce wastage rates onsite as they are made in a more controlled environment with greater precision than in-situ concrete. Offsite construction could facilitate a 50% reduction in waste while using 25% less energy.[97] Additionally, designers can have greater confidence using thinner parts that use material more efficiently due to the controlled environments in which they are made. Products are made to order which reduces wastage caused by product adaptation and 'just-in-time' delivery generates almost zero waste onsite due to less product damage caused by site storage and double handling. Prefabricated elements can come in the form of prefabricated formwork systems, prefabricated reinforcement cages or precast concrete.

Blockwork

Manufacturing concrete blocks is typically a low waste process, as they are essentially precast concrete of standard sizes. The highly repetitive and durable moulds result in very little waste produced during manufacture. Many concrete blocks can also be constructed from returned concrete products and other recycled materials. Take-back schemes for unused and/or damaged blocks further help to reduce waste to landfill. Additionally, wastage is thought to be lower when the product is purchased by the company installing the blockwork, unlike in 'free issue' arrangements to subcontractors.

Building information modelling (BIM)

BIM is a process for managing construction project information across its entire lifecycle that uses a digital description of every element of the building, including 3D models and production, execution and handover data. The coordination of design proposals from different consultants and suppliers can significantly improve the efficiency of the construction process. BIM can streamline operations through improved management of project data, collaboration between teams and enhanced multi-dimensional analysis of the design. Shared digital information can help consultants detect early clashes which results in more accurate measurement of materials needed and less abortive work onsite. This can help reduce over-ordering and other sources of concrete waste during the process. Additionally, early analysis can allow teams to identify more efficient building components to achieve lightweight structures.

5.2 Available sources

5.2.1 Literature review

The literature review found fifteen sources that identified waste reduction in concrete manufacturing as a resource efficiency measure, although there was little evidence on the current or future levels of resource efficiency that could be achieved through this measure. This comprised of:

[97] BuildOffsite (2013) Offsite construction: sustainability characteristics

- nine industry reports;[98] [99] [100] [101] [102] [103] [104] [105] [106]
- four academic papers;[107] [108] [109] [110]
- one technical study;[111] and
- one website article.[112]

The relevant sources were considered of high applicability and credibility when assessed against the data assessment framework, which recognises the relevance of the sources and the strength of the methodology within each. The sources exhibited an average IAS of 4.8 (out of 5), with almost all sources exhibiting a score of 4 or above. Nine of the sources were UK specific and ten of them were from 2016 or later. Overall, the literature was deemed to be applicable to the UK market. Some of the literature covered both quantitative and qualitative data while some of it covered qualitative information on the measure only.

5.2.2 Workshops

Measure 5 was amended between the workshops based on feedback from stakeholders in the pre-workshop survey. In workshop 1, Measure 5 was captured across two different measures: 'wastage of ready-mixed concrete' and 'precast of concrete frames.' Feedback from stakeholders stated that these methods were very specific ways to reduce concrete at the manufacturing stage and suggested it would be better to widen the measure to apply to all manufacturing and use efficiency techniques that improve resource efficiency. In workshop 2 the measure was broadened to include all manufacturing and use efficiency methods including building information modelling and prefabrication. The level of engagement in both workshops was as follows:

- **Workshop 1** – No measurable engagement as this measure was amended after the first workshop
- **Workshop 2** – Four stakeholders from industry were active on the mural board and three stakeholders actively contributed to verbal discussion.

[98] MPA (2010) Concrete Credentials: Sustainability
[99] MPA (2023) Concrete Quarterly (Spring 2023): Reassessing Concrete Wastage Rates
[100] Gibbons O P and Orr J J (2020) How to calculate embodied carbon
[101] Andrew Mullholland et al. - Low Carbon Conrete Group - The Green Construction Board (2022) Low Carbon Concrete Routemap
[102] MPA (2018) Material Efficiency
[103] Energy Transitions Commision (2019) Mission Possible Sectoral Focus: Cement
[104] WRAP - Dr Andrew Dunster. Partnered with BRMCA (2014) Ready-Mixed Concrete: a Resource Efficiency Action Plan
[105] BRE Group (2008) The Green Guide to Specification
[106] BuildOffsite (2013) Offsite construction: sustainability characteristics
[107] Giesekam, J., Barrett, J. R. and Taylor, P. (2016) Construction sector views on low carbon building materials
[108] W.Shanks, C.F.Dunant, Michał P. Drewniok, R.C. Lupton, A.Serrenho, Julian M. Allwood (2019) How much cement can we do without? Lessons from cement material flows in the UK
[109] Kazaz A et al (2018) Quantification of fresh ready-mix concrete waste: order and truck-mixer based planning coefficients
[110] Firehiwot Kedir, Daniel M. Hall (2021) Resource efficiency in industrialized housing construction: A systematic review of current performance and future opportunities
[111] Smith, A., WRAP, MPA British Precast (2013) Precast Concrete Resource Efficiency Action Plan
[112] Sika Group (2021) ReCO_2ver Concrete Recycling

5.3 Drivers & Barriers

The drivers and barriers influencing this measure were identified through a combination of literature review and stakeholder feedback at the workshops.

5.3.1 Drivers

Table 15 shows a list of identified drivers for waste reduction in concrete manufacturing and the most significant drivers are highlighted in bold. These drivers are discussed in further detail below.

Table 15: Drivers for cement & concrete Measure 5

Description	PESTLE	COM-B
Cost increase of cement and concrete	**Economical**	**Opportunity – social**
Client reporting requirements	**Environmental**	**Opportunity – social**
Climate policy	Environmental	Opportunity – social
Supplier takeback schemes	Technological	Capability - physical

Cost increase of cement and concrete

The cost of cement and concrete (along with many other construction materials) has already experienced an unprecedented increase in recent years due to supply chain issues and soaring energy prices arising from the Covid-19 pandemic and Russia's invasion of Ukraine. This could cause contractors to place a greater value on materials and encourage less material wastage; it may also push further investment in the use of various digital technologies. These technologies can better monitor concrete usage/waste and prevent the need for slump tests that cause additional concrete to be wasted during manufacturing; there are also additional digital technologies that can optimise building designs, or help to align the supply of over-ordered, unused concrete for other potential uses.

Client reporting requirements

Major clients are increasingly incorporating environmental considerations into their project evaluation processes, with particular interest in embodied carbon. These requirements are usually driven by increasing commitments to corporate social responsibility and decarbonisation targets. Clients require transparency from contractors on data surrounding material use and material waste to calculate accurate embodied carbon values, and client demand for embodied carbon reporting will therefore drive reductions in concrete use/wastage.

Other Drivers

- **Climate policy:** One stakeholder stated that business commitments to reduce carbon emissions is already driving change for this measure - future net-zero targets/roadmaps, coupled with the implementation of climate policies that place limits on carbon emissions, will make this a significant driver for waste reduction in concrete manufacturing in the future.

- **Supplier takeback schemes:** Ready mixed concrete suppliers can offer take back schemes for mixed concrete that would otherwise be wasted or unused during manufacturing, literature indicates that that this is already taking place in the UK to an extent[113], but a stakeholder highlighted during the workshop that further availability of the take-back schemes would help push the measure even further and would make it a much more significant driver for reducing concrete manufacturing waste.

5.3.2 Barriers

Table 16 shows a list of identified barriers to concrete manufacturing efficiency and the most significant barriers are highlighted in bold. These barriers are discussed in further detail below.

Table 16: Barriers for cement & concrete Measure 5

Description	PESTLE	COM-B
Over-ordering / cost of under-ordering	**Economical**	**Opportunity – social**
Push to construct as fast as possible	**Economical**	**Opportunity – social**
Lack of collaboration across the value chain	Social	Opportunity – social

Over-ordering / cost of under-ordering

Both stakeholders and literature indicated that there is currently no financial incentive for contractors to alter their current practice of over-ordering concrete, as the material cost is almost always smaller than the construction/programme implications of having to order more concrete after construction has already begun. The same applies for improvements to the design phase (such as BIM) - currently, poor estimations of the volumes of concrete required leads to over-ordering, with the cost premium from the use of more complex design formworks exceeding the financial savings achieved by reducing the volume of concrete used.

Push to construct as fast as possible

The extremely competitive nature of the construction industry leads to programmes that push contractors to construct as fast as possible. Stakeholders highlighted that this increases both the cement content of many concrete structures to be over that of what is required (Measure 1), and the overall volume of concrete used, due to strength and durability concerns arising from accelerated design phases. This leads to an increase in the amount of in situ concrete wastage and consequently the over-ordering of concrete. It is worth noting that this barrier is also exacerbated by the barrier: "Over-ordering / cost of underordering."

Lack of collaboration across the value chain

Highlighted by multiple stakeholders, the lack of collaboration across the value chain is a barrier to reducing waste in concrete manufacturing, as cement manufacturers have little to no bearing over how their cement is used in concrete production, or how this concrete is ultimately used. Likewise, a stakeholder stated there are other potential uses for over-ordered concrete,

[113] MPA. Concrete Credentials: Sustainability (2010). Available at: https://www.sustainableconcrete.org.uk/Sustainable-Concrete/What-is-Concrete/Ready-mixed-Concrete.aspx

but it currently very under-utilised due to a lack of incentives to make it worthwhile - greater collaboration across the value chain and incentives to do so would help to overcome this.

5.4 Levels of efficiency

Table 17: Levels of efficiency for cement & concrete Measure 5

Indicator: % concrete wasted per 100m^3 of concrete manufactured			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	2.5 – 7.5%	1 - 5%	1 - 5%
Evidence RAG	Amber-Green	Amber	Red-Amber

5.4.1 Current level of efficiency

The current level of efficiency was determined to be between 2.5 – 7.5%. Recent studies have found that overall waste from in-situ concrete is estimated to be around 5% annually,[114] ranging between 3-6% in the UK.[115] The BRE Group's Green Guide to Specification[116] uses a 2.5 – 7.5% wastage rate while WRAP's NetWaste tool uses a 5% baseline rate for in-situ wastage and suggests 2.5% is considered best practice. While the Green Guide to Specification was published in 2008, it is still in use today. The WRAP NetWaste tool ceased online support in 2021.[117]

During the workshop only two stakeholders opted to vote for the current level of efficiency, and both voted for the 1 – 5% range which is consistent with the range found in the literature. The stated current level of efficiency encompasses almost all rates found in the literature and for this reason we have indicated an amber-green evidence RAG rating for this measure.

5.4.2 Maximum level of efficiency in 2035

A 2023 study by Reusefully reviewed the wastage rates of blockwork and ready-mixed concrete and indicated that the wastage rates are 3 – 5% and 1 – 2% respectively.[118] This study involved a desktop review of existing literature, a survey of contractors and suppliers to compile waste and takeback data and interviews to gain further insight into the causes of waste. However, it is unknown what proportion of in situ waste can be saved by utilising blockwork or ready-mixed concrete, so while the wastage rates for interventions is presented in this study the overall change in wastage rate is not.

Another relevant literature source is the modelling done in the Low Carbon Concrete Routemap[119] which illustrates the potential carbon savings for various interventions across the concrete industry in the UK. This model was provided by a workshop stakeholder following the workshop. The analysis assumes that the avoidance of the use of concrete as filler between

[114] Gibbons O. P. & Orr J. J. (2020) How to calculate embodied carbon, Institution of Structural Engineers
[115] Kazaz A et al (2020) Quantification of fresh ready-mix concrete waste: order and truck-mixer based planning coefficients, International Journal of Construction Management 20, 1, 53-64.
[116] BRE Group (2008). Green Guide to Specification.
[117] WRAP (2021). WRAP's Built Environment Programme.
[118] MPA (2023). Concrete Quarterly (Spring 2023): Reassessing Concrete Wastage Rates.
[119] Low Carbon Concrete Group (2022). Low Carbon Concrete Routemap.

floor levels can offer a 3% reduction in concrete demand by 2035 and that reducing waste through use of BIM to avoid over-ordering can also offer a 3% reduction in concrete demand by 2035, providing an overall concrete wastage reduction of 6%. However, this represents a percent reduction in demand rather than the percentage of concrete wasted.

During the workshop, one stakeholder mentioned that some waste is inevitable due to losses during concrete transportation and placement so the maximum technical level of efficiency will always be above 0%. Only two workshop participants voted on this measure, and both voted for between 1 – 5% reduction in concrete demand, giving a maximum level efficiency of between 1 – 5% with an amber evidence RAG rating due to the lack of participation during the stakeholder workshops.

5.4.3 Business-as-usual in 2035

All data on the business-as-usual scenario came from the workshops. Engagement with this level of efficiency in the workshop was low, and only two workshop participants voted on this measure with both voting for between 1 – 5%. There appeared to be a consensus, but the lack of participants with expertise in this area gives a red-amber evidence RAG rating for this data point.

As in Measure 4, the main barrier discussed by stakeholders in the business-as-usual scenario is economic rather than technical, as many elements ready-mixed concrete and prefabrication are both tried and tested methods of construction. However, because the materials are so cheap there is low incentive to utilise new methods of manufacture to achieve the maximum technical level of efficiency. This explains why the business-as-usual level of efficiency is the same as the maximum technical level of efficiency. Again, this may change as climate policy drives an incentive to reduce wasted materials.

6.0 Measure 6 – Use of recycled content in concrete

6.1 Concrete resource efficiency measure

6.1.1 Description

Recycling of coarse recycled concrete aggregate (CRCA) as a substitute for raw natural aggregate in concrete production.

CRCA is a material which can be used in concrete manufacture to reduce the need for virgin aggregate in concrete production.[120] CRCA is produced by crushing construction and demolition (C&D) waste in two stages. First, significant residual reinforcement such as deformed steel bars or glass fragments, are removed by large electro-magnets. Secondly, the contaminants such as dirt and building waste are removed by screening.[121] This C&D waste contains primarily concrete alongside sand and gravel in lesser amounts. The properties of CRCA are dependent on the C&D waste quality and water requirement.[122] The CRCA replaces the natural aggregate in concrete mixtures which is subsequently used in the manufacturing process. According to the report by EnviroCentre, CRCA can only be specified as a coarse aggregate.[123] This implies that the fine aggregates which are also used in concrete manufacture cannot currently be used as substitutes for natural aggregates.

The quantities of CRCA that may be used in reinforced concrete are limited to up to 20% by mass fraction according to British Standard BS 8500.[124] However, the standard states that if 'the specification permits', a percentage greater than 20% may be used in concrete production.

This measure looks at the utilisation of CRCA as a replacement for natural aggregate in the concrete sector. The utilisation of FRCA that would provide resource efficiency benefits to the cement sector is covered in 'Measure 3 – use of concrete fines in cement or concrete production.' Note, CRCA and FRCA are both produced when concrete waste is crushed into recycled concrete aggregate. Because of this both of these measures can occur at the same time, and progress on one measure would likely drive further progress on the other as it would drive the development of RCA infrastructure and processes.

6.1.2 Measure indicator

The indicator selected for this measure was '**percentage average recycled concrete aggregate used in concrete by mass**' which is defined as 'the average mass of recycled concrete aggregate utilised' divided by 'the mass of concrete aggregate utilised each year.' There were no discarded indicators. This indicator is reported in % terms as it is consistent with the other indicators that are reported in the literature.

[120] MPA – The Concrete Centre (2020) Material Efficiency. Available at: link
[121] Marinkovic, S and Carevic, V (2019) Comparative studies of the life cycle analysis between conventional and recycled aggregate concrete. Available at: link
[122] Kirgiz, M (2022) Water requirement for recycled concrete. Available at: link
[123] EnviroCentre Ltd (2015) A report on the demolition protocol. Available at: link
[124] EnviroCentre Ltd (2015) A report on the demolition protocol. Available at: link

6.1.3 Examples in practice

Included below are descriptions of a few examples of this resource efficiency measure being put into practice.

- The Community in a Cube building located in Middlesborough was constructed using 50% CRCA in concrete as a replacement for natural aggregate.[125] This level of efficiency was achieved through utilisation of a locally available stockpile of precast units, whose quality levels were known; and
- The BRE Environmental building incorporated 40% CRCA in concrete as a replacement for natural aggregate.[126]

6.2 Available sources

6.2.1 Literature review

Nine literature sources were found which document the use of CRCA in concrete as a substitute for aggregate:

- Five technical studies;[127] [128] [129] [130] [131]
- Three academic publications;[132] [133] [134] and
- One industry report.[135]

The average IAS of the sources is 4.0, with six sources IAS 4 or higher and six sources from 2016 or more recent. Whilst the sources do discuss the topic of CRCA, there are few which provide quantifiable data points.

The quality of the sources is generally high with regards to the sector relevance. Publications are often published discussing concrete as a whole and some specialise in CRCA providing even higher relevance scores. Two of the academic publications have provided insight into descriptions of CRCA as a material and how it is made. They have also described what factors affect the final qualities of concrete.

6.2.2 Workshops

This measure was discussed in the two construction workshops, from two different viewpoints:

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[125] Post Tensioning Association (2011) Sustainable Construction with Post-Tensioned Slabs.
[126] EnviroCentre Ltd (2015) A report on the demolition protocol.
[127] The Post-Tensioning Association (2011) Sustainable Construction with Post-Tensioned Slabs.
[128] BRE (2006) The Environmental Building: A model for the 21st century.
[129] MPA The Concrete Centre (2017) Summary of Concrete Performance Indicators.
[130] EnviroCentre Ltd (2015) A report on the demolition protocol.
[131] WRAP (2021) Low Carbon & Resource Efficient Construction Procurement.
[132] Jimenez, L and Moreon, E.I (2015) Durability indicators in high absorption recycled aggregate concrete.
[133] Novakova, I and Mikulica, K (2016) Properties of Concrete with Partial Replacement of Natural Aggregate by Recycled Concrete Aggregates from Precast Production.
[134] Marinkovic, S and Carevic, V (2019) Comparative studies of the life cycle analysis between conventional and recycled aggregate concrete.
[135] MPA (2018) Material Efficiency

- In the first workshop the discussions were around the use of recycled content of all construction materials;
- In the second workshop the measure was presented as the use of recycled content for concrete specifically, so the discussion was more focused around the sector needs.

The measure received good engagement and many of the construction stakeholders provided useful insights. The level of engagement in both workshops was as follows:

- **Workshop 1** – No engagement as this measure was amended added after the first workshop.
- **Workshop 2** – Eleven stakeholders across industry and academia were active on the mural board and one stakeholder actively contributed to verbal discussion.

6.3 Drivers & Barriers

6.3.1 Barriers

Table 18 shows a list of identified drivers for the use of recycled content in concrete, the most significant drivers are highlighted in bold. These drivers are discussed in further detail below.

Table 18: Drivers for cement & concrete Measure 6

Description	PESTLE	COM-B
Client requirements for recycled content.	**Social**	**Motivation - reflective**
Aggregates levy/landfill tax.	Economic	Motivation - reflective

Client requirements for recycled content

This is related to the Measure 1 for the construction sector (see Appendix F), where one of the drivers includes clients specifying reused content in design briefs.

It was not immediately clear from stakeholders why clients are specifying greater CRCA content, and the literature does not provide this information either. It is possible that clients are specifying for CRCA as a result of guidance from bodies such as WRAP and its procurement guidance.[136] This document provides guidance on how to specify for recycled content in construction projects and what different levels of performance are related to this metric.

Aggregates levy/landfill tax

The landfill tax was also discussed as being significant, albeit to a much lesser extent than specifying for recycled content. The landfill tax represents a direct incentive for waste generators to incorporate concrete into aggregate production rather than bearing the cost of landfilling it.

[136] WRAP (2022) Low Carbon and Resource Efficient Construction Procurement. Available at: link

6.3.2 Barriers

Table 19 shows a list of identified barriers for the use of recycled content in concrete, the most significant barriers are highlighted in bold. These barriers are discussed in further detail below.

Table 19: Barriers for cement & concrete Measure 6

Description	PESTLE	COM-B
Availability of supply, and quality of the CRCA.	**Technological**	**Capability - physical**
Concrete strength is correlated to the % inclusion of recycled content in the concrete.	Technological	Capability - physical
Logistics challenges – lack of developed local distribution infrastructure.	Technological	Capability - physical
Method for demolition and separation to produce CRCA.	Technological	Capability - physical
Low cost and good availability of low carbon, natural aggregates.	Economic	Motivation - automatic
Potential for higher cement demand to compensate for aggregate quality	Environmental	Opportunity - physical
Uncertainty regarding the lifetime carbon impact of this measure	Environmental	Opportunity - physical

Availability of supply, and quality of CRCA

The market for recycled concrete is not very well established in the UK. Stakeholders identified local pockets of supply across the country, such as the supply used in the case of the Middlesborough example discussed in Section 6.1.3 Examples in practice, however, availability at an average national level is low due to a lack of concrete recycling infrastructure to produce CRCA at scale. Additionally, the technology used to segregate contaminants such as rebar from C&D waste is imperfect, leading to quality issues in the CRCA that is produced.

This lack of supply is likely driven by the need for a first mover in the CRCA market. There is limited supply because there is currently low demand for CRCA in construction project specification, and demand is limited because if there is known to be low supply, specifications will not include CRCA as a candidate material. Navigating what appears to be a stalemate will be supported by guidance, at a regional and national level, from organisations such as WRAP or the Institution of Civil Engineers. Driving this lack of demand could relate to a higher cost of production when using CRCA, although this was not verified by stakeholders in the workshops.

Recycled aggregates (RA) are already well established and used in mostly loose bound applications rather than in concrete. The MPA estimates that secondary aggregates account for 28% of the total market in the UK.[137] Using CRCA to produce concrete could impact the supple of RA that would have been used in these other applications which could require the use of virgin aggregate, thus reducing the effectiveness of this measure.

With the limited literature that discusses the use of CRCA in construction projects, it was challenging to ascertain the likelihood of these barriers being overcome. This could in part be

[137] MPA (2023), End of life recycling. Available at link

attributed to potential limitations that CRCA currently face, around maximum strength limits (discussed below). If further research is conducted into overcoming these obstacles, then it is possible there may be further demand for the material as confidence begins to grow.

Uncertainty regarding the lifetime carbon impact of this measure. There is a high degree of uncertainty in the literature relating to the actual impact of this measure on emissions and energy demand. Virgin aggregates are relatively low carbon and the process for recycling C&D waste to produce CRCA could potentially be more energy and emissions intensive than using virgin aggregate. The literature indicates that there are inconsistencies that exist in LCA processes and concrete mix which makes it difficult to compare and identify whether the use of CRCA has lifetime carbon impacts that are negative or positive.[138] The literature finds a mixture however some have estimated a negative carbon impact with one source identifying the environmental impact of using recycled aggregates to be twice as high as that of using natural aggregate.[139] It is therefore important to consider the actual environmental impact of employing this measure and work is needed to understand how best to measure this in a consistent way.

Other barriers

- **Concrete strength is correlated to the % inclusion of recycled content in the concrete:** The process of manufacturing CRCA involves the removal of contaminants such as glass or structural rebar from crushed aggregate, to improve the quality of CRCA. Stakeholders discussed the reality that often contaminants are not fully removed from the crushed aggregate, and as a result buyers are weary of utilising CRCA due to the perceived quality risk. Glass is identified as a material which, if present in concrete as a contaminant, will reduce the compressive and tensile strengths of concrete.[140] The reduction in strengths is driven by its irregular strength and poor surface characteristics. During the workshop, stakeholders commented that there could be no guarantee of performance now or in 2035, which leads to a limited market and low incentive to produce CRCA for concrete applications.

- **Logistics challenges – lack of developed local distribution infrastructure:** Reasons for limited supply could also be driven by the lack of capability to store the materials at distribution sites. Without a coordinated regional supply network, there will be limited uptake at a national level and use of CRCA will remain to be seen only at a much more local network.

[138] Xing et, al. (2022). Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review. Construction and Building Materials 317(11):125950. Available at link
[139] Park et, al. (2019). Analysis of Life Cycle Environmental Impact of Recycled Aggregate. *New Trends in Recycled Aggregate Concrete*. Available at link
[140] Poon, C-S and Chan, D (2007) Effects of contaminants on the properties of concrete paving blocks prepared with recycled concrete aggregates. Available at: link

6.4 Levels of efficiency

Table 20: Levels of efficiency for cement & concrete Measure 6

Indicator: % average recycled concrete aggregate used in concrete, by mass			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	0-5%	20-50%	0-5%
Evidence RAG	Red-Amber	Red-Amber	Red-Amber

6.4.1 Current level of efficiency

The current level of efficiency was determined to fall between 0 – 5%. Quantitative data on the current level of efficiency for this measure was not found in the literature. One workshop participant stated that at a national level, reflective of the scope of this measure, average levels of efficiency were very low at approximately 1%. However, where local supply was available, such as for a Middlesborough construction project identified in the literature which had a 50% inclusion of CRCA,[141] this can lead to a much higher CRCA level of efficiency. One stakeholder also mentioned that 20% CRCA inclusion had been achieved in Spain, for a structural concrete project, supporting this view.

Participants in the workshop all voted that the current level of efficiency is in the 0-5% range. However, <50% of participants voted on this measure. With the voting consistently in the 0-5% category, this was the reported range for current levels of efficiency. However, there was very little literature to corroborate this reported range. As such, a red-amber evidence RAG rating was assigned.

6.4.2 Maximum level of efficiency

The maximum level of efficiency was determined to fall between 20 – 50%. A technical study by the Post Tensioning Association states that 20% inclusion of CRCA in 2035 is achievable, further inclusion of CRCA is possible, but with 'further considerations'.[142] It is not stated what these considerations are or how much higher the level of efficiency can go when accounting for said considerations. The 20% maximum is gleaned from the BS8500 standard, which covers the use of recycled and secondary aggregates and is consistent with the findings in the Post Tensioning Association report.[143]

There is one academic journal publication which states that, on a lab scale, a maximum 50% level of efficiency is achievable.[144] The technical limiting factor prohibiting a further increase of recycled concrete aggregate was the increase of porosity, sorptivity and permeability which reduces the concretes resistance to environmental loads. This 50% level is consistent with the level achieved already in the Middlesborough concrete project and build consensus that 50% is the maximum technical level of efficiency for this measure.

[141] Post Tensioning Association (2011) Sustainable Construction with Post-Tensioned Slabs. Available at: link
[142] Post Tensioning Association (2011) Sustainable Construction with Post-Tensioned Slabs. Available at: link
[143] EnviroCentre Ltd (2015) A report on the demolition protocol. Available at: link
[144] Jimenez, L and Moreon, E.I (2015) Durability indicators in high absorption recycled aggregate concrete. Available at: link

Workshop voting gave a value of 0 – 5% for the maximum technical level of efficiency in 2035. However, this was 2 votes out of a total of 4 on this measure. The lowest voting range was 0 – 5% with one vote cast in the >25% category and one vote in the 16 – 20% range.

Two comments, not votes, did support that 20% replacement should be technically possible but is not currently achieved as the average rate across the sector. Others suggested that levels of 50% and 100% are technically possible. These comments clearly did not correlate to voting in the workshop. One stakeholder also mentioned the BRE Environmental building, stating it had a very high level of CRCA. Upon further investigation it appears that the stakeholder may have been referring to the recycled aggregate inclusion in non-structural concrete elements such as road sub-base which is often higher and was found to be 90%.[145] In fact, another source stated that the BRE environmental building achieved a 40% replacement of coarse aggregate by CRCA.[146]

Tying the data together, there is a complicated picture on maximum levels of efficiency for this measure. A rate of 50% has already been achieved in a case study in Middlesborough and shown to be technically possible on a lab scale. Furthermore, the BRE Environmental building was able to achieve a 40% level of efficiency. However, the standards currently defining use of CRCA limit its use to 20%. As such, a range of maximum technical level of efficiency will be defined for this measure, at 20-50%. The evidence RAG rating for this measure is classified as red-amber given the high diversity of opinions that was observed and the lack of corroboration from stakeholders.

6.4.3 Business-as-usual in 2035

The business-as-usual level of efficiency was determined to be between 0 – 5%. Four participants cast votes to predict the business-as-usual level of efficiency in 2035. The most votes received was in the 0 – 5% category.

This level of efficiency is much lower than the maximum efficiency and is the same as the current level of efficiency. This is potentially driven by the difficulty of extracting CRCA from C&D waste and concerns raised over whether use of CRCA was always a pragmatic choice for construction projects due to concerns over strength. Stakeholders suggested that, from a carbon perspective, CRCA involves impacts which may lead to a high embodied carbon level. The crushing and potentially high transportation distances are two areas raised by stakeholders which may lead to higher embodied carbon levels. This may be a further barrier to seeing increased CRCA levels of efficiency. However, no studies were found that quantified what this difference would be. Furthermore, there is no quantification of what the carbon benefit is from the recycled content.

The evidence RAG rating is classified as red-amber due to the limited stakeholder participation.

As previously mentioned, it is unclear from the literature what the lifetime carbon impact of this measure is, and there is a possibility that it could have a negative impact on emissions. It is vital that more is done to understand how best to identify this in a consistent way.

[145] BRE (2006) The Environmental Building. Available at: link
[146] EnviroCentre Ltd (2015) A report on the demolition protocol. Available at: link

7.0 Interdependencies

This report has discussed each of the measures identified for the cement and concrete sector and presented estimates for the maximum and BAU level of efficiency they could achieve independently, that is, not considering any interdependencies or interactions between measures.

However, in practice these measures are likely to occur in tandem, and the levels of efficiency that are reached in each will depend on progress against other measures. The precise nature of these interdependencies should be considered when using any of the level of efficiency estimates from this report in further research or modelling exercises that attempt to produce an estimate of the cumulative impact of these measures over time.

A summary of the key interactions/interdependencies between the measures in this report with other measures in the sector, and with measures in other sectors is presented below. Note, as Phase 2 of this research project is still in the fieldwork stage, the dependencies with other sectors reflect dependencies with other Phase 1 sectors only. The Phase 2 reports will seek to capture any further interdependencies with Phase 2 sectors.

Note, the estimates for the current level of efficiency will by their nature reflect the interactions and interdependencies between measures as they currently occur.

7.1 Interdependencies within the sector

Measures 1 & 3

- Measure 1 – Portland cement (CEM I) intensity in concrete
- Measure 3 - Use of recycled concrete fines in cement or concrete production

The use of recycled concrete fines as filler in cement may make it possible to use less cement overall in concrete products while achieving the same level of strength. Although the low reactivity of recycled concrete powder makes it less suitable to use as an SCM, the small amount of cementitious activity suggests that its use may enhance the performance of concrete produced using this material.

Measures 1 & 4

- Measure 1 – Portland cement (CEM I) intensity in concrete
- Measure 4 - Lean design of concrete structures

Concretes containing SCMs will often have a slower strength gain than concrete with a lower proportion of additions. As a result, SCMs are utilised less frequently in certain concrete structures such as post-tensioned slabs due to its effect on setting time. However, it may be possible to use an accelerating admixture to improve the setting time of these concretes. Additionally, designers can be aware that even when a larger proportion of cement is needed for higher-strength concrete, in some cases this can reduce the amount of cement used overall as a smaller volume of concrete may be required. Alternatively, superplasticiser admixtures may reduce the cement content while achieving the same strength by reducing the water in the mixture.

Measures 1 & 5

- Measure 1 – Portland cement (CEM I) intensity in concrete
- Measure 5 – Waste reduction in concrete manufacturing

The use of prefabricated concrete elements can help reduce wastage rates onsite as they are made in a more controlled environment than in-situ concrete. However, precast elements can utilise larger quantities of cement owing to the need for rapid demoulding and factory efficiency. As such, a compromise between the speed of production and the use of precast elements must be found to avoid negating the resource efficiency benefits.

Measures 3 & 6

- Measure 3 – Use of recycled concrete fines in cement or concrete production
- Measure 6 – Use of recycled content in concrete

Both Measures 3 and 6 relate to the use of recycled concrete aggregate (RCA), with Measure 3 using fine recycled concrete aggregate (FRCA), and Measure 6 using coarse recycled concrete aggregate (CRCA). Because of this both measures are dependant on the growth of RCA process and infrastructure, and progress in one measure is likely to drive progress in the other.

Measures 4 & 5

- Measure 4 - Lean design of concrete structures
- Measure 5 - Waste reduction in concrete manufacturing

Designers have a wide variety of structural frame options to choose from that may offer resource efficiency savings. Offsite construction of prefabricated elements allows for greater precision and control over structure production, giving designers greater confidence in using thinner parts and sculpted elements that would otherwise not be practical to form in-situ.

7.2 Interdependencies with other sectors

Construction

Due to the primary application of cement and concrete being construction, all the resource efficiency measures are linked to the construction sector. Specifically, while the Unlocking Resource Efficiency: Phase 1 Construction Report looks at resource efficiency measures across all building materials, this report looks at how these materials are impacted on a more granular level. For example, concrete Measure 4 (lean design of concrete structures) is a targeted study of Measure 3 (reduction of over-design and delivery in building structures) focused on concrete specifically.

Agriculture

- Measure 2 – Portland cement (CEM I) manufacturing waste recovered as raw material

The remaining CKD that is not recovered as raw material for cement manufacturing is often sent offsite and applied to agricultural land as a means of stabilising and raising soil pH in acidic soils as an agricultural liming substitute or as a fertilising agent. Improvements in efficiency in Measure 2 decreases the availability of CKD used elsewhere, which may in turn place greater demand on alternative sources of equivalent materials.

Steel

- Measure 1 – Portland cement (CEM I) intensity in concrete

GGBS is a by-product of iron production and has been used for many years as an SCM. However, the availability of GGBS is expected to decline as the steel industry decarbonises and moves towards using electric arc furnaces in a process that does not produce GGBS as a by-product. As a result, the decarbonisation of the steel industry will have a negative impact on the potential for GGBS to be utilised as an SCM to reduce the intensity of CEM I in concrete.

Coal

- Measure 1 – Portland cement (CEM I) intensity in concrete

PFA is another SCM (though not currently widely used in the UK). PFA is a by-product of electricity generation from coal, and so its availability is expected to decrease as the country moves away from coal-fired power stations.

Waste Management

The cement and concrete/construction sectors generate significant waste, including unused concrete and C&D waste. Resource efficiency practices promote waste reduction, recycling and reuse. This creates opportunities for waste management and recycling industries to collaborate with cement and concrete manufacturers to develop innovative recycling technologies, establish recycling facilities and provide solutions for utilising waste materials as alternative resources. Additionally, resource efficiency improvements that limit the generation of waste impact the size and composition of waste flows dealt with by waste management companies.

Glossary and abbreviations

AACM	Alkali-Activated cementitious materials
BAU	Business-as-usual
BIM	Building information modelling
C&D	Construction and demolition
CCUS	Carbon capture, utilisation and storage
CKD	Cement kiln dust
CRCA	Coarse recycled concrete aggregate
FRCA	Fine recycled concrete aggregate
GCCA	Global Cement and Concrete Association
GGBS	Ground granulated blast furnace slag
IAS	Indicative applicability score
MPA	Mineral Products AssociationPFA Pulverised fly ash
RE	Resource efficiency
SCM	Supplementary cementitious material
TMS	Target mean strength

Appendix A: IAS Scoring Parameters

Table 21: IAS Scoring Parameters

Criteria	High	Medium	Low
Geography	Specific to UK	Non-UK but applicable to the UK	Non-UK and not applicable to the UK
Date of publication	< 10 years	10 to 20 years	> 20 years
Sector applicability	Sector and measure-specific, discusses RE and circularity	Sector and measure-specific, focus on decarbonisation	Cross-sector
Methodology	Research methodology well defined and deemed appropriate	Research methodology well defined but not deemed appropriate / Minor description of research methodology	No research methodology
Peer Review	Explicitly mentioned peer review	Not explicitly mentioned, but assumed to have been peer reviewed	Unknown

Appendix B: Search strings

- (cement OR concrete) AND (low carbon OR decarbon*)
- cement AND alternative binding material*
- cement AND (circular economy OR circular*)
- cement AND clinker substitute*
- cement AND (clinker ratio OR clinker product*)
- cement AND (coal fly ash OR blast furnace slag OR slag)
- cement AND pulverised fuel ash
- cement AND lightweight*
- cement AND longevity
- cement AND material efficiency
- cement AND material substitution
- cement AND (post tension* OR post-tension*)
- cement AND (post tension* OR post-tension*) AND resource efficiency
- cement AND (precast OR pre-cast)
- cement AND (precast OR pre-cast) AND resource efficiency
- cement AND raw material AND efficiency
- cement AND (recycl* OR waste recycle*)
- cement AND reduction AND content AND concrete
- cement AND resource efficiency
- cement AND resource efficiency AND barriers OR challenge
- cement AND resource efficiency AND drivers
- cement AND resource efficiency AND UK
- cement AND silica fume
- cement AND sustainability
- cement AND use AND efficiency measures
- cement AND (waste reduction OR waste minimisation)
- (cement kiln dust OR CKD) AND (reduction OR recycl*)

- cement production AND (recycling OR waste recycle*)
- concrete AND binder intensity
- limestone mining AND (recycle* OR waste recycle* OR waste reduction)
- supplementary cement* material OR clinker subst*
- use AND recycl* concrete fine*

Appendix C: Literature sources

Table 22 below lists the literature sources for the cement & concrete sector. Sources with an (*) are related to Measure 1, which is the measure with the highest number of sources (47 out of 91).

Table 22: List of literature sources for the cement and concrete sector

Title	URL	Author	Year	IAS
*2050 Carbon Neutrality Roadmap	link	Cembureau	2020	4
*A blueprint for a climate friendly cement industry	link	WWF	2008	4
A Review on Cement Kiln Dust (CKD), Improvement and Green Sustainable Applications	link	Saleh, H.J., Faheim, A.A., Salman, A.A., El Sayed, A.M.	2021	3
*Alternative cement clinkers	link	Gartner & Sui	2016	5
*Alternative Cement substitutes materials	link	Constro Facilitator	2019	3
Alternative Raw Materials Study	link	Cembureau	n.d.	3
An investigation on the recycling of hydrated cement from concrete demolition waste	link	D. Gastaldi, F. Canonico, L. Capelli, L. Buzzi, E. Boccaleri, S. Irico	2015	5
*Cement and Concrete Research: Material Performance Lessons	link	Arnon Bentur and Denis Mitchell	2007	4
*Cement and Types of Cement Used in Construction	link	Muyiwa Ajumobi	2020	3
*Cement Fact Sheet 12: Novel cements: low energy, low carbon cements	link	MPA	n.d.	4
*Cement Industry Energy and CO_2 Performance. Getting the Numbers Right (GNR)	link	wbcsd	2017	4
Cement Kiln Dust (CKD): Potential Beneficial Applications and Eco-Sustainable Solutions	link	Ali Albakri	2022	3
*Cement substitution by a combination of metakaolin and limestone.	link	Antoni, M., Rossen, J., Martirena, F., Scrivener, K.	2012	5
*Circular Economy strategies for concrete: implementation and integration	link	Alastair T.M. Marsh, Anne P.M. Velenturf, Susan A. Bernal	2022	5

Title	URL	Author	Year	IAS
*Clinker substitutes	link	Global Cement and Concrete Association	n.d.	3
*Clinker Substitution	link	The European Cement Association	2018	3
Comparison of embodied carbon in concrete structural systems	link	MPA	2022	5
Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors	link	López-Mesa, B., Pitarch, A., Tomas, A., Gallego, T.	2009	5
Complete re-utilization of waste concretes–Valorisation pathways and research needs	link	Yury A. Villagrán-Zaccardi a e, Alastair T.M. Marsh b, María E. Sosa c e, Claudio J. Zega d e, Nele De Belie a, Susan A. Bernal	2022	5
Concrete Credentials: Sustainability	link	MPA	2010	4
*Concrete Industry Sustainability Performance Report 2019	link	MPA	2019	3
Concrete Quarterly (Spring 2023): Reassessing Concrete Wastage Rates	link	MPA	2023	5
*Concrete Quarterly Application: Collected Technical Articles 2020-21	link	MPA	2020	5
Concrete Quarterly, summer 2019: Return of the Rib	link	MPA	2019	5
*Concrete Quarterly: spring 2022	link	MPA	2022	5
Concrete Recycling Positioning Paper	link	Cembureau	n.d.	3
*Construction sector views on low carbon building materials	link	Giesekam, J., Barrett, J. R. and Taylor, P.	2016	5
*Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry	link	Scrivener, K. L., John, V. M. and Gartner, E. M	2018	5
Environmental impact assessment of post tensioned and reinforced concrete slab	link	Miller, D., Doh, J., Guan, H., Mulvey, M., Fragomeni, S., McCarthy, T., Peters, T.	2013	5
*Evaluating Biomass Ash Properties as Influenced by Feedstock and Thermal Conversion Technology towards Cement Clinker Production with a Lower Carbon Footprint	link	Tosti, L. et al.	2021	5

Title	URL	Author	Year	IAS
Everything you need to know about Cement Kiln Dust Generation and Management	link	Garth J. Hawkins, Javed I. Bhatty, and Andrew T. O'Hare	2003	1
Fines extracted from recycled concrete as alternative raw material for Portland cement clinker production	link	Joris Schoon, Klaartje De Buysser, Isabel Van Driessche, Nele De Belie	2015	3
*Fly Ash and Blast Furnace Slag for Cement Manufacturing	link	BEIS (Sacha Alberici, Jeroen de Beer, Irina van der Hoorn, Maarten Staats)	2017	5
*Future trends for PFA in cementitious systems	link	Dr Lindon K A Sear, UKQAA	2011	3
Good early stage design decisions can halve embodied CO_2 and lower structural frames' cost	link	Cyrille F. Dunant, Michał P. Drewniok, John J. Orr, Julian M. Allwood	2021	5
High tension: An introduction to specifying post-tensioned slabs	link	MPA, the Concrete Centre	2020	3
*How much cement can we do without? Lessons from cement material flows in the UK	link	W.Shanks, C.F.Dunant, Michał P. Drewniok, R.C. Lupton, A.Serrenho, Julian M. Allwood	2019	5
How to calculate embodied carbon	link	Gibbons O P and Orr J J	2020	5
*IEA Report - Cement	link	International Energy Assoication	2022	3
Kiln Dusts - Material Description	link	Recycled materials resource center	n.d.	1
*Laying the foundation for zero-carbon cement	link	Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers	2020	3
*Low Carbon Concrete Routemap	link	Andrew Mullholland et al. - Low Carbon Conrete Group - The Green Construction Board	2022	5
*Low Carbon Concrete Technologies. Understanding & Implementation. Second revision	link	Hibbert, A. F., Cullen, J. M., Drewniok, M. P.	2022	5
*Low-carbon concrete: separating greenwash from reality	link	Kristina Smith	2023	3
*Making cement manufacturing more efficient	link	GCP Applied Technologies	2019	3
Material Efficiency	link	MPA	2018	5

Title	URL	Author	Year	IAS
*Minimum cement content requirements: A must or a myth?	link	Wasserman, R.	2009	5
*Mission Possible Sectoral Focus: Cement	link	Energy Transitions Commision	2019	5
*Net Zero: In a Binder	link	Industry Tracker	2022	5
*Options for the future of cement	link	Scrivener	2014	5
*Performance Indicators - Resource Efficiency	link	Sustainable Concrete	2019	3
Portland Cement Production from Fine Fractions of Concrete Waste	link	Zhutovsky, Shishkin - Israel Institute of Technology	2020	4
Post Tension Slab	link	ConstructionOR	2021	3
Post Tensioning Benefits for Developers	link	Post Tensioning Association	2018	3
Post-tensioned Concrete Floors	link	MPA	2017	5
Precast concrete flooring	link	Bison Precast Ltd.	2007	4
Precast Concrete Resource Efficiency Action Plan	link	Smith, A., WRAP, MPA British Precast	2013	5
*Properties of activated blended cement containing high content of calcined clay	link	Mwiti, M. J., Karanja, T. J. and Muthengia, W. J.	2018	5
Quantification of fresh ready-mix concrete waste: order and truck-mixer based planning coefficients	link	Kazaz A et al	2018	5
Quantification of Residual Unhydrated Cement Content in Cement Pastes as a Potential for Recovery	link	Daniele Kulisch, Amnon Katz and Semion Zhutovsky	2023	5
Ready-Mixed Concrete: a Resource Efficiency Action Plan	link	WRAP - Dr Andrew Dunster. Partnered with BRMCA	2014	5
ReCO_2ver Concrete Recycling	link	Sika Group	2021	3
Recycling concrete	link	Cembureau	n.d.	3
Recycling of Cement Kiln Dust as a Raw Material for Cement	link	Minhye Seo,Soo-Young Lee,Chul Lee andSung-Su Cho	2019	3

Title	URL	Author	Year	IAS
Recycling of End of Life Concrete Fines into Hardened Cement and Clean Sand	link	Somayeh Lotfi, Peter Rem	2016	5
Relationships between building structural parameters and embodied carbon Part 1: Reinforced concrete floors solutions	link	Drewniok, M.	2021	5
Report to Congress on Cement Kiln Dust: Alternative CKD Managment	link	US EPA	1993	1
*Resource Efficiency and Lifetime Emissions	N/A	MPA	2022	3
Resource efficiency in industrialized housing construction: A systematic review of current performance and future opportunities	link	Firehiwot Kedir, Daniel M. Hall	2021	5
*Resource Efficiency: Additional Cementitious Materials	link	Sustainable Concrete, The concrete Centre	2019	3
*Rethinking Cement	link	Michael Lord	2017	3
Role of recycled concrete powder as sand replacement in the properties of cement mortar	link	Yuan Jiang, Bo Li, Shu Liu, Jun He, Alvaro Garcia Hernandez	2022	5
*Should Minimum Cementitious Contents for Concrete Be Specified?	link	Karthik H. Obla, Rongjin Hong, Colin L. Lobo, and Haejin Kim	2017	5
*Silica Fume Concrete: Properties, Advantages and Applications	link	The Constructor - Building Ideas	2021	3
*Slag Substitution as a Cementing Material in Concrete: Mechanical, Physical and Environmental Properties	link	María Eugenia Parron-Rubio, Francisca Perez-Garcia, Antonio Gonzalez-Herrera, Miguel José Oliveira, and Maria Dolores Rubio-Cintas	2019	5
*State-of-the-Art Report on Use of Limestone in Cements at Levels of up to 15 %	link	Tennis, P. D., Thomas, M. D. A. and Weiss, W. J.	2011	5
Sustainability	link	MPA	2021	5

Title	URL	Author	Year	IAS
Sustainable Construction with Post-Tensioned Slabs	link	The Post-Tensioning Association	2011	4
*Sustainable infrastructure development through use of calcined excavated waste clay as a supplementary cementitious material.	link	Zhou, D., Wang, R., Tyrer, M., Wong, H., Cheeseman, C	2017	5
*Sustainable Materials: With Both Eyes Open	link	Allwood J.M. & Cullen, J. M.	2012	4
*Technical and environmental performance of lower carbon footprint cement mortars containing biomass fly ash as a secondary cementitious material	link	Tosti, L., van Zomeren, A., Pels, J. R., Comans, R. N.J	2018	5
*Technical Summary: Alternative Cement	link	Jay H. Arehart, Delton Chen; Senior Fellows: Ryan F. Allard, Tala Daya; Senior Director: Chad Frischmann	2018	4
*Technology Roadmap - Low-Carbon Transition in the Cement Industry	link	International Energy Assoication & Cement Sustainibilty Initiative	2018	4
The Cement Sustainability Initiative - Recycling Concrete	link	WBCSD	2009	4
*The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete	link	GCCA	2020	4
The Green Guide to Specification	link	BRE Group	2008	5
*UK Concrete and Cement Industry Roadmap to Beyond Net Zero	link	MPA	2020	5
Use of recycled aggregates for cement production	link	Trauchessec, R., Krour, H., Diliberto, C., Lecomte, A.	2019	3
Value added recycling routes for CKD - summary	link	Engineering and Physical Science Research Council	1998	1
Waste management solutions by the cement industry	link	World Business Council for Sustainable Development	2014	3

Appendix D: List of discarded measures

During the literature review, several measures were discarded due to several reasons, such as overlaps in the definition, or outside of the agreed scope (e.g., relating to energy efficiency such as kiln fuel substitution as well as carbon capture, usage and storage). These discarded measures are listed below alongside the reason for exclusion.

Table 23: List of discarded resource efficiency measures for the cement & concrete sector

Theme	Sub-theme	Measure name	Measure indicator	Reason for De-prioritisation
Use	Waste reduction upon assembly	Product durability - improved curing methods	average % reduction in sorptivity (k(m3/(m2s1/2)) × 10–2) after 28 days	Concrete is durability is included in the construction sector, removed to prevent overlap
Design	Material substitution	Kiln fuel substitution - waste derived fuels	% of thermal energy required for cement manufacture % of primary fuel substituted	Outside of scope – alternate fuels are primarily an energy measure, not an RE measure
Design	Process Control	Carbon capture and storage/sequestration	$MtCO_2$ saved / year	Outside of scope – CCUS is primarily a decarbonisation measure, not an RE measure
Design	Material substitution	Use of cement additives to enable clinker substitution	Percentage point increase in clinker substitute use	Included as an enabler of Measure 1
Use	Waste reduction upon assembly	Reduction in self-mixing on site, to provide properly mixed products which will have superior strength for the same use of concrete	Not specified	Included as an example in practice of Measure 5
Design	Light weighting	Reduction of cement required for concrete production through carbon curing.	Not specified	Out of scope – primarily a decarbonisation measure

Appendix E: Cement grades and standards

There are six grades of cement, which are each defined by its proportion of Portland cement and any addition content. The types of cement are:

- CEM I Portland Cement – 95% -100% Portland cement
- CEM II Portland Composite Cement – maximum additive content of 35%
- CEM III Blast Furnace Cement – maximum blast furnace slag content of 95%
- CEM IV Pozzolanic Cement – maximum addition content 55% (mixture of silica fume, pozzolans, fly ash)
- CEM V Composite Cement – maximum addition content 80% (blast furnace slag and pozzolan or fly ash)
- CEM VI Composite Cement – maximum addition content 65%

Standards are used widely in the UK as a compliance requirement for the construction regulations and to ensure performance of materials and structures. The most widely accepted technologies in the UK are typically included in the British Standards (BS) and British Standards incorporating a European Standard (BS EN). A list of relevant UK standards and guidance for concrete can be found below:

- BS 8500:2019 Concrete – Complementary British Standard to BS EN 206
- BS EN 1992:2004 Eurocode 2, Design of concrete structures
- BS EN 197-1:2011 Cement – Composition, specifications and conformity criteria for common cements
- BS EN 197-5:2021 Cement – Portland-composite cement CEM II/C-M and composite cement CEM VI
- BS EN 206:2013+A1:2016 Concrete – Specification, performance, production and conformity
- PAS 8820:2016 Construction materials – Alkali-activated cementitious material (AACM) and concrete specification

Appendix F: List of construction measures

#	Stage	Sub-theme	Measure name	Measure indicator
1	Design	Use of secondary raw materials	Use of reused content in buildings	% reused content used in building by mass
2	Design	Material substitution	Use of materials substitution for embodied carbon reduction across the whole lifecycle	% CO_2 reduction in whole life carbon for the entire lifecycle associated with material substitution
3	Design	Light-weighting	Reduction of over-design & delivery in building structures	% reduction in material mass in construction
4	Manufacture and Assembly	Reduction in production wastes	Reduction of construction process wastage	% of total construction materials wasted by mass
5	Use	Lifetime extension	Reducing need for primary material production by building lifetime extension	% new builds avoided by repair/refurbishment of the existing building stock
6	End of Life	Recycling and Reuse	Reuse / recycling of building materials	% of C&D waste recovered for reuse / recycling

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