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Evaluating technology options to mitigate greenhouse gas emissions

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International Standards and Testing for Novel CO_2-Containing Building Materials

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IEA GREENHOUSE GAS R&D PROGRAMME

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About IEAGHG

Blazing the way to net zero with leading CCS research. *We advance technology to accelerate project development & deployment.*

We are at the forefront of cutting-edge carbon, capture and storage (CCS) research. We advance technology that reduces carbon emissions and accelerates the deployment of CCS projects by improving processes, reducing costs, and overcoming barriers. Our authoritative research is peer-reviewed and widely used by governments and industry worldwide. As CCS technology specialists, we regularly input to organisations such as the IPCC and UNFCCC, contributing to the global net-zero transition.

About the IEA

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate is twofold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy. The IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics.

International Standards and Testing for Novel CO_2-Containing Building Materials

Part I – Review of Standards,

Part II – Market Entry of CO_2-Containing Materials into Construction Industry (including methods for certifying and measuring embodied carbon in carbonated building materials)

(IEA/CON/22/291)

Over 4 billion tonnes of cement are produced each year, equating to approximately 8% of global anthropogenic CO_2 emissions, and this industry will continue to grow with the expansion of the built environment at a time that emissions need to be reduced. The utilisation or reduction of CO_2 within cement, concrete and building materials could be a valuable way to contribute to emissions reductions in the sector[1], but there are several barriers, including the current state of standards, regulations and policies. This study will provide useful information for the technical and research community, the CCUS industry, the construction industry, and policymakers, providing an unbiased and non-prescriptive evaluation of international standards and testing relevant to novel carbonaceous building materials to address some of those barriers. The market potential for CO_2 utilisation processes in the construction industry is also investigated, and the methods for certifying and measuring embodied carbon content of carbonated building materials is evaluated and the challenges therein.

Key Messages

- Over the past two decades an increasing number of companies have emerged with a focus on developing innovative materials that utilise CO_2 to lower the carbon emissions intensity of construction products.
- Climate change is an extremely important priority throughout the building materials industry, with CO_2 intensity or other measures being increasingly common to be part of tendering processes and shareholder pressure to decarbonise an important factor. However, safety and testing is seen as vital to maintain high standards.
- Developing confidence in new materials is likely to be achieved by using them first in non-safety critical operations (e.g. retaining walls).
- Knowledge sharing across industries and countries is important, particularly as the main growth area will be in emerging nations rather than developed countries.
- Support in terms of legislation and tax credits is important from governments to deploy new materials, cases where this is happening include New York and New Jersey.
- Performance based standards are preferable but take longer to develop and it is a challenge to include every possible combination of materials in a performance-based standard. A transition to performance-based specifications will require the development of rapid and reliable (appropriate) performance test methods. Some test methods need to be altered for new materials.
- Effort, time and funding is required to speed up the currently slow drift from mainly prescriptive to performance-based standards that are needed. The work of experts on both the RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) and BSI (British Standards Institution) Flex committees to develop performance-based standards for novel cements is an example of ongoing work in this area.

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[1] The Royal Institute of International Affairs (2018), '**Making Concrete Change Innovation in Low-carbon Cement and Concrete**'. Chatham House Report, June 2018 [*Online*]. Available at: https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf

- Comparing specifications for cements or concrete between international standards is difficult because cement types are defined using different criteria either using end-use requirements or composition.
- Within the same overarching standard there are large differences in values between countries, because they can set limits on specific properties when specifying the same material property (e.g. compressive strength) for a material exposed to a particular set of conditions.
- The number of potential new supplementary cementitious materials (SCM) is much larger than those currently permitted in existing standards. The need for consensus for new SCMs to enter the standard may hinder the adoption and exploration of locally available materials, which is important considering resources of traditional SCMs like coal fly ash have declining availability.
- The aggregate market is estimated to currently be 46Gt per year. Recycled aggregates and those produced as industrial by products, including those utilising CO_2 in production are becoming prevalent.
- Other ways to use CO_2 in the production of building products include:
    - Accelerated CO_2 curing of concrete,
    - Use of alternative cement chemistry produced using CO_2.
- Some material such as carbonated concrete slurry waste can act in a complex manner within cement, allowing reduction of the total amount of cement clinker. There is a large potential resource of concrete slurry waste and it could be profitably used.
- There is a significant potential market for carbonatable materials, but lifecycle emissions and commercial factors could potentially reduce CO_2 savings and the total market available.
- An analysis of the CO_2 capture potential of industrial by-products from five industrial sectors found that up to 0.56 Gt of CO_2 emissions could be captured by 3.6 Gt of carbonatable materials each year using CO_2 mineralisation
- Emissions reductions for the substitution of other materials could save between 0.01 and 0.49 $kgCO_2$ - eq per kg material substituted. The greatest reduction occurs with the use of carbonated lightweight aggregate,
- It is strongly suggested that “low carbon” terminology be significantly better classified in the production of building products.

Background to the Study

Decarbonising the economy through carbon capture, utilisation and storage (CCUS) relies not only on viable methods to capture carbon dioxide (CO_2) but also efficient utilisation and / or storage of that CO_2. In some instances, (e.g. where large transport distances are required, or for countries which do not have large geological storage resources) utilising the captured CO_2, or carbon capture and utilisation (CCU), may be the most effective way to decarbonise rather than transporting to a storage site. CCU also provides additional revenue streams and allays any public perceptions issues associated with underground storage.

A large, and potentially near-term, market for carbon utilisation is the incorporation of CO_2 into carbonaceous building materials. The production of aggregates can use CO_2, energy and waste material and use waste carbonation to convert it to building aggregates. Concrete curing can use CO_2 and cement or aggregates, and using carbonation during the concrete mixing can output CO_2-cured concrete. Methods to develop alternative cements, build synthetic aggregates, or cure concrete can all utilise CO_2 and produce greenhouse gas (GHG) reductions within a product’s lifecycle assessment (LCA). The recent IEAGHG study, ‘From Carbon Dioxide to Building Materials – Improving Process Efficiency’[2],

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[2] IEAGHG (2022), ‘**From Carbon Dioxide to Building Materials – Improving Process Efficiency**’. March 2022, IEAGHG Technical Report 2022-04.

looks into the effects of carbonation on material utilisation, the design of a potential typical carbonation plant, and undertook a market analysis of carbonated building products, providing a valuable insight on how captured CO_2 can be used in building materials.

Each major improvement to cement chemistry or new incremental change to concrete formulation will face the eventual hurdle of navigating construction standards and testing. Different countries will have different standards and testing protocols that must be considered and followed to ensure compliance within certain chemical and physical limits; in the UK there are British Standards (BS), the International Organization for Standardization (ISO) have several relevant standards; the European EN standards and the United States conform to various standards from the American Society for Testing and Materials (ASTM). Within the US in particular, construction industry standards are often difficult to change and can take years for new entrants to gain approval. In addition, standards are prescriptive rather than performance based. This results in standards defining the composition of materials such as Ordinary Portland Cement (OPC) which the industry has established for decades. The value of novel materials like quicker curing periods, improved tensile strength, or greater compressive strength are not captured in these conventional systems. The IEA agrees that in particular for concrete products, trials and updating of product standards may be required to support broader deployment[3].

The purpose of this study is to perform a comprehensive evaluation and comparison of international building materials standards and testing procedures that are applicable to novel carbonaceous building materials, that is, aggregates, cement, concrete and other building materials that have utilised CO_2 in their production.

Scope of Work

The contract was awarded to ICON consultants at Imperial College London and their work covered the following approach.

- A summary and comparison of existing standards and testing worldwide, focussing on UK, European, US, ISO and Chinese standards (they represent 63% share of the cement/concrete market in 2019).
- A discussion of international approaches to standardisation.
- Eight open structured interviews conducted with global experts in construction materials, the construction industry, and CO_2 utilisation.
- The market potential for CO_2 utilisation processes in the construction industry is investigated by analysing a number of different companies which are producing carbonated building materials for the construction industry. Three companies were examined in more depth as case studies, with confidential interviews and literature reviews, chosen to span a range of products.
- Regulations which apply to new types of cement (including new blends of Ordinary Portland Cement), their use in concrete, and new constituents of cement and concrete such as supplementary cementitious materials, fillers, and CO_2 are discussed.

Approach

The following report comprises two parts: Part I is a review of the standards for cement, concrete and aggregates (Table 1) and Part II is about market entry of CO_2 containing materials into the construction industry.

Part I is structured as follows:

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[3] IEA (2019), '**Putting CO_2 to Use**'. IEA, Paris, September 2019 [*Online*]. Available at: https://www.iea.org/reports/putting-co2-to-use

- an initial literature review of existing international standards, codes and test methods, for concrete, cement and aggregate;
- international approaches to standardisation are explored in the USA, Europe, China, East Africa and ISO;
- the development of models for safe and reliable performance-based standards are discussed; and
- structured interviews with global experts in construction materials, the construction industry, and CO_2 utilisation are conducted.

An appendix with a comprehensive set of comparison tables is provided that includes: exposure classes in international concrete standards; review of prescriptive and performance-based specifications in international concrete standards; comparison of exposure categories for international concrete standards; comparison of limiting values: minimum cement contents, maximum water/cement and compressive strength in international concrete standards; curing requirements in international concrete standards; review of prescriptive and performance-based specifications in international cement standards; cement types in international cement standards; review of prescriptive and performance-based specifications in international aggregate standards; source materials in international aggregate standards; and list of international standards for building materials reviewed in this work.

Part II investigates in more detail companies that are developing carbonated building materials and follows three case studies. It then looks at methods for certifying and measuring embodied carbon content of carbonated building materials and the challenges therein.

Findings of the Study

CCUS features as an essential component and often the largest reduction measure in the decarbonisation roadmaps of many major cement and concrete manufacturer and associations. However, the relative contributions towards the reduction of CO_2 emissions intensity from CO_2 storage and utilisation are not often stated in these decarbonisation roadmaps.

In 2019, the global cement production was 4.1 Gt/yr, with China producing over half and the EU and USA a further 4.4% and 2.2.% respectively. Standards from these countries/regions were selected on their market share.

Standard	Description
Concrete	
EN 206:2013+A2:2021	Concrete. Specification, performance, production and conformity
EN 1992-1-1	Eurocode 2. Design of concrete structures. Part 1-1. General rules. Rules for buildings, bridges and civil engineering structure
EN 13670:2019	Execution of concrete structures
ACI 301-20	Specifications for Concrete Construction
ACI 318-19(22)	Building Code Requirements for Structural Concrete and Commentary
ISO 22965-1:2007	Concrete. Methods for specifying and guidance for the specifier
ISO 22965-2:2007	Concrete. Specification of constituent materials, production of concrete and conformity of concrete
ISO 15673:2016	Guidelines for the simplified design of structural reinforced concrete for buildings
GB/T 50476-2019	Code for durability design of concrete structures
JTG/T 3310-2019	Code for Durability Design of Concrete Structures in Highway Engineering
GB 50666-2011	Code for construction of concrete structures
Cement	
EN 197-1:2011	Cement. Composition, specifications and conformity criteria for common cements
EN 197-5:2021	Cement. Portland-composite cement CEM II/C-M and Composite cement CEM VI
ASTM C150/C150M-22	Standard Specification for Portland Cement
ASTM C595/C595M-21	Standard Specification for Blended Hydraulic Cements
ASTM C1157/C1157M-20a	Standard Performance Specification for Hydraulic Cement
GB 175-2007	Common Portland cement
Aggregate	

EN 12620:2002+A1:2008	Aggregates for concrete
EN 13055:2016	Lightweight aggregates
ASTM C33/C33M-18	Standard Specification for Concrete Aggregates
ASTM C330/C330M-17a	Standard Specification for Lightweight Aggregates for Structural Concrete
ISO 19595:2017	Natural aggregates for concrete
GB/T 14684-2011	Sand for construction
GB/T 14685 -2001	Pebble and crushed stone for construction

Table 1 List of international standards for building materials reviewed in this work.

Standards are comprised of two main components – prescriptive and performance-based elements. An analysis is performed of current standards (Table 1) to consider whether a shift from prescriptive (crudely composition based) to performance-based standards would assist global efforts to allow the use of more novel cementitious materials. Comparing specifications for cements (or concrete) between international standards is difficult because cement types are defined using different criteria.

Standards and codes for concrete

Exposure classes is a classification system used to determine the environmental conditions to which a concrete structure or element will be subjected during its service life. It is common across all international concrete standards. The exposure class is a crucial consideration in concrete design and specification, as it helps engineers and construction professionals select the appropriate concrete mix and protective measures to ensure the durability and long-term performance of the structure. For example in Europe they are based in European climate conditions, experiences and expected deterioration, exposure classes must be interpreted locally, whereas the Chinese standards are defined based on degradation mechanism and subdivided into 16 subclasses – these are generally better defined than the EN, ISO and ACI standards.

The exposure classification system is used to simplify the design process by specifying the minimum durability requirements for concrete to remain serviceable for a certain period of time when exposed to specific environmental conditions. However, a drawback of this system is that broad assumptions must be made, making it challenging to develop universally applicable guidelines for all environments. Concretes can also be under or overdesigned if the wrong environmental subclass is chosen and local conditions are not considered. This is particularly significant for the ISO standard, where perception of terms such as moderate humidity is subjective and varies significantly across the world.

EN 206 is a non-harmonised European standard, therefore the recommendations may be altered when adopted by each member country in their National Annex. As a result, large differences in the limiting values for the requirements exist between member countries for the same exposure subclasses, shown in Figure 1. The large variation in minimum concrete strength shows that while the requirement is performance-based, the limiting values to ensure durability are prescriptive. This is an important point – a performance-based standard can have prescriptive limits on composition to ensure that the rigorous testing which has been undertaken in producing the standard is applicable; cements outside the range of testing cannot be guaranteed to be compliant.

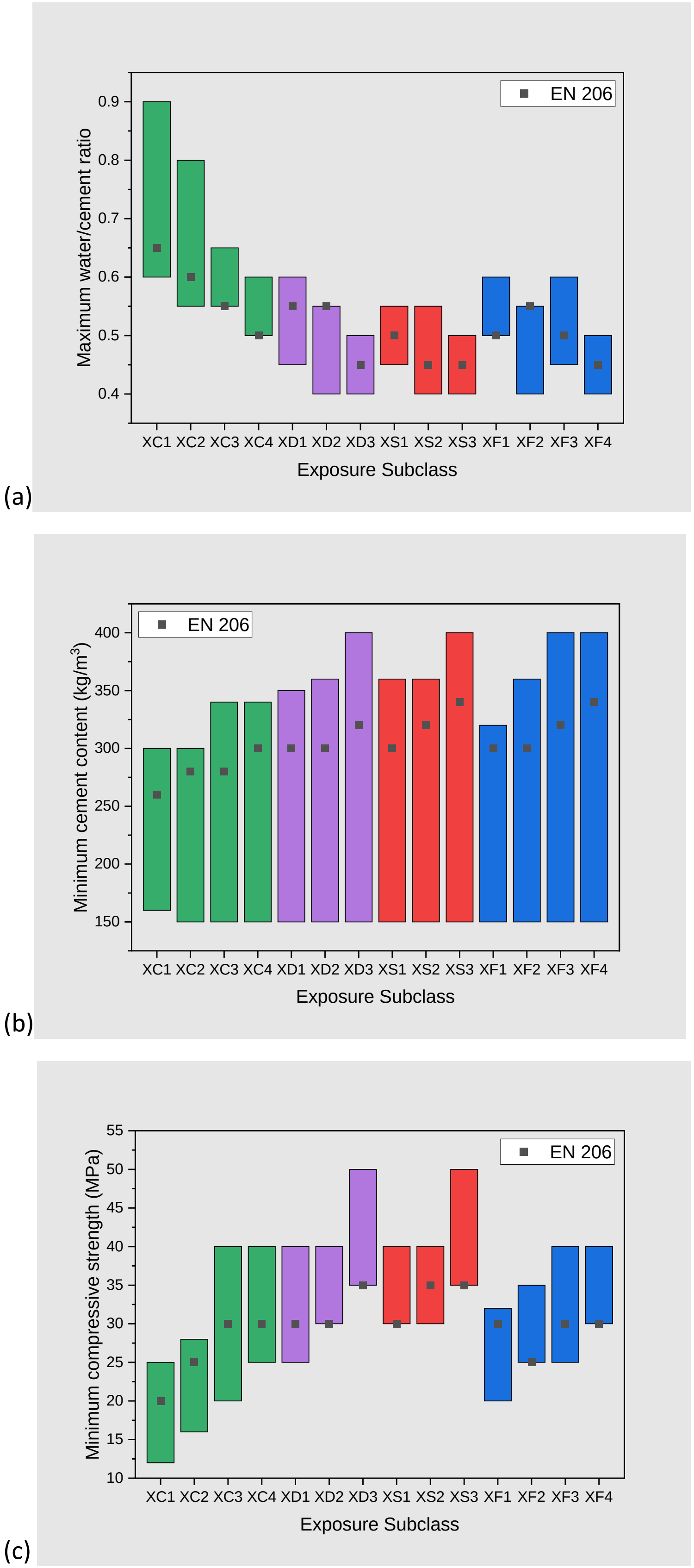

Figure 1. Variation of (a) minimum water/cement ratio (b) minimum cement content, and (c) minimum compressive strength requirements specified in national annexes for the application of the non-harmonised EN 206 standard. The baseline values given in informative annex F of EN 206 are shown for reference.

In the most widely used international concrete standards and codes, the traditional approach to control concrete durability of concrete is to set prescriptive limiting values for indirect durability indicators such as: minimum cement contents; maximum water or cement ratios; and minimum compressive strength. Those are mainly based on historical experience using concrete produced using ordinary Portland cement and natural high quality aggregates. These prescriptive limits may not correlate with the properties that affect the durability of concrete, concerning perhaps for modern concretes that incorporate new constituents and mixes beyond traditional concrete e.g. containing CEM 1-V[4] type cements.

The most widely used performance specification for concrete is compressive strength. However, in the context of concrete codes and standards, requirements for minimum compressive strength are specified and used as an indirect durability indicator based on exposure classes. This practice is increasingly being called into question. Two examples that demonstrate the poor correlation between strength and durability are, (i) air-entrained concretes which require much lower water/cement ratios to achieve the same strength as non-air-entrained concrete and exhibit lower penetrability, and (ii) high (and ultrahigh) strength concretes that use low water/cement ratios and high cement contents, which lower the concrete workability and therefore require high amounts of water-reducing admixtures, that can make the concrete suspectable to early age cracking and hence early deterioration.

Comparing concrete specifications between international standards is challenging because of their different exposure classification systems. A comparison between the exposure classes given in the standards is conducted with their respective limiting values for minimum cement contents, maximum water/cement and compressive strength compared. The EN XF1, ACI F1 and GB/T II-D exposure classes were identified as equivalent exposure classes for moderate exposure to a freeze-thaw environment. The three standards set similar limiting values for the maximum water/cement ratio (0.50-0.55). However, the minimum compressive strength requirement in the Chinese concrete standard (35 MPa) is much higher than the European and American standards (24-25 MPa). The minimum compressive strength requirements in GB/T 50476 for each exposure class are typically 10-14 MPa higher than their equivalent exposure class in EN 206 and ACI 318. The minimum air content specifications are similar for the American and Chinese standards and are based on the nominal aggregate size, whereas the European standard specifies one value for the minimum air content for all concrete mixes designed for exposure class XF1.

Standards and codes for cement

A comparison of the prescriptive and performance specifications in international cement standards is outlined in Table 2. The specifications generally fall under three categories: chemical, mechanical and physical. With prescriptive specifications generally used to control the chemical composition of cement, whilst the mechanical and physical requirements are typically related to performance.

Cement standards that categorise cements by clinker content and composition of additions (EN 197-1, EN 197-5, GB 175 and ASTM C595) can become confusing due to the large number of cement types with no specific end use given. For example, 39 cement types are currently specified in EN 197-1 and EN 197-5, including 27 types of CEM II. The number of potential new supplementary cementing materials (SCMs) (including locally available materials) is much larger than those currently permitted in existing standards. Including these materials would further increase the number of composite cement types specified in EN 197. This not practical and may stretch the already complicated relationship between cement composition and performance. The need for consensus for new SCMs to enter the

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[4] CEM denotes the grades of cement based on their composition and the proportion of ordinary Portland cement (OPC) and additives, with CEM I being 100% OPC, CEM II a mixture of OPC and up to 35% additives like fly ash and CEM III a mixture of OPC and blast furnace slag. CEM IV is pozzolanic cement and CEM V a composite cement.

standard may hinder the adoption and exploration of locally available materials, which is important because resources of traditional SCMs like coal fly ash have declining availability. The limits for cement constituents are based on experience, but are somewhat arbitrary, and therefore can result in unnecessarily higher clinker contents and high CO_2 intensity of the cement.

Specification	EN 197-1	EN 197-5	ASTM C150	ASTM C595	ASTM C1157	GB 175
Amount of constituents, e.g. limestone, fly ash, pozzolans, slag, etc.	Prescriptive	Prescriptive	Prescriptive	Prescriptive	No requirement	Prescriptive
Chemical composition	Prescriptive	Prescriptive	Prescriptive	Prescriptive	No requirement	Prescriptive
Chloride content	Prescriptive	Prescriptive	Prescriptive	Prescriptive	No requirement	Prescriptive
Sulphate content	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Performance-based	Prescriptive
Air content	No requirement	No requirement	Prescriptive	Prescriptive	Prescriptive	Prescriptive (GB 50119-2013)
Loss on ignition	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Prescriptive
Compressive strength	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based
Setting time	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based
Expansion	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based
Heat of hydration	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based (GB 50496-2018)

Table 2 Review of prescriptive and performance-based specifications in international cement standards.

The prescriptive approach of the European and Chinese standards may prohibit innovation regarding introducing new cement formulations with lower embodied CO_2 emissions due to their alternative chemistries and potentially less energy-intensive manufacturing conditions. One example is Solidia Cement, a carbonatable calcium silicate clinker-based cement that reacts with CO_2 during curing and requires lower clinkering temperatures than conventional ordinary Portland cement (OPC). As a result, the company claims that the production of Solidia Cement requires less energy and emits less CO_2 emissions than OPC. While the use of Solidia Cement is inhibited by the prescriptive European and Chinese cement standards, the alternative cement may be used in the USA under ASTM C1157, although its use may be limited due to limited experience and the industry concerns regarding ASTM C1157 outlined previously.

Standards and codes for aggregates

Aggregates account for up to 80 per cent of concrete by volume, however the relationship between aggregate properties and concrete performance has received much less focus than that between paste and concrete.

The permitted sources of aggregates and their geometrical, physical, chemical and mechanical specifications are defined by international standards. The specifications in these standards are categorised into either prescriptive and/or performance-based specifications. The geometrical and chemical specifications are generally prescriptive, while the physical and mechanical are mainly performance-based.

The ISO 19595 standard contains the strictest prescriptive limits for sources of aggregates, permitting only natural aggregate from mineral sources that have been subjected to nothing more than mechanical processing, inhibiting the use of carbonated aggregates. The Chinese standards GB/T 14684 and GB/T 14685 are similarly strict, mainly allowing aggregates from natural sources, however, manufactured sand produced from mine tailings and industrial waste residue are permitted for use as fine aggregate. In addition to aggregates from natural mineral sources, EN 12620 and ASTM C33 also permit normal weight aggregates derived from manufactured sources and recycled aggregate, permitting the use of carbonated aggregates that meet the remaining aggregate specifications. ASTM C33 states that "certain recycled aggregate sources may contain materials and properties not addressed as part of the document specifications, limits, or test methods", implying the use of recycled aggregates may require additional considerations and test method not currently included in the standard. EN 12620 explicitly provides additional specifications for recycled aggregate and states that new test methods are at an advanced stage of preparation.

Carbonated aggregate derived from wastes, such as those produced by Carbon8 Systems and OCO Technology, generally fall under lightweight aggregate standards. Therefore, the specification of carbonated aggregates is inhibited in EN 13055 unless the specific source materials are included in the standard. EN 13055 also states that the committee will continually review new source materials for incorporation into the standard. The use of carbonated lightweight aggregates wastes is not possible according to the terminology used in ASTM C330.

The prescriptive limits in existing standards may fail to accurately predict concrete durability, particularly considering the use of new source materials (i.e. other than from natural sources). The EN and ISO standards hardly contain any required specifications and many of the limits in ASTM standards can be disregarded, demonstrating that the committee understands that prescriptive limits have shortcomings and evidence of proven performance can be used in place.

International Test Methods

Performance-based specifications require rapid and reliable performance test methods. The following test methods are compared: cement, compressive strength; concrete, resistance to sulphate attack; aggregates, resistance to fragmentation. Existing test methods are then evaluated as barriers for CO_2 utilised building products/modern mix designs.

Existing test methods for concrete and cement were generally developed considering the behaviour of traditional concretes prepared using large amounts of Portland cement and high-quality aggregates from natural sources. Modern concrete mix designs contain many new components that can affect concrete performance. These include new SCMs, admixtures and aggregates from alternative sources. Therefore, existing test methods may fail to capture the potential benefits (or drawbacks) of new mix designs. The three test methods for concrete, cement and aggregates discussed illustrate some key issues with existing testing methods:

- Concrete, resistance to sulphate attack. The ASTM test method C1012 for resistance to sulphate attack demonstrates that some test methods need to be altered for new materials. Some cementitious materials develop properties at different rates than Portland cement and, therefore, may fail to meet testing criteria if testing is performed too early. Typically, the test duration can take 3-18 months.
- Cement, compressive strength. Standard strength testing of cements is based on mortars produced using a standard amount of cement and standard sand. The curing temperature requirements may not match field conditions and can penalise alternative materials that show superior performance at high temperatures.
- Aggregate, resistance to fragmentation. The Los Angeles testing method is used to determine the resistance to fragmentation of aggregates in the EN and ASTM standards and suffers from inadequate correlation with field performance and does not reflect the in-service environmental conditions.
- Other concerns, e.g. ASTM C151 autoclave expansion tests monitor volume instability due to delayed hydration of MgO or CaO. Novel cement formations may not contain these components and contain new components that could cause unknown instability issues. These need to be understood, test methods designed, and limits set in the standards.

International approaches to standardisation

Standards are technical specifications that may contain requirements for design, construction, durability, testing, maintenance, repair, and restoration. They are written in explicit language and their requirements can be either mandatory or voluntary. Standards organisations commonly form technical committees to draft, revise, approve, and manage technical standards and building codes using a consensus-based process. Table 3 provides a list of the relevant international subcommittees for building materials. The report goes into more detail into the process of these committees, their structure and how they develop standards.

In the USA, ASTM International (formerly the American Society for Testing and Materials) and ACI are the main standardisation agencies responsible for developing and maintaining building material standards. To develop standards, ACI establish Technical Activities Committees (TACs) which form technical committees responsible for a specific knowledge area. The European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Standards Institute (ETSI) are responsible for developing and maintaining European standards. The Standardization Administration of China (SAC) is the main standards organisation in China and represents the country in major international standards groups. SAC assigns a standard to one of five broad categories: national standards, industry standards, local or regional standards, enterprise standards for individual companies, and association standards. National standards, also known as guobiao (GB), are the highest-level standards and the most relevant for building materials. The International Organization for Standardization (ISO) is an independent non-governmental organisation that consists of members from the national standardisation bodies of 163 countries. ISO forms technical committees that develop and maintain standards in specific subject areas. The relevant technical committees for standardisation of building materials are ISO/TC 71 Concrete, reinforced concrete and pre-stressed concrete and ISO/TC 74 Cement and lime.

Committee	Title	Technical subcommittees	Published Standards
ASTM International			
C01	Cement	19	over 50
C09	Concrete and Concrete Aggregates	31	over 176
ACI			
300	300 – Design and construction	-	10
EN			
CEN/TC 250	Structural Eurocodes	11	140
CEN/TC 104	Concrete and related products	4	178
CEN/TC 51	Cement and building limes	0	40
CEN/TC 154	Aggregates	5	60
ISO			
ISO/TC 71	Concrete, reinforced concrete and pre-stressed concrete	7	73
ISO/TC 74	Cement and lime	0	7 (standby)[A]
Chinese standards body			
TC184	National Cement Standardization Technical Committee	0	128
TC458	National Concrete Standardization Technical Committee	1	20

[A] Standby status indicates the committee has no work items in progress or in the foreseeable future. The committees are still required to review the standards for which they are responsible.

Table 3. Committees with jurisdiction over building material standards

Development of models for safe and reliable performance-based standards.

This section of the report aimed to address the following: is there an effective way to create performance-based standards without comprising safety and dependability; and are there tools or models that can predict long-term performance and the effect of wide-scale application. Firstly, it is expensive and time intensive to establish a standard. E.g. ~£150,000 for a BSI standard combined with time resource from highly qualified experts. Testing can also take years to develop the standard and prove costly, with performance-based standards requiring more tests than prescriptive standards.

Some of the key performance criteria for cement concrete performance standards include: compressive strength at the time of curing; slump, indicating workability; and resistance to deterioration, indicating durability. Compressive strength and slump are simpler to incorporate into performance-based standards whereas durability is more challenging, and no comprehensive/generalised model exists to quantify it (which presents a research gap in cement and concrete science). A short review of state-of-the-art research is presented in the report, highlighting recent and promising progress.

Interviews

Eight, one hour-long, structured interviews were held with: the Mineral Products Association; Heidelberg Materials; an anonymous construction industry supplier; GCPAT; Carbon8 Systems; CarbonCure; John Ballentyne (Jacobs Engineering); and Karen Scrivener (EPFL). They were each asked six main questions which included:

1. "Is there an effective way to create performance-based standards with respect to not compromising safety and reliability?"
2. "Have any external factors such as local policy or legislation helped new materials gain approval and adoption?"
3. "Are there tools or models that can predict long-term performance and the effect of wide-scale application?"
4. "Potential markets and business models for novel carbonaceous building materials? "
5. "Is there anything we have missed? Questions we should add?"
6. "Who else shall we contact?"

Each of the contributors were invited to review the draft prior to submission.

Climate change is seen as an extremely high priority throughout the industries interviewed, and its increasingly common to see CO_2 intensity or other measure to be part of the tendering process, especially in government contracts. Shareholder pressure to decarbonise is also a factor.

Safety, however, is a vital component and testing must remain rigorous. Unless a material was within an existing and well-respected code (e.g. EN standards) it would not be specified except under exceptional circumstances. The ability to insure is a key question if using novel materials.

Developing confidence in new materials is key and can be done by using them initially in non-safety critical operations (e.g. retaining walls) to test them in real life situations, although this can result in decades of time before full implementation occurred in other areas.

The next decade will see large amount of infrastructure built in the developed world. In some African nations, for example, the standards are based on the EN standards but with modifications due to for example higher ambient temperatures. There are challenges around access to devices specified in the standards in developing nations.

Incentives and tax benefits for low-carbon construction are in place in New York (with the Low-Embodied-Carbon Concrete Leadership Act (LECCLA)) and New Jersey. Finland requires that planning demonstrates that low carbon options have been considered. Whereas the UK is perceived as not providing support or incentives.

The tests which have been developed for existing concrete and cements may not be suitable in practice for a new generation of cementitious materials – there is a plethora of potential tests, and a great incentive for testing houses to develop their own tests and have them incorporated into a standard – regardless of suitability. It was mentioned a number of times that it is substantially easier to add parts to an existing standard, rather than to develop a new standard from scratch – the time taken to develop a new EN standard was frustrating to some.

Setting a standard typically takes a very long time and relies on time from experts given in goodwill. Several respondents mentioned that limestone calcined clay cement (LC^3) cement is important for the future, and it is noted that there is a RILEM committee working towards the development of a standard for its use.

The consensus from the interviews was that designers would use lower-carbon materials as soon as the materials are included in the standard. However, the most common challenge identified from the interviews is that an extensive performance and testing history is required for new materials to be incorporated into a standard. New materials used in a large public infrastructure project can increase confidence as the performance of the materials can be continually analysed over time – satisfying the industry need for a 5 to 10-year period of demonstrated performance before they take on the risk e.g. HS2 project in the UK use of low carbon cements in low-risk applications like culverts and retaining walls.

Part II

The Global Cement and Concrete Association (GCCA) estimate that the 2020 global cement and concrete product market was valued at ~$440 billion, with 14 billion m^3 of concrete and 4.2 giga tonnes of cement produced. The demand for both ready mix and pre-cast concrete products is expected to increase in emerging markets due to population growth and urbanisation, and will stabilise or contract in developed countries.

Over the past two decades, an increasing number of companies have emerged with a focus on developing innovative materials that utilise CO_2 to lower the carbon emissions intensity of construction products. In Part II of the report an analysis of companies currently developing novel carbonated materials is undertaken (Table 4), before considering supply and demand factors for the commercialisation of the materials. The three main technologies for CO_2 utilisation to produce carbonated building materials are: CO_2 curing of concrete; carbonated aggregates (inert additives); and alternative cements (reactive additives). Of the 13 companies investigated, four currently offer commercial products.

Company	Product	Technological Approach	CO_2 source	Process conditions	Field application/ demonstration	Product commercially available?
CarbonCure Technologies	Carbonated ready mix concrete	Injection of CO_2 during the delivery of ready mix concrete	Pure CO_2	Ambient pressure and temperature	2022: General Motors Spring Hill Assembly Plant, USA (20 800 m^3 of concrete)[2] 2022: Amazon HQ2, Arlington, Virginia, USA (106 600 m^3 concrete)[3]	Yes
	Carbonated precast concrete	Injection of CO_2 during the production of precast concrete	Pure CO_2	Ambient pressure and temperature	2020: Retrofit of Coreslab Structures (TEXAS) Inc facilities, USA[4] 2016: MGM National Harbor, USA (195 000 units)[5]	Yes
	Carbonated reclaimed water	Injection of CO_2 to create ultrafine CO_2-stabilised suspended solids in reclaimed water which can be recycled for use as binder in new concrete mixes	Pure CO_2	Ambient pressure and temperature	2018: Trio Ready mix Commercial Pilot, Canada[6]	Yes
Solidia	Carbonated pre-cast concrete based on alternative cement	CO_2 curing of pre-cast concrete containing low lime calcium silicate clinker-based cement with a low kiln burning temperature	Flue gas	Ambient pressure and moderate temperature (30[7] to 60 °C[8])	2015: Demonstration in Pecs, Austria (6000 tonnes of cement)[9] 2014: Demonstration in Whaiutehall, USA (5000 tonnes of cement)[9]	No
CarbonBuilt	Carbonated pre-cast concrete with partial cement replacement	CO_2 curing of concrete containing partial replacement of OPC with portlandite and fly ash	Flue gas	Ambient gas pressures and flue gas temperatures (<75 °C[10]	2021: Field demonstration at the National Carbon Capture Center, USA (>15 000 concrete masonry units)[11]	Yes
Carbstone (VITO / Orbix)	Carbonated pre-cast concrete based on steel slag cement	Autoclave CO_2 curing of concrete produced using steel slag (after metal recovery for recycling) as an alternative cement	Flue gas	Autoclave conditions, i.e. high pressure (20 bar) and temperature (140 °C)[12]	2020: Construction of a footpath[13] 2013: Construction of pilot plant in Wallonia, Belgium[14]	No
CO_2-SUICOM (Kajima Corporation, The Chugoku Electric Power Company, Denka Company, and Landes Corporation)	Carbonated pre-cast concrete based on special additions	CO_2 curing of pre-cast concrete with reduced cement content using special admixture (γ-C_2S) and fly ash	Flue gas	Ambient pressure and moderate temperature (50 °C)[15]	2012: Brillia ist Nakano Central Park, Japan (apartment block for balcony ceilings) [16] 2011: Fukuyama Solar Power Plant, Japan (75 boundary, 40 fence foundation, and 5500 paving blocks)[16]	No

Company	**Product**	**Technological Approach**	**CO_2 source**	**Process conditions**	**Field application/ demonstration**	**Product commercially available?**
Carbicrete	Carbonated pre-cast concrete based on steel slag cement	CO_2 curing of pre-cast concrete containing steel slag as an alternative cement	Pure CO_2	Ambient temperature and CO_2 partial pressure equal to 1.5 bar[17]	2021: Pilot plant under construction (target of 2400 blocks/day in 2022, 25 000 blocks/day in 2023) at Patio Drummond, Drummondville, Canada[18]	"Available soon" on seller website, over 500 000 units reserved[19]
Fortera (IP acquired from Calera)	Carbonated SCMs	Process involving the dissolution/ reprecipitation of calcined limestone (source of Ca ions and calcined at a lower temperature than OPC) which react with dissolved CO_2 to produce reactive calcium carbonate cement	Flue gas	n/a	2021: Small commercial plant planned for 2022 in collaboration with Lehigh Hanson (HeidelbergCement subsidiary)[20]	No
Carbon8 systems	Carbonated construction products, e.g. carbonated aggregates	Accelerated carbonation technology demonstrated using the CO_2ntainer (carbonation of materials within a converted shipping container)	Flue gas	Ambient pressure and temperature	2021: Commercial deployment with Vicat Cement Group, France[21] Pilot demonstration projects in the Netherlands (2020), UK (2019) and Canada (2018)[21]	Yes
Blue Planet	Carbonated aggregates	Process involving the dissolution/ reprecipitation of waste/end of life concrete (containing calcium ions), which react with dissolved CO_2 to produce $CaCO_3$ coated aggregates and remediated recycle concrete aggregate	Flue gas	Ambient temperature and close to ambient pressure[22] Dissolved CO_2 solution with sufficient pH[22]	2016: San Francisco International Airport specified minimum 5% of lightweight coarse aggregate to be provided by Blue Planet. Aggregates were used for 40 yards of concrete (15 kg of Blue Planet coated aggregate and 280 kg of non-coated aggregate)[23] 2016: Commercial plant under construction in Pittsburg, USA. (Blue Planet subsidiary San Francisco Bay Aggregates)[24]	No
O.C.O Technology	Carbonated aggregates	Manufactured limestone aggregate from air pollution control residue (APCr)	Pure CO_2 Flue gas	Ambient temperature and pressure	2018: Plant established in Leeds, UK 2016: Plant established in Avonmouth, UK 2012: Plant established in Brandon, UK The three plants produce >200,000 t/y carbonated aggregate (>100 000 t/y APCr)[25]	Yes

Company	Product	Technological Approach	CO_2 source	Process conditions	Field application/ demonstration	Product commercially available?
Mineral Carbonation International	Carbonated building materials	Wet carbonation of crushed low-grade alkaline minerals and wastes	Pure CO_2 Flue gas	Higher than ambient pressure and temperature[26]	2016: Operation of pilot plant[27]	No
Greenore	Carbonated building materials	Wet carbonation of crushed low-grade alkaline minerals and wastes	Flue gas	Ambient temperature[28]	2022: Construction of 100 000 tonne/year steel slag plant[29] 2018: Operation of 3000 t/year steel slag pilot plant[29]	No
Cambridge Carbon Capture	Carbonated building materials	Wet carbonation of magnesium silicate from mine tailings	Pure CO_2 (from direct air capture)	n/a	2022: GBP 3 M awarded for pilot[30]	No

Table 4 Overview of companies producing carbonated build materials

In addition, three companies were examined in more depth in the form of case studies and (anonymous) interviews, chosen due to their involvement in producing carbonated aggregates (Carbon8 systems), those carbonating the cement within concrete (CarbonCure) and a company that develops pre-cast concrete products (CarbonBuilt). The case studies were used to assess the market entry of carbonated materials into the construction industry, in particular from companies that were offering a commercial or semi-commercial product in different markets (CO_2 injection, aggregate production, and low-carbon cement production). Of these, CarbonCure has achieved the highest level of commercialisation, licensing over 700 systems to concrete producers globally. CarbonBuilt has recently finished its first retrofit project at a concrete block manufacturing plant in the USA, with commercial production of concrete blocks using its technology already underway. While the first commercial deployment of Carbon8 Systems' CO₂ntainer technology is currently in progress at a cement facility in Europe.

Decarbonisation potential of carbonated building materials

Carbonatable by-products from industrial processes offer significant CO_2 emissions reduction potential through CO_2 mineralisation. The global production rates of carbonatable by-products from the construction, power, iron and steel, fertiliser and aluminium industrial sectors were estimated to determine their CO_2 capture potential (Table 5). The results show that up to 0.57 Gt of CO_2 emissions could be captured by 3.6 Gt of carbonatable materials each year using CO_2 mineralisation.

An important step for the market entry of novel carbonated building materials is to have an appropriate methodology for assessing their carbon content. When considering carbon as a funding criterion, it becomes imperative to be able to compare and contrast bids transparently. This involves calculating the carbon content, also known as the embodied carbon, which is achieved through the implementation of life-cycle assessment (LCA) methodologies.

Industry	Carbonatable material	Global production (Gt)	CO_2 capture potential (Gt)
Construction	End-of-life binder (concrete)	1.1	0.052
	End-of-life binder (mortar)	0.25	0.012
	Cement kiln dust	0.24	0.082
	Concrete slurry waste	0.23	0.058
Power	Coal ashes	0.70	0.093
Iron and steelmaking	Blast furnace slag	0.34	0.10
	Steel slag	0.21	0.07
Fertiliser	Phosphogypsum	0.38	0.10
Aluminium	Bauxite residue	0.20	0.0056
Total		3.6	0.57

Footnote: The CO_2 capture potentials were determined by assuming 100% of the CaO content of the materials could be carbonated and that half of the loss on ignition (LOI) is due to the release of CO_2 from $CaCO_3$

Table 5: Global production and CO_2 capture potentials of carbonatable industrial materials in 2020.

A combination of lifecycle assessment and technoeconomic analysis was used to compare the increased production costs of the carbonated building materials relative to their conventional counterparts and the CO_2-eq avoidance costs of the mineralisation technologies. Of the eight carbonated building materials investigated, cement from carbonated end-of-life cement paste was determined to have the lowest CO_2 avoidance cost and was the only carbonated building material to have a lower avoidance cost than CCS[5]. The CO_2 injected ready mix concrete and cement from carbonated end-of-life cement paste products were found to have cost-competitive production costs with their conventional counterparts, while the significantly increased production cost for lightweight aggregates is likely to be a barrier to commercialisation.

The results in this section highlight the importance of focusing on the deployment of carbonated building materials with high environmental and/or economic performance. The current poorly defined approach for classifying carbonated building materials may lower the overall CO_2 emissions reduction benefits of low carbon materials if purchasers can get the same credit (financial or reputational) by specifying a material whose CO_2 emissions benefit is fractionally smaller than the conventional material. Lifecycle analysis is important to quantify the actual emissions reduction, and it is important to not be taken in by “wonder” solutions that do not seriously reduce the overall CO_2 emissions when considered holistically. Therefore, the implementation of a standardised grading system for low carbon building materials could improve the deployment of the materials in the construction industry.

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[5] Cement from carbonated end-of-life cement paste was determined to have the lowest CO_2 avoidance cost (€22/tCO_2-eq) and was the only carbonated building material to have a lower avoidance cost than CCS (€80-100/tCO_2-eq). Driver JG, Bernard E, Patrizio P, Fennell PS, Scrivener K, Myers RJ. Global decarbonisation potential of CO2 mineralisation in concrete materials. *Prep* 2023.

Conclusions

Over the past 20 years the buildings materials industry has become increasingly aware of climate change as a priority and companies have emerged with a focus on developing innovative products that utilise CO_2 to lower the carbon emissions intensity. The main challenges that the companies commercialising technologies face are the conservative nature of the industries, and challenges in getting the materials into the design codes (EN codes being a particular issue). It is not just a case of developing a new code though, until small-scale demonstrations have taken place in non-safety-critical applications, developing comfort and familiarity for specifiers (and importantly ensuring that findings are shared widely), large-scale applications will be unlikely. For companies whose products are compliant with existing codes, market pull is important, with buyers' clubs and government departments in particular able to take a leading role. Developing confidence in new materials is likely to be achieved in using them first in non-safety critical operations, although this will take time.

In this study international standards and codes for concrete, cement and aggregates have been evaluated and compared, reviewing the prescriptive and performance-based specifications and requirements. Performance based standards are preferable but take time, effort and cost to develop, and comparing standards is difficult given the differing criteria used, for example end-use requirements or composition.

The second part of the study assessed the market potential from the supply side and total sequestration capacity of products from companies currently producing carbonated building materials for use in the construction industry. In evaluating methods of incorporating CO_2 into building materials, it's evident that there is significant potential market for carbonatable material, but lifecycle emissions and commercial factors could potentially reduce CO_2 savings and total market available. The aggregate market is seeing recycled aggregates and industrial by-products (including utilising CO_2 in their production) more commonly used. Other ways to use CO_2 include accelerated CO_2 curing of concrete and the use of alternative cement chemistries produced using CO_2. Carbonated concrete slurry waste can act as a supplementary cementitious material in cement and allowing a reduction in cement clinker.

An analysis of the CO_2 capture potential of industrial by-products from five industrial sectors found that up to 0.56 Gt of CO_2 emissions could be captured by 3.6 Gt of carbonatable materials each year using CO_2 mineralisation. Research found that when substituting for other materials, savings of CO_2 between 0.01 and 0.49 kgCO_2-eq per kg material substituted were found. The greatest emissions reduction was found for carbonated lightweight aggregate. Cement from carbonated end-of-life cement paste has the lowest CO_2 avoidance cost.

This report strongly suggests that "low carbon" terminology be better classified in the production of building materials.

Expert Review

The report (Part I and Part II) was reviewed by six external reviewers from three organisations (the IEA, Element Energy and US DOE).

The general consensus was that it was interesting, informative and relevant, in essence a useful set of reports and the reviewers were grateful for the opportunity to review the documents.

Some of the feedback included the following and were addressed by:

- Part I and II initially read like two separate studies. This was addressed by adding a reference to the standards to Part II and references to companies producing carbonated building materials added to sections in Part I, links between the two parts have been added to produce a more coherent report.

- There is no reference to the implications for carbonaceous building materials when reviewing the standards (Part I) and missing a section highlighting recent progress or challenges related to measuring and certifying the performance of CO_2-containing building materials. This was addressed by:
    - Updated sections (4.2.2 and 4.3.2 in Part I) and adding sections "Findings Relating Specifically to Measuring and Certifying the Performance of Carbonated Building Materials" to the interview findings.
    - Recent progress in measuring/certifying the performance of CO_2-containing building materials is shown in the field application/demonstration column in Table 4-1 (Part II), which reports the latest and/or largest demonstrations of materials developed by companies.
    - Additional information was added to the company profiles in Part II section 4 based on the literature review (references to applicable standards) and interviews (references to demonstration/trials) conducted in Part I.
    - Best practice methods for measuring the uptake of CO_2 in CO_2-containing building materials are currently being developed through a large industry-academic working group: MCP : Accelerated Mineral Carbonation for the production of construction materials (rilem.net). An author of this report (Myers) is leading a section on CO_2 quantification in this working group. There are numerous challenges, including quantification and deconvolution of H_2O and CO_2 uptake during measurement, and instrumentation/protocols for measurement at industrial scale.
- Could cost estimates be included as part of the overview and comparison of standards? This was felt that it would warrant further study and out of the scope of this study, however the authors have added a discussion of some relative costs but felt that the differences between setting costs for setting different standards are immense.

Other edits included:

- A glossary was added for further clarification of some key concepts.
- A new table 5-2 was added similar to table 5-3.
- Section 6.4 (Part I) on East Africa under the chapter 'International approaches to standardisation' as per reviewers suggestion.
- Part II, clarification was added to the choice of the three companies for case studies and what made them 'leading'.
- Cross references to the IEAGHG study 'From Carbon Dioxide to Building Products – Enhancing Process efficiency' were added to the text.

Recommendations

The following represent the IEAGHG's recommendations on the basis of the results of this study.

- To conduct more research in models (comprehensive or generalised) to quantify concrete durability (resistance to deterioration), this is a key performance criteria for cement/concrete performance-based standards.
- It is strongly suggested that the term "low carbon" must be significantly better classified in the production of building products. Materials that could reduce the CO_2 emissions associated with the material that they are substituting by 5% should not be in the same category as those that reduce CO_2 by 50%, for example.
- Cost estimates of setting standards is little understood and would warrant a more thorough and detailed study.

To note, the following report is in two parts. Part I is numbered from pages 1-88, Part II follows on as pages 1-32.

International Standards and Testing for Novel CO_2-Containing Building Materials (IEAGHG/CON/22/291)

Part I – Review of Standards

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1 Abbreviations

ACI	American Concrete Institute
ACT	Accelerated Carbonation Technology
AFm	Alumino-Ferrite-mono cement hydrate phase
AFt	Alumino-Ferrite-tri cement hydrate phase
APC	Air Pollutant Control
ASTM	American Society for Testing and Materials
BAT	Best Available Technology
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BOFS	Basic Oxygen Furnace Slag
C-(A-)S-H	Calcium aluminate silicate hydrates. Components of set cement.
C_3S, C_2S, C_3A, C_4AF	Different phases in Portland cement clinker
CAPEX	Capital Cost
CBD	Cement Bypass Dust
CBI	Climate Bonds Initiative
CCS	Carbon Capture and Storage
CEM I / II	Two standardised Portland cement types
CKD	Cement Kiln Dust
C-S-H	Calcium Silicate Hydrate. The key binding phase in hydrated cement.
CSW	Concrete Slurry Waste
DMS	Demetalisation Slag
DSR	Direct Separation Reactor
EAFS	Electric Arc Furnace Slag
ECRA	European Cement Research Academy
EN	Euro Norm (standard)
FA	Fly Ash
FCC	Fixed Capital Cost
GGBFS	Ground Granulated Blast Furnace Slag
ISO	International Standards Organisation
LEILAC	Low Emission Intensity Lime and Cement
LOI	Loss on Ignition
M-S-H	Magnesium Silicate Hydrate
MSW	Municipal Solid Waste
Mt	Million Tonnes
OPC / PC	Ordinary Portland Cement / Portland Cement
OPEX	Operating Cost
RCA	Recycled Concrete Aggregates
RDF	Refuse Derived Fuel
RILEM	***R**éunion **I**nternationale des **L**aboratoires et **E**xperts des **M**atériaux*
SCM	Supplementary Cementitious Material
TAC	Technical Activities Committees
TPC	Total Purchase Cost
UCLA	University of California, Los Angeles

2 Glossary

Compressive strength is a measure of the ability of concrete to withstand loads before failure. It is one of the essential mechanical properties used to assess the quality and performance of concrete in structural applications. Compressive strength tests are made on cylinders or cubes made from the concrete being placed to check the strength of a concrete.

Concrete curing: is the process of maintaining adequate moisture, temperature, and time conditions to allow the cement hydration reaction to continue and complete, leading to the development of desired properties in the hardened concrete.

Exposure classes is a classification system used to determine the environmental conditions to which a concrete structure or element will be subjected during its service life. The exposure class is a crucial consideration in concrete design and specification, as it helps engineers and construction professionals select the appropriate concrete mix and protective measures to ensure the durability and long-term performance of the structure.

Fineness refers to the particle size distribution of the cement used in the concrete mix. It is a measure of how finely the cement particles are ground, and it plays a significant role in the properties and performance of the concrete.

Heat of hydration is the quantity of heat developed by the hydration of a cement in a given period of time. This exothermic chemical reaction generates heat as it progresses. In large concrete pours or mass concrete elements (*e.g.* foundations), excessive heat generation can lead to thermal cracking.

Setting time: The initial setting time and final setting time are two important properties that describe the hardening process of concrete after mixing with water.

The **initial setting time** of concrete refers to the period from the moment water is added to the cement until the concrete begins to lose its plasticity, stiffening to a certain degree. This stage marks the end of the mixing and placing phase and the beginning of the setting process. During the initial setting time, the concrete can still be worked and moulded into the desired shape.

The **final setting time** of concrete is the duration from the moment water is added to the cement until the concrete achieves its full rigidity and can support some load without any significant deformation.

Soundness refers to the ability of cement to not undergo significant volume changes after it has set and hardened that can lead to cracks and other forms of damage, compromising the integrity and durability of the concrete structure. Unsoundness can arise from the presence in the cement of too much free magnesia or hard-burned free lime.

3 Executive Summary

The IEAGHG commissioned researchers from Imperial College London to investigate whether performance-based standards (simply: how a sample of a material *behaves* in response to a particular test), as opposed to a prescriptive standard (*e.g.* what the material is made of) might assist in the more rapid adoption of new construction materials or improvements to existing materials, with the overall aim of reducing CO_2 emissions from the construction industry. The project comprises both literature-based work to summarise existing codes for cement, concrete, and aggregates, and structured interviews with global experts in construction materials, the construction industry, and CO_2 utilisation. We also investigate the market potential for CO_2 utilisation processes in the construction industry. The regulations which apply to new types of cement (including new blends of Ordinary Portland Cement), their use in concrete, and new constituents of cement and concrete such as supplementary cementitious materials, fillers, and CO_2, are also discussed.

The first and most important finding from almost all interviewees was that climate change is an extremely important priority throughout the industries represented, with a number of interviewees stating that it is increasingly common for CO_2 intensity or another measure of climate change impact to be part of the tendering process. Shareholder pressure to decarbonise was also found to be important. However, there was a large groundswell of opinion that safety is critical and that testing must remain rigorous. A number of respondents referred to the importance of first developing confidence in new materials, by using them in non-safety critical operations (e.g. retaining walls) to gain an understanding of how they behaved in real life situations. Part II of this work shows that there are a number of companies developing knowledge in the field by doing exactly this. Knowledge sharing across industry(ies) and countries was mentioned by a number of respondents as being very important – each company / country does not have to replicate what everyone else has done.

In terms of support mechanisms to help with the deployment of new materials, support (in terms of legislation, tax credits, etc.) from governments (such as the UK) for CO_2 utilisation in construction materials is important. Some jurisdictions are providing significant incentives for low-carbon construction: there are tax benefits in state procurement for using low CO_2 materials in New York and New Jersey; it is necessary to take into account lifecycle emissions for construction in Finland. It was noted that performance-based standards take longer to develop, and that it was a challenge to include every possible combination of materials in a performance-based standard. Some types of standards require extended tests over months, and in particular, durability standards are more difficult to accelerate.

Considering now the literature-based comparison of the different standards: Comparing specifications for cements (or concrete) between international standards is difficult because the cement types are defined using different criteria – either end-use requirements or composition. Our analysis has shown that within the same overarching standard (for example EN206), where individual countries can set limits on specific properties when specifying the same material property (such as compressive strength) for a material exposed to a particular set of conditions, there are large differences in the values between countries (see Figure 5-2 below).

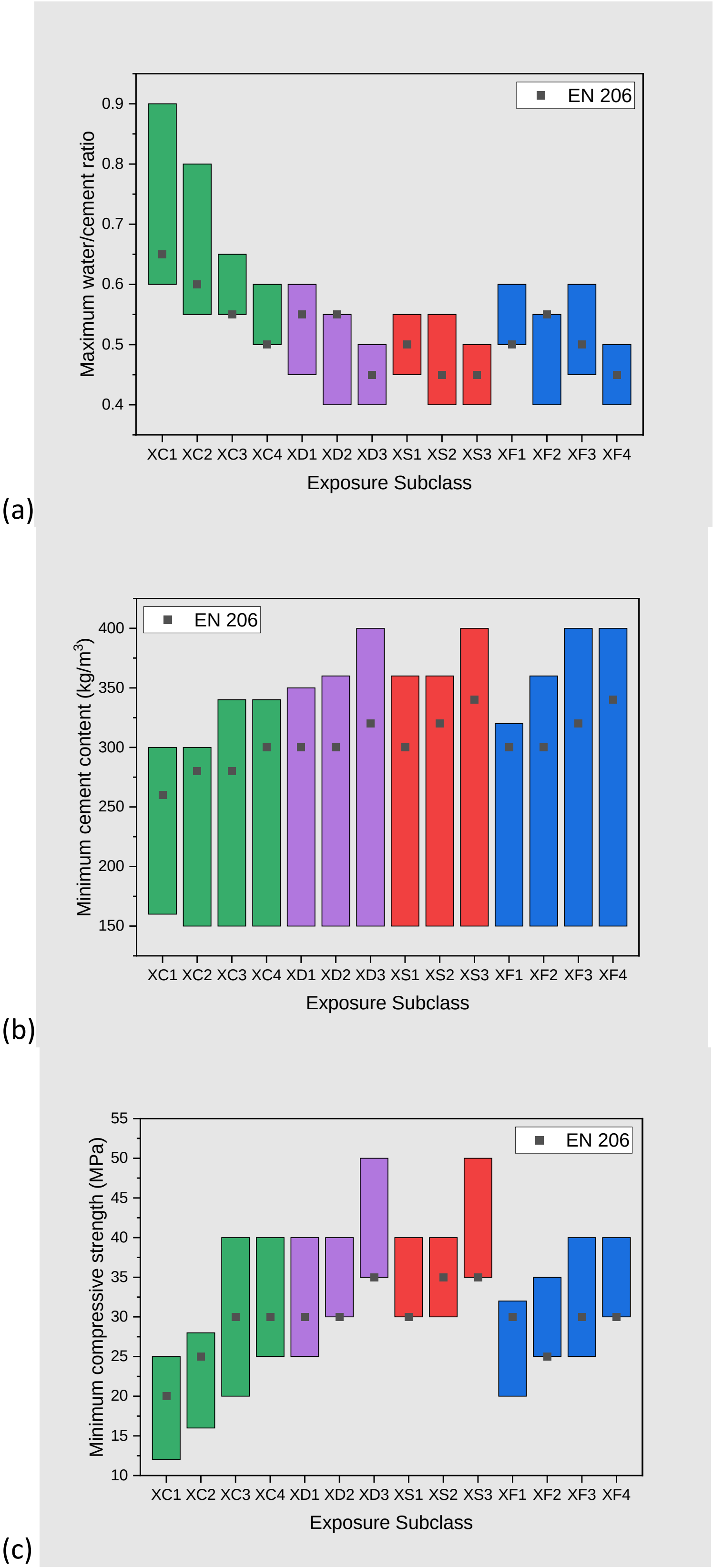


Figure 5-2. Variation of (a) minimum water/cement ratio (b) minimum cement content, and (c) minimum compressive strength requirements specified in national annexes for the application of the non-harmonised EN 206 standard. The baseline values given in informative annex F of EN 206 are shown for reference.

For example, in Figure 5-2, the large variation in minimum concrete strength shows that while the requirement is performance-based, the limiting values to ensure durability are prescriptive. In the most widely used international concrete standards and codes, the traditional approach to control concrete *durability* is by setting prescriptive limiting values for indirect durability indicators such as minimum cement contents, maximum water/cement ratios and minimum compressive strengths, alongside maximum depth of cover to concrete reinforcement and crack widths. These concepts are mainly based on historical experience using concrete produced with ordinary Portland cement and natural high quality aggregates. However, these prescriptive limits may not correlate with the properties that affect the durability of concrete, particularly considering the use of new source materials (i.e. other than from natural sources) which could either be present as a supplementary cementitious material (SCM) or an aggregate (in concrete). It is important to consider also that a significant majority of cement is used for the production of concrete, and so effort should be focussed not only on reducing the CO_2 intensity of cement, but also that of concrete. The number of potential new SCMs (including locally available materials) is much larger than those currently permitted in existing standards. The need for consensus for new SCMs to enter the standard may hinder the adoption and exploration of locally available materials, which is important considering resources of traditional SCMs like coal fly ash have declining availability. The limits for cement constituents are based on experience, but are well considered and technically proven. However, different degrees of experience with different cement types can result in unnecessarily high clinker contents and high CO_2 intensity of the cement.

A transition to performance-based specifications will require the development of rapid and reliable (appropriate) performance test methods. Some test methods need to be altered for new materials. For example, the curing temperature in the lab (20 to 23 °C) may not be representative of the in-the field climatic conditions experienced in many parts of the world and where much of the concrete production will be based in the coming decades. Test methods can therefore sometimes penalise alternative materials that show superior performance at high temperatures. Another concern is that tests are designed for known issues, for example, the ASTM C151 autoclave expansion tests are designed to monitor volume instability due to the delayed hydration of MgO or CaO. Novel cement formulations may not contain these components but, instead, contain new components that could cause unknown instability issues. These issues must be understood to design test methods and set limits in the standards. Compressive strength and slump are simpler properties to incorporate into performance-based standards since: (i) they can be measured at relatively short times of curing, i.e., minutes to hours for slump, and days for compressive strength; (ii) the general inverse relationship between porosity and strength is well known in materials science and specific micromechanical models exist for cementitious materials;[1] and (iii) predictive models for slump exist, e.g. based on the relative paste volume in a concrete mix.[2] Durability, meaning the resistance to deterioration, is more challenging to incorporate because deterioration of concrete: (i) can occur over years to many decades, or centuries, (ii) proceeds via several physical and chemical pathways (e.g. abrasion, chloride-induced corrosion), and (iii) is affected by both intrinsic material composition and handling/manufacturing conditions (on-site placement or factory-based production). The use of thermodynamic modelling in this framework is important with regard to chemical damages since it captures long-term changes in materials and thus improves reliability in its results. An important example where thermodynamic modelling using data now currently available could have avoided structural failure from concrete deterioration is the use of calcium aluminate cement concretes in the mid-late 20th century in Great Britain. These failures occurred from volume and solid phase changes that thermodynamic modelling can now reliably predict.

ASTM C1157 is a performance-based standard, which has not been widely used. Barriers to adoption included a lack of interest and familiarity with the specification, lack of adoption in current standards and building codes, lack of commonly tested properties in other standards, concerns with the lack of appropriate performance test methods, and difficulties interpreting the standard, which was seen as complex.

Overall, it is clear that whilst the industry view is that performance-based standards are preferable, they are also challenging to enact in practice. It is likely that there will continue to be a blend of performance and prescriptive standards and that unless serious effort is made to increase the slow drift from mainly prescriptive to mainly performance-based standards (for example, by governmental intervention to fund the work of standards setting committees, and to fund the development of harmonised performance tests) this drift will likely be significantly slower than the climate crisis requires. The work of experts on both the Rilem and BSI Flex committees (discussed in section 8.2) and section 10.1.8 to develop performance based standards for novel cement blends is an example of ongoing work in this area.

4 Introduction to the Project

Adherence to a standard is a simple way to claim that certain specifications are met. Standards are set by technical committees comprised of experts in the field and overseen by a governing body, which regulates the process of setting the standards.

The IEAGHG has commissioned researchers from Imperial College London to investigate whether performance-based standards might assist in the more rapid adoption of new construction materials or improvements to existing construction materials, with the overall aim of reducing CO_2 emissions from the construction industry. In part I of this work, we will examine new types of cement, their use in concrete, and new admixtures such as supplementary cementitious materials (SCMs), fillers, and CO_2. Part II is a survey of a number of companies who are producing building materials in such a manner as to take up CO_2 during their production.

In the context of the construction industry, standards are comprised of two main components – prescriptive and performance-based elements. A particular overall standard (say for the use of a type of cement in a particular usage case) may have different elements within it which are performance-based or prescriptive.

Prescriptive standards state that *e.g.* a material must be composed of particular grades of materials, combined in a specific manner, and each within a set range. For example, the minimum cement content in concrete (kg/m^3) is commonly specified. Performance-based standards are more about what the material *does* when subjected to certain tests. Such tests may comprise *e.g*. the compressive strength after a certain period of time, when measured in a specific manner (the testing apparatus will be specified, as will how the tests are to be carried out). Other characteristics which are specified can include the sulphate resistance and the durability of the material. Since materials in the built environment are likely to be in place for many years, it is frequently necessary for tests within standards to accelerate the processes under study, compressing years of use (for example freezing and thawing) into months of tests. The trouble with accelerated tests is that they can never 100 % recreate the actual situation undergone by a particular material in its actual daily use, since inherently the accelerated process involves different chemistry and exaggerated physical processes compared to the natural ones.

Standards are used by many stakeholders within the construction industry to enable the safe construction of buildings and other structures. Stakeholders can include Design Houses (including architectural firms), building materials companies, construction contractors and end users.

Key to the use of standards is the requirement for a designer to demonstrate that their design is fit for the job. It is possible (and sometimes happens, particularly for very novel or significant constructions such as a new and exciting stadium designs, and HS2[3]) to demonstrate that a design is fit for purpose by e.g. model-based validation where an existing standard is not suitable. For basic structures, it is frequently possible to look up *e.g.,* the wind loading from a standard, but where the structure is highly novel these may not be available. Usually, the concretes that were used within the structure would have been mixed and used within existing codes, however it is possible under exceptional circumstances for non-standardised materials to be used, but this comes with the additional liability of doing so. It is generally easier to demonstrate that the design is fit for the job by using a standard that has been written and validated for a particular usage case, and then validating that the design has been built in compliance with the standard. This then allows building control and insurers a straightforward route to certifying a structure e.g., for sale and or occupancy. Some stakeholders and interactions between them are shown in Figure 4-1.

It is important to note that the designer can choose which standards they will specify in their design – standards will be designed with a particular use in mind, but will also specify either the performance of the materials in place, the composition of those materials, or a combination of both. Different jurisdictions will have different standards covering ostensibly the same overall material (for example "cement") but will frequently have a large number of subdivisions within them, allowing the use of different materials within them ("cement including coal fly ash between X and Y %", *e.g.*, in EN 197-1:2011). One reason for this is that durability depends greatly on the environmental conditions that concrete is exposed to, and environmental conditions vary from location to location.

We begin with an analysis of current standards, to determine what the baseline of standards worldwide is, before considering whether a shift from prescriptive (crudely, composition-based) to performance-based standards would assist global efforts to allow the use of more novel cementitious materials.

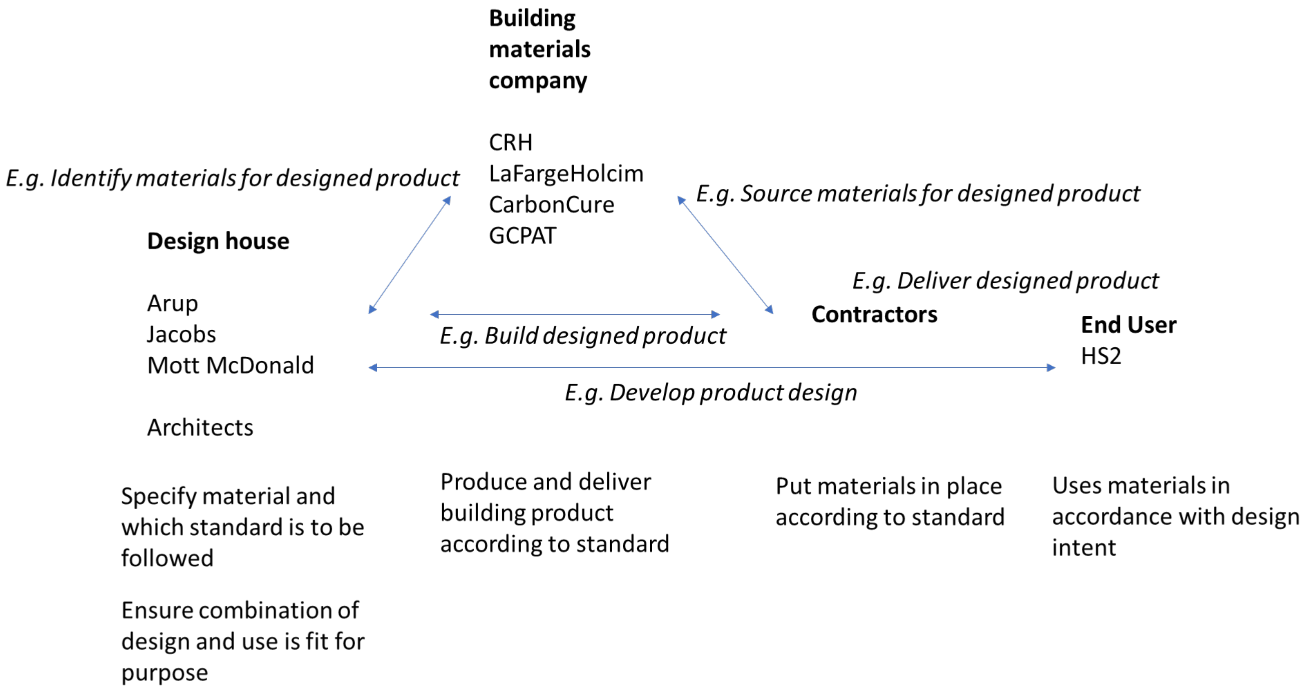


Figure 4-1. Interactions between various stakeholders using building standards.

5 Literature Review of International Standards & Testing

This section provides an overview of the current international standards, codes and test methods for concrete, cement and aggregates. The relevant standards used in China, Europe and the USA were reviewed based on their large shares of global cement production (Figure 5-1) and the widespread use of European and American standards internationally. In addition, the standards from the International Organization for Standardization (ISO) were also reviewed. The ISO provides common standards for the global community to ensure that products are safe, reliable, and of good quality.

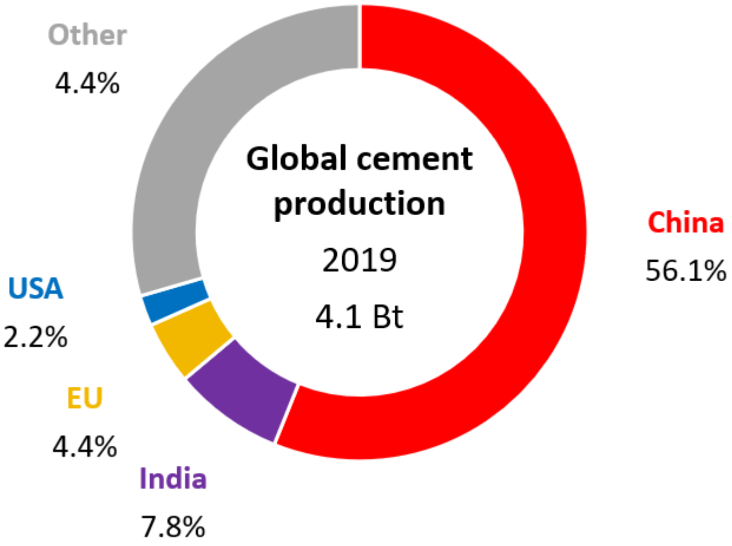


Figure 5-1. Global production of cement in 2019 (before the COVID-19 pandemic).[4]

5.1 Review of Current Standards and Codes for Concrete

5.1.1 Exposure classes in international concrete standards

Exposure classes are common across all the international concrete standards we surveyed (see Table 9-1). Exposure classes are used to predict the severity of an environmental exposure that leads to concrete deterioration. Based on the class designation, prescriptive limits on the concrete properties and constituents are often given in standards to specify concrete durability.

The exposure classes defined in the European Standard EN 206 and ISO standard ISO 22965-1 are based on European climate conditions, experiences, and expected deterioration mechanisms. Concrete can be assigned to six main exposure classes (Table 9-1) which are further divided into 18 subclasses based on severity. The subclasses are described by broad, non-quantified descriptors such as “moderate”, “low” and “very low” to describe the intensity of humidity conditions, “near to the coast” to describe the location of a structure, and “moderate” and “high” to describe water saturation. Additional environmental parameters that may accelerate the degradation mechanism, e.g. temperature and salinity, are also not described. As such, the exposure classes must be interpreted locally. EN 206 is a non-harmonised European standard, and a survey of nationally determined provisions found that 10 countries (out of 16 replies) have changed the guidance given in EN 206 for exposure classes in their national annex.[5] These changes include additional remarks, informative examples, and exposure classes and subclasses.

In ACI 318, four main exposure classes are defined based on degradation mechanism (Table 9-1) which are further subdivided into 23 sub-classes based on severity. Similar to the exposure classes defined in EN 206 and ISO 22965-1, general descriptors such as “limited” and “frequent” are used to describe exposure to water. However, the subclasses in ACI 318 are better defined than in EN 206, and therefore easier to assign to concrete.

Two Chinese standards are used co-ordinately: GB/T 50476 (for all concrete structures) and JTG/T 3310 (for bridges and highways). The framework of JTG/T 3310 is based on GB/T 50476; these two standards use similar classifications of exposure conditions. Five main exposure classes are defined based on degradation mechanism, which are further divided into 16 subclasses (Table 9-1). The conditions for each subclass are generally more well defined than the EN, ISO and ACI standards. Temperature ranges are given for freeze-thaw environments and although some broad descriptors are used, each subclasses is sufficiently distinct.

The exposure classification system is used to simplify the design process by specifying the minimum durability requirements for concrete to remain serviceable for a certain period of time when exposed to specific environmental conditions. However, a drawback of this system is that broad assumptions must be made, making it challenging to develop universally applicable guidelines for all environments. Concretes can also be under or overdesigned if the wrong environmental subclass is chosen and local conditions are not taken into account. This is particularly significant for the ISO standard, where perception of terms such as moderate humidity is subjective and varies significantly across the world. Additional environmental classes and subclasses could be added to existing standards, however this may increase the complexity of design.[6]

5.1.2 Use of prescriptive and performance-based specifications in international concrete standards

Concrete standards often provide prescriptive “deemed-to-satisfy/comply” requirements based on the assigned exposure subclasses as indirect methods of ensuring durability. Common requirements include minimum compressive strengths, maximum water/cement ratios, depth of concrete cover, crack widths, and minimum cement contents (Table 9-2).

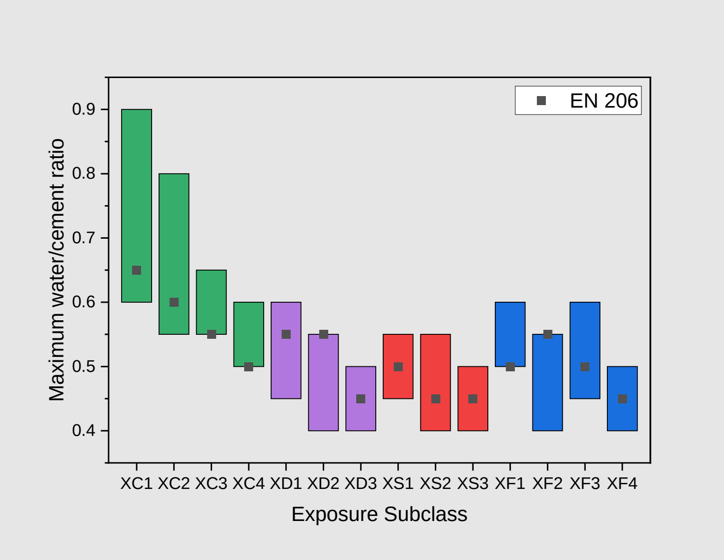
EN 206 contains recommendations based on exposure class for maximum water/cement ratios and minimum cement contents, and for some subclasses, minimum air contents, aggregates with freeze-thaw resistance and the use of sulphate-resisting cements. These recommendations are informative and based on concrete designed for an intended working life of 50 years, using cements conforming to EN 197-1 and normal weight aggregates with maximum diameter in the range of 20 mm to 32 mm. The characteristic compressive strength of a concrete is defined in EN 206 by its compressive strength class and is an important performance-based design parameter. Recommendations for minimum compressive strength classes are also given for all exposure classes, these are not required to be specified for each exposure class. In addition, according to the interviews conducted during the writing of this report, the primary design parameter for the majority of concrete is strength, not durability.

EN 206 is a non-harmonised European standard, therefore the recommendations may be altered when adopted by each member country in their National Annex. As a result, large differences in the limiting values for the requirements exist between member countries for the same exposure subclasses, shown in Figure 5-2. For example, for subclass XC1, the maximum water/cement ratio varies from 0.6 to 0.9, the minimum cement content varies from 160 to 300 kg/m^3, and the minimum compressive strength from 12 to 25 MPa between national standards. The large variation in minimum concrete strength shows that while the requirement is performance-based, the limiting values to ensure durability are prescriptive. This is an important point – a performance-based standard can have prescriptive limits on composition to ensure that the rigorous testing which has been undertaken in producing the standard is applicable; cements outside the range of testing cannot be guaranteed to be compliant.

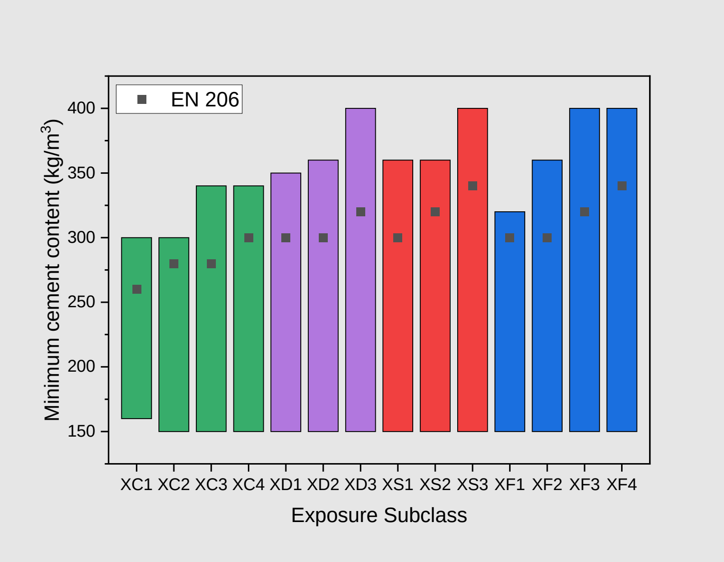
A *k*-value (or efficiency factor) is used in EN 206 and ISO 22965-1 to determine the contribution of supplementary cementitious materials (SCMs) to the minimum water/cement ratio. The water/cement ratio then becomes the water/(cement + *k**SCM) ratio, the rest of the SCM is effectively treated as aggregate. Importantly, the US standard ACI 318 and the Chinese standards GB/T 50476 and JTG/T 3310 do not make this distinction, and treat SCMs as equivalent to cement (i.e. k = 1). The *k*-value does not apply to SCMs used to produce blended cements (EN 197-1), only to SCMs added with cement to produce concrete. In the EN and ISO standards, *k*-values apply to fly ash, silica fume and ground granulated blast furnace slag. A provision exists within EN 206 to alter the prescriptive requirements for durability relating to exposure class using the equivalent concrete performance concept (ECPC) and equivalent performance of combinations concept (EPCC). These concepts may be used provided the concretes use cements conforming to EN 197-1, and the concrete shows equivalent performance to a reference concrete for the relevant exposure classes. This allows for high *k*-values to be used by concrete producers.

Alternatively, EN 206 states that the requirements for each exposure class may be established using performance-based methods for durability and may be specified in terms of performance-related parameters. The standard states that a suite of European performance-related tests is being developed and the framework for equivalent durability procedure has been published as technical report CEN/TR 16563.[7] The technical report outlines the principles of the equivalent durability procedure (EDP) and only applies to concrete compositions containing constituents that are covered by European technical specifications referred to in EN 206 or provisions valid in the place of use. The performance-based concrete must be compared to a reference concrete. This comparison could be misleading if the reference concrete is based on outdated prescriptive requirements for an exposure subclass.

ACI 318 specifies limiting values for maximum water/cement ratio and minimum compressive strength for each subclass. Minimum cement contents are not given. For certain subclasses, requirements for air content, chloride ion content, aggregate, admixtures, and cement types are also specified. The standard is primarily prescriptive with few performance-based specifications. One performance-based specification is for resistance to sulphate attack. In ACI 318, the permitted types of cementitious materials used to produce concrete with



(a)



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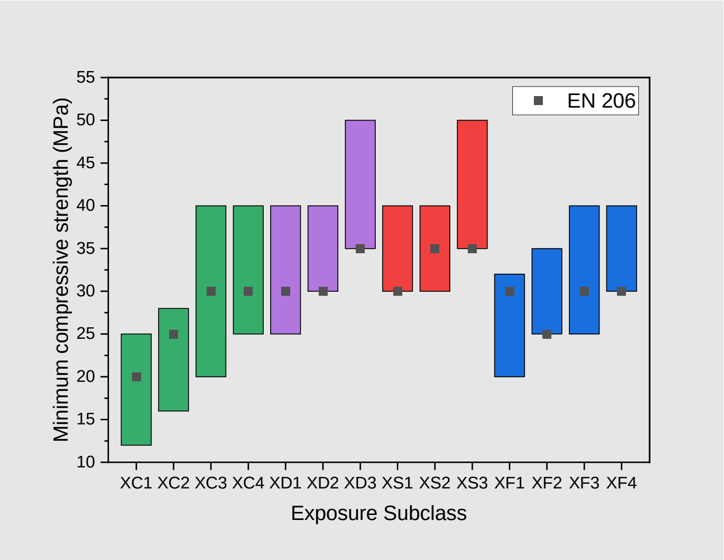

(c)

Figure 5-2. Variation of (a) minimum water/cement ratio (b) minimum cement content, and (c) minimum compressive strength requirements specified in national annexes for the application of the non-harmonised EN 206 standard.[5]*. The baseline values given in informative annex F of EN 206 are shown for reference.*

sulphate exposure subclasses is limited unless the criteria for sulphate resistance is met using performance-based test method ASTM C1012.

ISO 22965-1 does not provide any numerical values but states that a prescribed concrete specification should contain requirements for the cement content and type (and strength class if applicable), the water/cement ratio or consistency (class or target value), type of admixture or addition, and aggregate type, category, maximum chloride content, maximum size and grading. The standard also states that durability requirements may also be specified in terms of performance-based parameters and provides guidance in informative Annex B. The performance-based approach is based on the Model Code for Service Life Design published by fib (International Federation for Structural Concrete)[8]. The guidance states that the performance-based design method is relevant to corrosion resistance and possibly freeze-thaw resistance of concrete – not alkali-silica reaction, sulphate attack or abrasion, which are best dealt with by a prescriptive approach.

The Chinese standard JTGT 3310 is mainly based on a prescriptive approach by limiting parameters such as minimum water/cement ratio, some performance-based requirements are also provided in section 5 of JTGT 3310. Different performance-based indicators and parameters are used to control the durability of concrete in various environmental conditions, as shown in Table 5-1.

Table 5-1. Performance-based durability indicators considered in JTGT 3310.

Deterioration mechanism	**Performance-based parameters**	**Related test method in standards**
Freeze-thaw resistance	Freeze-thaw durability factor (DF)	Quick freezing test (GB/T 50082)
Chloride ingress	Chloride diffusion coefficient (D_{RCM}); Electric flux value	Chloride diffusion and electric flux test (GB/T 50082)
Sulphate attack	Sulphate attack deterioration Index (KS)	Sulphate crystallization resistance test (GB/T 50082)

As reported by ACI committee 329, the first barrier against corrosion of reinforcement is adequate concrete cover, and delivering concrete with high resistance to penetration of water, CO_2, O_2 and salts[9]. The minimum cover depths specified in ACI 318 are prescriptive. They are given based on the structural element (beam, joint, wall, etc.), type of reinforcement and exposure condition (exposed to weather and/or permanently in contact with the ground) - not the exposure class. The minimum cover depths range between 19 mm and 76 mm. A provision specifies that the cover shall be increased as necessary for concrete in corrosive environments or other severe exposure conditions.

ISO 22965-2 states that minimum covers to reinforcement should be specified in the national annex, however, minimum cover depths are specified in ISO 15673. The cover depths are based on those given in ACI 318. The minimum cover depths for each exposure condition, structural element and type of reinforcement are similar to those in ACI 318, ranging from 25 to 75 mm.

In Europe, minimum cover depths are specified in Eurocode 2 based on the exposure class of the concrete and the structural class of steel used as reinforcement. The minimum cover depths range between 30 mm and 50 mm for reinforced concrete with a service life of 50 years. An increase in minimum cover depth is required when the service life is increased to 100 years (+10 mm) and for uneven surfaces (+5 mm). The cover depth can be decreased by using additional protection (e.g. protective coatings), stainless steel, air entrainment, and a higher strength class than is required by EN 206 for the specific exposure class.

Minimum cover depths in GB/T 50476 are specified according to exposure class and type of structural element (board, wall plate, etc.). The minimum cover depths range from 20 – 65 mm for a service life of 50 years. The service life can generally be reduced to 30 years or increased to 100 years by lowering or increasing the minimum cover depth by approximately 5 mm, respectively.

EN 13670 states that concrete is cured to minimise plastic shrinkage, ensure adequate surface strength and zone durability, and protect from harmful weather conditions, freezing and harmful vibration, impact or damage. The standard sets out four curing classes defined by curing period or the required strength at the end of the curing period, as a percentage of the characteristic 28 day compressive strength. The curing classes are further categorised by the required strength development rate: rapid, medium or slow. The curing environment and minimum curing periods are given in Table 9-5 for curing class 3, which requires a concrete surface strength equal to 50% of the characteristic compressive strength. The curing requirements are a mixture of prescriptive and performance-based specifications. The minimum curing period is prescriptive, while the performance-based durability requirements are given in terms of compressive strength, which indicates that a certain level of hydration has been achieved. The standard also accounts for the different temperatures experienced in the field by providing lower minimum curing durations with increasing temperature from 5 to 25 °C. The curing requirements specified in ISO 22965-2 are identical to those given in EN 13670.

Two options for strength development during curing can be used in ACI 318, normal and high early strength development. From Table 9-5, a temperature of at least 10 °C must be maintained during curing in a moist environment. Accelerated curing (different to high early strength curing) is also permitted using high-pressure steam, steam at atmospheric pressure and heat and moisture (or other processes accepted by the licensed design professional), but must not reduce the durability of the concrete.

In China, curing requirements are covered by standard GB 50666 (see Table 9-5). The curing requirements are based on exposure class and cement type (Portland cement or SCM-based). The requirements for concrete with the lowest risk exposure class, I-A, are prescriptive and specify the minimum curing temperature, environment and duration. An additional performance requirement based on attaining a certain percentage of the minimum compressive strength is also given for the remaining exposure classes.

The workability of freshly mixed concrete is an important design parameter that determines the ease of mixing, placing, consolidating, and finishing concrete while maintaining homogeneity. The workability depends on the consistency of the concrete, which is the ability of the freshly mixed concrete to flow, *i.e.* its fluidity or stiffness. In ACI 301, the slump at the point of delivery should be specified to allow for proper placement and compaction (< 230 mm) and determined in accordance with the performance-based test method ASTM C143. In EN 206, concrete can be classified with respect to consistence using the performance-based slump, compaction, flow and slump-flow consistence classes. EN 206 also allows consistence to be specified by target values for slump, degree of compactability, flow diameter, slump flow diameter, t_{500} (time in seconds to flow to a diameter of 500 mm in a slump-flow test) and t_V (time in seconds of the flow in a V-funnel test). Informative Annex L of EN 206 notes that consistence should only be specified by target values in special cases.

5.1.3 Problems with prescriptive-based specifications to ensure durability

As discussed, in the most widely used international concrete standards and codes, the traditional approach to control concrete durability of concrete is by setting prescriptive limiting values for indirect durability indicators such as minimum cement contents, maximum water/cement ratios and minimum compressive strength. These concepts are mainly based on historical experience using concrete produced using ordinary Portland cement and natural high quality aggregates. However, these prescriptive limits may not correlate with the properties that affect the durability of concrete. This concern is particularly valid for modern concretes that incorporate new constituents and mixes beyond traditional concrete, e.g. containing CEM I-V type cements.

The most widely used performance specification for concrete is compressive strength. However, in the context of concrete codes and standards, requirements for minimum compressive strength are specified and used as an indirect durability indicator based on exposure classes. This practice is increasingly being called into question[10]. Two examples that demonstrate the poor correlation between strength and durability are, (i) air-entrained concretes which require much lower water/cement ratios to achieve the same strength as non-air-entrained concrete and exhibit lower penetrability[11], and (ii) high (and ultrahigh) strength concretes that use low water/cement ratios and high cement contents, which lower the concrete workability and therefore require high amounts of water-reducing admixtures, that can make the concrete suspectable to early age cracking and hence early deterioration.[10]

The role of cement content in prescriptive standards is less clear. The minimum cement content can vary considerably (e.g. from 150 to 400 kg/m^3 for subclass XD3) for the same exposure subclass in countries that adopt EN 206 (Figure 5-2b), and in some standards, e.g. ACI 318, the parameter is not used at all. Historically, minimum cement contents may have been specified to (i) control the water/cement ratio and maintain workability before the use of admixtures, (ii) ensure that there is adequate paste to fill voids between aggregate, and (iii) for the protection of steel in concrete by reducing the penetration of chlorides and CO_2.[12] While prescriptive minimum cement contents are useful, providing guidance to an inexperienced concrete producer, reasons (i) and (ii) are not relevant for concretes produced using modern admixtures that enable the production of workable concretes with low water/cement ratios and low cement contents. Considering (iii), a concrete with the same water/cement ratio but a higher cement content than a reference concrete will have a higher paste content with different properties (Figure 5-3). The concrete with a higher paste volume contains more pores, which increases the permeability of the concrete, increases the penetration of aggressive species and increases the risk of thermal and shrinkage cracking.[13–17]

The water/cement ratio is used extensively as a durability indicator in concrete standards. Concretes produced using high water/cement ratio and OPC are generally more porous than those produced using lower water/cement ratio, and therefore more permeable and less durable.[16,18–20] However, the water/cement ratio specification assumes all cements perform identically. The use of other cement types and aggregates, and contributions of SCMs to the porosity and thus transport properties of the concrete means that existing prescriptive limiting values for water/cement ratios in EN 206 and ACI 318 may be outdated.

For reinforced concrete, the quality of the first few centimetres of concrete (covercrete) is important, not only that of the bulk concrete[20]. The covercrete is much more affected by poor construction procedures (poor compaction and curing) and environmental conditions than the water/cement ratio and compressive strength (governed by the internal bulk of the concrete)[20,21]. However, EN 206 contains a provision to lower the minimum cover depths if concrete with compressive strength higher than the limiting values given in EN 206 is used for an exposure class. This implies a direct relationship between compressive strength (governed by the bulk) and the durability of concrete, which has previously been discussed. Prescriptive specifications for minimum cover depths are also based on historical practice with traditional mix designs. The chemical composition of the cement binder also affects the resistance of concrete to fluid penetration from the external environment and therefore can alter the cover requirements[22].

The curing specifications in the standards are primarily based on obtaining adequate strength, rather than curing to obtain adequate durability. Standards usually specify a minimum curing duration which assumes that the strength gain rate is equivalent for all mix designs. Some standards specify the required strength at the end of the curing period as a percentage of the design strength. Minimum curing duration specifications are based on experience with traditional Portland cement-based concretes and may not be valid for alternative mix designs that use novel admixtures and SCMs that may develop strength differently, e.g. requiring longer times or higher temperatures. The prescriptive curing requirements also prevent using alternative curing techniques that may demonstrate better performance, e.g. accelerated curing, which is often used in the precast concrete industry.[23]

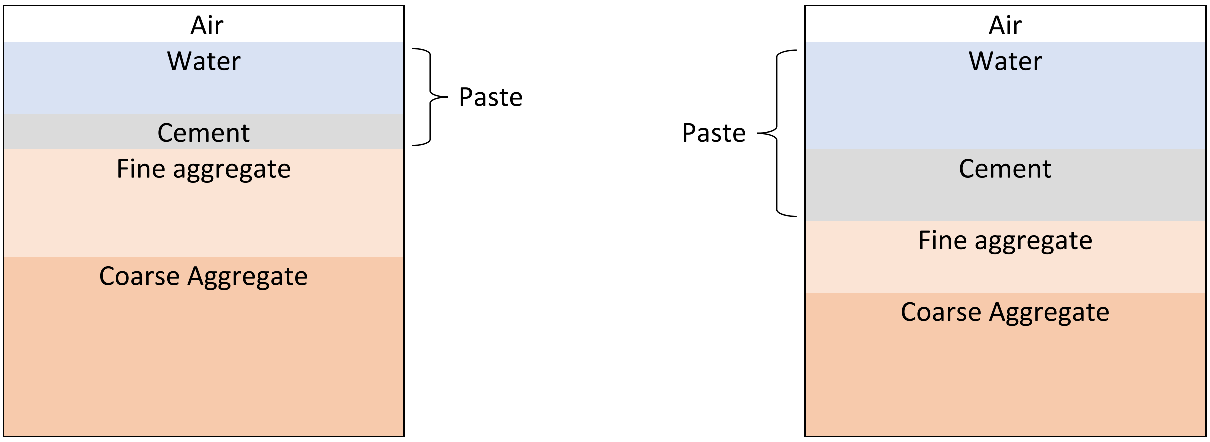

Figure 5-3. Concrete mix designs with the same water/cement ratio but low and high paste volumes.

Comparing concrete specifications between international standards is challenging because of their different exposure classification systems. A comparison between the exposure classes given in the standards is shown in Table 9-3 with their respective limiting values for minimum cement contents, maximum water/cement and compressive strength compared in Table 9-4. From Table 9-3, the EN XF1, ACI F1 and GB/T II-D exposure classes were identified as equivalent exposure classes for moderate exposure to a freeze-thaw environment. A comparison of the specifications given for the exposure classes is shown in Table 5-2. The three standards set similar limiting values for the maximum water/cement ratio (0.50-0.55). However, the minimum compressive strength requirement in the Chinese concrete standard (35 MPa) is much higher than the European and American standards (24-25 MPa). In Table 9-4, the minimum compressive strength requirements in GB/T 50476 for each exposure class are typically 10-14 MPa higher than their equivalent exposure class in EN 206 and ACI 318. The minimum air content specifications are similar for the American and Chinese standards and are based on the nominal aggregate size, whereas the European standard specifies one value for the minimum air content for all concrete mixes designed for exposure class XF1.

Table 5-2. Comparison of specifications for concrete exposed to moderate freeze-thaw environment.

Specification	**EN 206 – XF2**	**ACI 318 – F1**	**GB/T 50476 – II-D**
Cement type	EN 197-1 EN 197-5 EN 14647 EN 15743	ASTM C150 ASTM C595 ASTM C1157	GB 175
Supplementary cementitious materials	Prescriptive maximum contents of: Fly ash Silica fume Ground-granulated blast-furnace slag	No limits on cementitious materials	JTGT 3310 Prescriptive maximum contents of: Fly ash Ground-granulated blast-furnace slag
Contribution of supplementary cementitious material to water/cement ratio	Prescriptive k-value concept[A]	Entire content	Entire content
Aggregate	EN 12620	ASTM C33 ASTM C330	GB/T 14684 GB/T 14685
Maximum water/cement ratio	0.55[C,D]	0.55	0.5

Minimum cement content (kg/m^3)	300[C,D]	None	None
Minimum compressive strength (MPa)	25[C,D]	24	35
Minimum air content (%)	4.0	3.5 – 6.0 depending on nominal aggregate size	4.5-6.0 depending on nominal aggregate size, and wet or salt environment

[A] equivalent concrete performance concept can be applied but is not widely used

[B] only valid for specific cement classes in ISO 22965

[C] values are provided in informative annex F in EN 206 based on concrete producing using cements conforming with EN 197-1, normal weight aggregates and designed for a working life of at least 50 years.

[D] performance-based route possible

5.2 Review of Current Standards and Codes for Cement

5.2.1 Use of prescriptive and performance-based specifications in international cement standards

A comparison of the prescriptive and performance specifications in international cement standards is outlined in Table 9-6. The specifications generally fall under three categories: chemical, mechanical and physical. Prescriptive specifications are generally used to control the chemical composition of cements, while the mechanical and physical requirements are typically related to performance.

The specification of cements in Europe primarily falls under the harmonised standard EN 197-1, which sets out five main types of cement, CEM I through V, and the non-harmonised addition EN 197-5, which sets out the requirements of a sixth cement type, CEM VI. The six cement types are categorised by limits on the amount of Portland cement clinker and amounts and types of additions (i.e. slag, silica fume, etc.). Similarly, the Chinese standard GB 175 specifies cement types based on clinker content and type of additions. In the United States, ASTM C150 defines five main types of Portland cement (Type I through V) based on end use requirements (e.g. high early strength). A further four cement types are defined for blended cements in ASTM C595 based on the type addition(s). ASTM C1157 is an alternative performance specification for hydraulic cement and defines an additional six cement types based on end use requirements, with no restrictions given for cement composition or additions. The use of alternative cements not covered by the ASTM standards is permitted in ACI 318 if approved by the licenced design professional and building official. According to ACI 318, approval must be based on test data demonstrating that the proposed concrete mixture created with the alternative cement meets the performance requirements for the application.

The chemical composition of Portland cement clinker in EN 197-1 is prescribed by setting limits for the in terms of C_3S, C_2S, CaO/SiO_2 and MgO content. Additional requirements for C_3A content are also given for sulphate-resisting cements. In ASTM C150, composition limits are given for the cement instead of the Portland cement clinker by setting composition limits for C_2S, C_3S, C_3A and MgO content. For some cement types, additional limits are specified for the Al_2O_3 and Fe_2O_3 content and the sum of ($C_2S + 4.75C_3A$) and ($C_4AF + 2C_3A$). Composition limits for MgO, the sum of (C2S + C3S) and the ratio of CaO/SiO_2 are also given in GB 175. Bogue calculations are carried out to approximate proportions of the four main clinker phases (C3S, C2S, C3A and C4AF). The Bogue calculations input the oxide analysis of the clinker into ratios and moduli relating the oxides, despite the fact that calculated values are often significantly different to the real ones.[24] Bogue calculations ASTM C595 refers to ASTM C150 for Portland cement requirements, and ASTM C1157 contains no chemical requirements.

Additional chemical requirements in the European standards include limits for loss on ignition, insoluble residue, sulphate content as SO_3, and chloride content. ASTM C150 specifies additional limits for loss on ignition, insoluble residue and the sulphate content as SO_3. The limits given for sulphate content depend on the amount of C_3A present. ASTM C595 also limits loss on ignition and sulphate content as SO_3, and for specific cement types, the insoluble residue and sulfide content as S^{2-}. GB 175 includes additional chemical requirements for sulphate and chloride contents, loss on ignition and insoluble residue.

The mechanical requirements in cement standards refer to performance-based minimum compressive strengths measured after a specified amount of time. Concrete strength is evaluated on different days as part of the concrete curing process. Concrete gains strength over time due to the hydration process, where cement particles react with water and form a hardened matrix. The strength of concrete is not fully developed immediately after placement but continues to increase over days, weeks, and even months. Different construction projects may have specific requirements for concrete strength at various stages of construction. For instance, in some cases, an early-age strength evaluation may be necessary to determine if the concrete is strong enough to support the next construction phase. In European cement standards, each cement can be obtained in three strength classes: 32.5, 42.5 or 52.5 MPa minimum compressive strengths at 28 days. The strength class is then divided based on strength development requirements (high early strength (R), ordinary (N) or low (L)) and must comply with 2 or 7 day compressive strength requirements. In ASTM C150, C595 and C1157, the minimum compressive strength requirements are given as a combination of 1 day, 3 day, 7 day and 28 day strengths. In the Chinese standard GB 175, each cement can be obtained in four cement classes: 32.5, 42.5, 52.5 and 62.5 MPa minimum compressive strength at 28 days. Each strength class is assigned either high early strength (R) or ordinary (N) strength development and must comply with 3 day strength requirements.

The physical requirements in European standards are specified as limits for the initial setting time, soundness and heat of hydration at 7 days or 41 h. ASTM C150 sets limits for the air content and initial and final setting times of the cement, and for most cement types, limits for fineness. In ASTM C595, limits are given for soundness (autoclave expansion and contraction), initial setting time and air content. In ASTM C1157, limits are given for air content, initial setting time, length change in an autoclave, and mortar bar expansion, and specifies limits for the heat of hydration at 3 or 7 days and sulphate expansion at six months or one year for some cement types. GB 175 sets limits for air content, setting time, soundness, and heat of hydration.

The method of controlling resistance to sulphate attack is a good example of prescriptive and performance-based approaches in cement standards. In ASTM C150, the sulphate resistance of the cement is controlled a prescriptive chemical specification for the amount of tricalcium aluminate (C_3A) in Portland cement. However, in ASTM C1157, the sulphate resistance is controlled using a performance-based specification for the maximum expansion of a mortar bar when it is stored in water in accordance with test method ASTM C1038. ASTM C150 does include a provision for amounts of SO_3 to exceed the limit specified in the standard if test method ASTM C1038 is used. However, limits to C_3A content still apply.

Comparing specifications for cements between international standards is difficult because the cement types are defined using different criteria – either end-use requirements or composition. A comparison of common specifications for general use Portland cement with high Portland cement clinker fraction is shown in Table 5-3. The chemical specifications for SO_3, MgO and chloride content are similar across the three standards. The maximum loss on ignition and insoluble residue permitted for CEM I are much greater than those for Type I and Type P·1 and P·II cements. For the mechanical specifications, CEM I does not have a 3 day compressive strength requirement, while the final strength for Type I must be achieved within 7 days, compared to 28 days for CEM I and Type P·1 and P·II cements. The values for minimum compressive strength are semi-quantitatively comparable because of the different methods used to produce the test specimens (composition and shape). The physical specifications for CEM I have greater maximum limits than the other standards. CEM I and Type P·1 and P·II cements have no air content requirements, and CEM I has no final setting time requirement. The maximum initial and final setting times specified for Type I and Type P·1 and P·II cements are similar. In addition to the maximum prescriptive limits on MgO content, the physical specifications include performance-based test methods for soundness. The European and Chinese standards use the Le Chatelier test (EN 196-3 and GB/T 1346, respectively), while the ASTM standard uses an accelerated autoclave expansion test (ASTM C151). The Le Chatelier test determines the expansion of 1 day old paste samples confined in a split cylinder when boiled in water for 3 h. Test method ASTM C151 determines the expansion of a 1 day old paste bar when exposed to autoclave conditions (2 MPa steam for 3 h). The autoclave expansion test is considered overly severe[31] and cements with a good history under field conditions and MgO content well below the limit given in Table 5-3 have failed the autoclave expansion test[32]. Therefore, this test is not widely used in standards outside the US and Canada[30].

Table 5-3. Comparison of specifications for general use cements with high Portland clinker fraction.

Specification	EN 197-1	ASTM C150	GB 175
	CEM I – 32.5N	Type I	Type P·I and P·II – 32.5N
Chemical			
Mineral addition (max, %)	5	5	5
Minor additional constituent (max, %)	Considered a mineral addition	Limestone only	Limestone and GGBS
MgO content (max, %)	5 (in clinker)	6 (in cement)	6 (in cement)
Loss on ignition (max, %)	5	3	3.0 (P·I) and 3.5 (P·II)
Insoluble residue (max, %)	3.5	0.75	0.75 (P·I) and 1.5 (P·II)
SO_3 content	3.5	3.0 (C_3A < 8 %) 3.5 (C_3A > 8 %)	3.5
Chloride ion content	0.10	0.02 (optional)	0.10
Mechanical			
Minimum compressive strength (MPa)			
1 day	-	-	-
3 days	-	12.0	12.0
7 days	16.0	19.0	-
28 days	32.5	-	32.5
Physical			
Air content (max, %)	-	12	-
Initial setting time (min, minute)	75	45	45
Final setting time (max, min)	-	375	390
Soundness (max, mm)	10 (Le Chatelier)	0.80 (autoclave expansion)	5 (Le Chatelier)

5.2.2 Problems using a prescriptive approach to cement standards

Prescriptive specifications simplify the process of cement manufacture and provide well-defined criteria for the manufacturer to demonstrate compliance. They are also helpful for the consumer receiving a well-defined and certified product with approved application rules. However, the prescriptive approach may prohibit innovation regarding introducing new materials and technologies to improve the performance and reduce the CO_2 emissions intensity of cements. This was mentioned several times in the interviews in section 8.

Cement standards that categorise cements by clinker content and composition of additions (EN 197-1, EN 197-5, GB 175 and ASTM C595) can become confusing due to the large number of cement types with no specific end use given. For example, 39 cement types are currently specified in EN 197-1 and EN 197-5, including 27 types of CEM II. The number of potential new SCMs (including locally available materials) is much larger than those currently permitted in existing standards. Including these materials would further increase the number of composite cement types specified in EN 197. This not practical and may stretch the already complicated relationship between cement composition and performance. The need for consensus for new SCMs to enter the standard may hinder the adoption and exploration of locally available materials, which is important considering the fact that resources of traditional SCMs like coal fly ash have declining availability.[25] The limits for cement constituents are based on experience, but are somewhat arbitrary, and therefore can result in unnecessarily higher clinker contents and high CO_2 intensity of the cement.

In contrast to the cement types specified in EN 197-1, EN 197-5, GB 175 and ASTM C595, the cement types in ASTM C1157 are specified based on end use requirements, with no restrictions on cement composition or additions. Theoretically, the standard permits the use of completely new types of binders. However, a 2001 survey on the acceptance and use of the standard found uptake was limited due to perceived barriers and concerns held by specifiers and manufacturers.[26] Barriers to adoption included a lack of interest and familiarity with the specification, lack of adoption in current standards and building codes, lack of commonly tested properties in other standards, concerns with the lack of appropriate performance test methods, and difficulties interpreting the standard, which was seen as complex. The survey was carried out over 20 years ago; therefore, the industry's opinions may have changed (as is partially evidenced by the interviews undertaken as part of this project, discussed below), considering ASTM C1157 is now included in ACI 318, and modern environmental and resource pressures.

The prescriptive approach of the European and Chinese standards may prohibit innovation regarding introducing new cement formulations with lower embodied CO_2 emissions due to their alternative chemistries and potentially less energy-intensive manufacturing conditions. One example is Solidia Cement, a carbonatable calcium silicate clinker-based cement that reacts with CO2 during curing and requires lower clinkering temperatures than conventional OPC. As a result, the company claims that the production of Solidia Cement requires less energy and emits less CO2 emissions than ordinary Portland cement (OPC).[45] While the use of Solidia Cement is inhibited by the prescriptive European and Chinese cement standards, the alternative cement may be used in the USA under ASTM C1157, although its use may be limited due to limited experience and the industry concerns regarding ASTM C1157 outlined previously.

5.3 Review of Current Standards and Codes for Aggregates

5.3.1 Use of prescriptive and performance-based specifications in international aggregate standards

The permitted sources of aggregates and their geometrical, physical, chemical and mechanical specifications are defined by international standards. The specifications in these standards are shown in Table 9-8 and categorised into either prescriptive and/or performance-based specifications. The geometrical and chemical specifications are generally prescriptive, while the physical and mechanical are mainly performance-based.

In European standards EN 12620 and EN 13055, most specifications are given on a "when required" basis, meaning aggregates need only meet certain specifications if required by the specifier. For example, if a specifier requires aggregates with an aggregate abrasion value (AAV) category of AAV_{10}, the aggregates must possess an $AAV \leq 10$ in accordance with EN 1097-8. Guidance on selecting appropriate categories for specific applications is given in national provisions. The ISO 19595 standard is based on EN 12620 and works on the same basis but includes an additional optional specification for petrographic description. Compared with the ISO and EN standards, ASTM C33 and C330 require aggregates to comply with all specifications listed in the standards. However, many of the limits specified in the ASTM standards may be modified or ignored if the supplier can demonstrate that the concrete made with the aggregate has a demonstrated performance record or has equivalent performance for the required properties. The ASTM standards provide little guidance on which properties are "required properties" to consider for different applications. Instead, specifiers are directed to an informative document, Significance of Tests and Properties of Concrete and Concrete-Making Materials (STP 169D6).[27] In China, specifications for aggregates are split into two standards, for fine and coarse aggregates, GB/T 14684 and GB/T 14685, respectively. All of the specifications are required, with the exception of water absorption tests which can be requested by the specifier. The Chinese standards contain comparable geometrical, chemical and mechanical requirements to the EN and ASTM standards. However, the Chinese standards contain fewer physical specificiations, with only requirements for resistance to fragmentation and density given, and no requirements included for freeze-thaw resistance, magnesium sulphate soundness or volume stability.

While all standards include geometrical, physical and chemical specifications, EN 13055 and ASTM C330 standards for lightweight aggregates also contain mechanical specifications. EN 13055 contains an optional specification for the confined compressive strength of the aggregates, while ASTM C330 requires the compressive strength and splitting tensile strength of a concrete specimen produced using the aggregates to comply with limits set out in the standard.

5.3.2 Problems using a prescriptive approach to aggregate standards

The source materials permitted by the standards are a prescriptive specification and are shown in Table 9-9. The ISO 19595 standard contains the strictest prescriptive limits for sources of aggregates, permitting only natural aggregate from mineral sources that have been subjected to nothing more than mechanical processing, inhibiting the use of carbonated aggregates. The Chinese standards GB/T 14684 and GB/T 14685 are similarly strict, mainly allowing aggregates from natural sources, however, manufactured sand produced from mine tailings and industrial waste residue are permitted for use as fine aggregate. In addition to aggregates from natural mineral sources, EN 12620 and ASTM C33 also permit normal weight aggregates derived from manufactured sources and recycled aggregate, permitting the use of carbonated aggregates that meet the remaining aggregate specifications. ASTM C33 states that "certain recycled aggregate sources may contain materials and properties not addressed as part of the document specifications, limits, or test methods", implying the use of recycled aggregates may require additional considerations and test method not currently included in the standard. EN 12620 explicitly provides additional specifications for recycled aggregate and states that new test methods are at an advanced stage of preparation.

For lightweight aggregate standards, more source materials are permitted in EN 13055 than ASTM C330. The use of carbonated lightweight aggregates wastes is not possible according to the terminology used in ASTM C330, i.e. aggregates covered by the specification include those prepared by (i) expanding, pelletizing, or sintering products such as blast-furnace slag, clay, diatomite, fly ash, shale, or slate (ii) processing natural materials, such as pumice, scoria, or tuff. However, aggregates that do not adhere to ASTM C33 or C330 are permitted for use in ACI 318 if they have been demonstrated by test or actual service to produce concrete of acceptable strength and durability and are approved by the building official. However, no guidance is given in ACI 318 for which performance criteria should be tested. In EN 13055, only source materials with a positive use history are considered for use. Carbonated aggregate derived from wastes, such as those produced by Carbon8 Systems and OCO Technology, generally fall under lightweight aggregate standards. Therefore, the specification of carbonated aggregates is inhibited in EN 13055 unless the specific source materials are included in the standard. EN 13055 also states that the committee will continually review new source materials for incorporation into the standard.

While aggregates account for up to 80 per cent of concrete by volume, the relationship between aggregate properties and concrete performance has received much less focus than that between paste and concrete. Though it is well known that the aggregate can significantly impact the strength, workability, and durability of concrete,[28–31] studies have shown the complexity of the relationship between the aggregate and paste can prevent the correlation of aggregate characteristics with concrete properties[32] The aggregate standards were initially designed to produce durable concrete with high-quality coarse aggregates. However, the prescriptive limits in existing standards may fail to accurately predict concrete durability, particularly considering the use of new source materials (i.e. other than from natural sources). The EN and ISO standards hardly contain any required specifications and many of the limits in ASTM standards can be disregarded, demonstrating that the committee understands that prescriptive limits have shortcomings and evidence of proven performance can be used in place.

5.4 Comparison of International Test Methods

A transition to performance-based specifications will require the development of rapid and reliable performance test methods. In this section we compare currently approved performance-based test methods for a single property specified in existing codes and standards for each of concrete, cement and aggregates to demonstrate the key problems with existing testing methods.

5.4.1 Cement – compressive strength

In EN standards, the compressive strength of cements is determined in accordance with EN 196-1. The mortars are prepared using one part cement, three parts of CEN reference sand, and one-half part of water (water/cement ratio of 0.5). Compressive strength is determined from 40 mm x 40 mm x 160 mm mortar bar specimens which are cured in water at 20 °C. The Chinese test method GB/T 17671 and ISO test method ISO 679 are based on EN 196-1. In ASTM C109, the test specimens are prepared using 1 part cement, 2.75 parts of sand (with a narrower gradation than in EN 196-1), and sufficient water to obtain a desired flow (consistence). The test specimens are formed into 50 mm mortar cubes and cured in lime water at 23 °C.

The significant difference between the EN and ASTM test methods is the amount of water used to prepare the mortars. ASTM C109 is based on the consistency of mortars, whereas EN 196-1 is based on a constant cement/water ratio. For ASTM C109, flow is strongly affected by the total surface area of the aggregate in contact with the paste, so using sand can exacerbate flow problems in the mortar. Therefore, a higher amount of water may be needed to obtain a constant consistency, resulting in a lower compressive strength. Conversely, insufficient compaction may occur when preparing test specimens using blended cements at constant water/cement ratio according to EN 196-1, producing unreliable compressive strength measurements. Another issue with the test methods is that the curing temperature in the lab (20 to 23 °C) may not be representative of the in-the field climatic conditions experienced in many parts of the world and where much of the concrete production will be based in the coming decades. The higher temperature experienced in these regions may benefit the reaction of certain SCMs and increase clinker substitution and would not be recognised using the current test methods. A new RILEM committee on the performance testing of hydraulic cements is set to start work in 2023 and will explore the development of a more robust testing procedure for mechanical strength.[33] In particular, the formulation of the mortar will be altered to better reflect the total surface area of aggregate in concrete and so more realistically represent its workability.

5.4.2 Concrete - resistance to sulphate attack

Reactions between sulphates and cement constituents can cause concrete deterioration. In ACI 318, prescriptive limits for water/cement ratio, compressive strength, and permitted cementitious materials are given based on the sulphate exposure class. However, alternative combinations of cementitious materials are permitted if the criteria for sulphate resistance in Table 5-4 is met using performance-based test method ASTM C1012. Test method ASTM C1012 is an accelerated test method that evaluates the expansion of mortar bars with a compressive strength of 20 MPa, submerged in a sodium sulphate solution. The test duration and expansion limits depend on the severity of sulphate exposure. The test has a minimum duration of 6 months, and 18 months can be required for exposure class S3, in addition to the curing duration for the strength to reach 20 MPa. Therefore, the use of this test method as an "accelerated" method is arguable.

ASTM C1012 was developed for blended cements as an alternative to test method ASTM C452 for Portland cements.[34] When tested using ASTM C452, the mortar bars produced using blended cements were found to require longer times to develop their potential resistance to sulphate solution. The mortar bars were more likely to exceed the expansion limits than those prepared using Portland cements. Therefore, ASTM C1012 contains a provision for the test specimens to reach sufficient maturity by specifying the minimum compressive strength before immersion in sulphate solution. During the development of the test method, the compressive strength was initially specified as 27.6 MPa and was successively reduced to the 20 MPa strength used today in ASTM C1012. A lower strength was specified to reduce the test duration, as the behaviours of bars of different strength were similar, but the weaker bars failed considerably earlier. The fundamental principle behind the test method is enabling the mortar bar to reach sufficient maturity to enable the SCMs to react, therefore, a criticism of lowering the strength requirements is that it contradicts the test's original purpose. The expansion limits in Table 5-4 are also based correlations using Type II (maximum C_3A = 8%) and Type V (maximum C_3A = 5%) cements. Therefore, the applicability of these limits for blended cements is uncertain.

Table 5-4. Permitted cementitious materials for exposure classes S1, S2 and S3 and expansion criteria for establishing the suitability of alternative cementitious materials tested in accordance with ASTM C1012.

		Permitted cementitious materials			Expansion limit (mm)		
Exposure Subclass		ASTM C150	ASTM C595	ASTM C1157	6 months	12 months	18 months
S1		Type II	Types with (MS) designation	MS	0.10	No requirement	No requirement
S2		Type V[A]	Types with (HS) designation	HS	0.05	0.10 [B]	No requirement
S3	Option 1	Type V plus pozzolan or slag cement[C]	Types with (HS) designation plus pozzolan or slag cement[C]	HS plus pozzolan or slag cement[C]	No requirement	No requirement	0.10
	Option 2	V	Types with (HS) designation	HS	0.05	0.10[A]	No requirement

[A] Other available types of cement such as Type I or Type III are permitted in Exposure Classes S1 or S2 if the C3A contents are less than 8 percent for Exposure Class S1 or less than 5 percent for Exposure Class S2.

[B] the 12 month expansion limit applies only if the measured expansion exceeds the 6 month maximum expansion limit

[C] the amount of specific source of the pozzolan or slag cement to be used shall be at least the amount that has been determined by service record to improve sulphate resistance when used in concrete containing Type V cement, or the amount tested in accordance with ASTM C1012 and meeting the expansion criteria for option 1.

In EN 206-1, there are currently no standard test methods for evaluating the sulphate resistance of concrete. Instead, the standard gives prescriptive limits for the water/cement ratio, compressive strength class and minimum cement content based on the expected exposure to sulphate attack in the field (exposure category XA). Exposure subclasses XA2 and XA2 also contain requirements for using one of the seven types of sulphate-resisting cements included in EN 197-1. A RILEM technical committee, TC 251-SRT, Sulphate Resistance Test Methods was established in 2013 and concluded in 2019. The technical committee aimed to develop appropriate test methodologies and protocols for the analysis of sulphate resistance.[35] The recommendations from the committee, including proposals for test methods, have not yet been published.

In China, resistance to sulphate attack is determined using accelerated sulphate erosion test method GB/T 50082. Test specimens are formed into 100mm cubes and cured for 28 days (56 days is also permitted). The samples are then dried at 80 °C for 48 h and naturally cooled to room temperature for testing. The specimen is then subjected to multiple (N) 1 day wet-dry cycles. Each cycle consists of a wet period where the specimen is immersed in a 5 % sodium sulphate solution for 15 h followed by an 8 h drying period. The sulphate deterioration resistance factor is calculated using the following formula:

$$K_f = f_{cn} / f_{c0} \quad \times 100$$

Where: K_f is the sulphate deterioration resistance factor (%) to sulphate attack of concrete; f_{cn} is the average value of compressive strength (MPa) after N wet-dry cycles under sulphate attack; f_{c0} is the average value of compressive strength (MPa) of the control group concrete.

The dry-wet cycles are carried out until the K_f decreases to 75 % (the compressive strength of the concrete decreases to 75 % of the initial value), or 150 cycles is reached. The resistance to sulphate attack is then estimated using the concrete resistance level to sulphate crystallisation damage (K_S), which is determined by the number of wet-dry cycles for K_f to reach 75 % (Table 5-5). For example, if 80 wet-dry cycles are needed to decrease K_f to 75 %, the concrete is KS 90. The minimum KS for the relevant exposure classes given in GB/T 50476 are shown in Table 5-6. The duration of the test method can be considerable, e.g. to meet the minimum KS level specified in Table 5-6 for a 30 or 50 year service life, the test must be performed for at least 30 1-day wet-dry cycles (30 days total).

Table 5-5. Sulphate attack resistance levels in GB/T 50082.

Resistance level to sulphate crystallization damage	KS 15	KS 30	KS 60	KS 90	KS120	KS 150
Maximum wet-dry cycles to reach Kf = 75%	15	15~30	30~60	60~90	90~120	120~150

Table 5-6. Minimum KS based on expected service life for exposure classes specified in GB/T 50476.

Exposure class	The required sulphate attack resistance class	
	100-year service life	50 or 30-year service life
V-D	≥KS 90	≥KS 60
V-E	≥KS 120	≥KS 90
V-F	≥KS 150	≥KS 120

5.4.3 Aggregates - resistance to fragmentation

While many tests for the degradation of aggregates are included in ISO and EN standards (Table 9-8), these are not generally specified in ASTM standards. The one exception is the resistance to fragmentation (or abrasion) using the Los Angeles test method. The test method ASTM C131 is used for ASTM C33, and EN 1097-2 for ISO 19595 and EN 12620. The Los Angeles test determines the amount of fines that are generated when 5000 g of a standard grading of aggregate is subjected to a charge of steel balls in a Los Angeles machine (a ball mill) for 500 revolutions. The Los Angeles value is equal to,

$$\frac{Initial\ mass - final\ mass\ retained\ on\ standard\ sieve\ after\ 500\ revolutions}{Inital\ mass} \times 100$$

The dimensions of the Los Angeles machine and the weight and diameter of the steel balls are generally uniform across the test methods. The main differences between the test methods are the gradings used, the total mass of the steel ball charge and the sieve size used to evaluate the final mass (1.6 mm for EN 1097-2 and 1.7 mm for ASTM C131). ASTM C33 specifies that the aggregate grading used for Los Angeles testing should reflect the grading to be used in concrete. Therefore, four grading options (A, B, C and D, in order of decreasing upper particle size range) can be chosen for testing using ASTM C131. The total mass of the steel ball charge depends on the particle size range of the grading and decreases with decreasing particle size (Table 5-7).

Table 5-7. Comparison of LA testing variables in EN 1097-2 and ASTM C131.

Test parameter	EN 1097-2	ASTM C131
Grading	10, 11.2 and 14.0 mm[A]	A: 37.5 - 9.5 mm
	10, 12.5 and 14.0 mm[B]	B: 19.0 - 9.5 mm
		C: 9.5 - 4.75 mm
		D: 4.75 - 2.36 mm
Steel ball charge	4690 - 4860 g	A: 5000 g
		B: 4584 g
		C: 3330 g
		D: 2500 g

[A] 30 - 40 % passing a 11.2 mm sieve,

[B] 60 - 70 % passing a 12.5 mm sieve

Evaluation of the resistance to fragmentation using ASTM C131, where grading corresponds with that to be used in concrete, could reasonably be assumed to provide more accurate results than EN 1097-2, which has limited grading options.[36] Studies have also shown that 3-5 wt% of the fines generated in the Los Angeles machine are produced by rounding and abrasion, not fragmentation.[37] Therefore, the Los Angeles value may be a misleading metric for fragmentation. In the absence of robust correlations linking Los Angeles values with resistance to fragmentation, a maximum limit for abrasion of 50 % is given for all aggregates in ASTM C33, regardless of the end-use case.

There are no requirements for resistance to fragmentation in the Chinese aggregate standards.

5.4.4 Problems with existing test methods as barriers for CO_2 utilised building products/modern mix designs

Existing test methods for concrete and cement were generally developed considering the behaviour of traditional concretes prepared using large amounts of Portland cement and high-quality aggregates from natural sources. Modern concrete mix designs contain many new components that can affect concrete performance. These include new SCMs, admixtures and aggregates from alternative sources. Therefore, existing test methods may fail to capture the potential benefits (or drawbacks) of new mix designs. The three test methods for concrete, cement and aggregates discussed in the previous sections illustrate some key issues with existing testing methods:

(i) Concrete: resistance to sulphate attack.

The ASTM test method C1012 for resistance to sulphate attack demonstrates that some test methods need to be altered for new materials. Some cementitious materials develop properties at different rates than Portland cement and, therefore, may fail to meet testing criteria if testing is performed too early. ASTM C1012 was adapted from ASTM test method C452 for Portland cement by stipulating a minimum compressive strength before testing to ensure the mortar is sufficiently mature. Despite this change, the testing criteria given in standards are still based on relationships for traditional Portland cements. A substantial amount of time is required to carry out the performance-based test methods ASTM C1012 and GB/T 50082. Typically, a minimum of 3 months is needed, however, the test duration can reach 18 months.

(ii) Cement: compressive strength.

The test methods determining the standard strength of cements, currently used in standards, are based on mortars produced using a standard amount of cement and standard sand. The consistency of the mortar is unlikely to relate to that of the concrete, which will likely use optimised aggregate gradings and admixtures, which affect the workability. Also, the requirements for curing temperature in these test methods may not match field conditions and can penalise alternative materials that show superior performance at high temperatures.

(iii) Aggregate: resistance to fragmentation.

The Los Angeles testing method is used to determine the resistance to fragmentation of aggregates in the EN and ASTM standards. The test method suffers from inadequate correlation with field performance and does not reflect the in-service environmental conditions[38].

Another concern is that tests are designed for known issues, for example, the ASTM C151 autoclave expansion tests are designed to monitor volume instability due to the delayed hydration of MgO or CaO. Novel cement formulations may not contain these components but, instead, contain new components that could cause unknown instability issues. These issues must be understood to design test methods and set limits in the standards.

The fixed conditions and mix designs used in existing test methods may need to be updated to evaluate novel concrete constituents and mix designs fairly, and better reflect the conditions experienced in-service. It may be difficult to change test methods to more closely resemble field conditions since there may not be enough technical data to establish suitable criteria using test methods. The development of new performance-based tests that accelerate exposure to the relevant deteriorating mechanism must be applicable to new materials and combinations.

6 International approaches to standardisation

Standards are technical specifications that may contain requirements for design, construction, durability, testing, maintenance, repair, and restoration. They are written in explicit language and their requirements can be either mandatory or voluntary. A building code specifies the minimum requirements for designing, constructing and maintaining buildings and non-building structures. Building codes are developed and maintained by a standards organisation but are independent of the jurisdiction responsible for enacting the code. For example, the American Concrete Institute (ACI) develops and maintains building code ACI 318, which is frequently incorporated into the requirements of many US governmental bodies, thereby granting the code legal standing.

Standards organisations commonly form technical committees to draft, revise, approve, and manage technical standards and building codes using a consensus-based process. Table 6-1 provides a list of the relevant international subcommittees for building materials. Voting is a critical part of the standardisation process. Balance is needed among producers, users, consumers and general interest members to protect different interests and prevent a single viewpoint from dominating the discussion. A wide geographical distribution of members prevents creating standards that are restricted to local practices. Negative votes opposing parts or the entire standard often prevent the standard from moving forward. However, the resolution of negative votes is considered the most important part of the process and ensures the technical credibility of a standard.

Table 6-1. Committees with jurisdiction over building material standards.

Committee	Title	Technical subcommittees	Published Standards
ASTM International			
C01	Cement	19	over 50
C09	Concrete and Concrete Aggregates	31	over 176
ACI			
300	300 – Design and construction	-	10
EN			
CEN/TC 250	Structural Eurocodes	11	140
CEN/TC 104	Concrete and related products	4	178
CEN/TC 51	Cement and building limes	0	40
CEN/TC 154	Aggregates	5	60
ISO			
ISO/TC 71	Concrete, reinforced concrete and pre-stressed concrete	7	73
ISO/TC 74	Cement and lime	0	7 (standby)[A]
Chinese standards body			
TC184	National Cement Standardization Technical Committee	0	128
TC458	National Concrete Standardization Technical Committee	1	20

[A] Standby status indicates the committee has no work items in progress or in the foreseeable future. The committees are still required to review the standards for which they are responsible.

6.1 United States of America

In the USA, ASTM International (formerly the American Society for Testing and Materials) and ACI are the main standardisation agencies responsible for developing and maintaining building material standards. In addition to the standards developed by ASTM and ACI, federal and state agencies, *e.g.* the Federal Highway Administration (FHWA), may also specify further requirements.

ASTM standards cover physical and chemical specifications for cements, aggregates and other construction materials used in concrete mixtures. The organisation has also developed the test method standards for these materials and concrete. ACI building codes cover the specification and performance of concrete mixtures and the design of building and non-building structures. Although there is some overlap in the building material standards, ASTM and ACI formally work together to make their standards consistent and complementary. To avoid duplicating work, the standards developed by ACI rely on the technical specifications and test methods produced by ASTM where satisfactory consensus standards exist.

6.1.1 ASTM International

ASTM International form technical committees to develop standards. Most committees share the same basic structure for their activities (Figure 6-1). The main committee is a semi-autonomous group responsible for developing and maintaining standards within a specific subject area. Subcommittees are formed to address particular subjects within the scope of the main committee, while task groups are small working groups assigned to specific tasks, such as drafting a standard or conducting a study. The relevant ASTM International technical committees for building materials are C01 Cement and C09 Concrete and Concrete Aggregates.

The ASTM International standardisation process follows seven stages, shown in Figure 6-2.

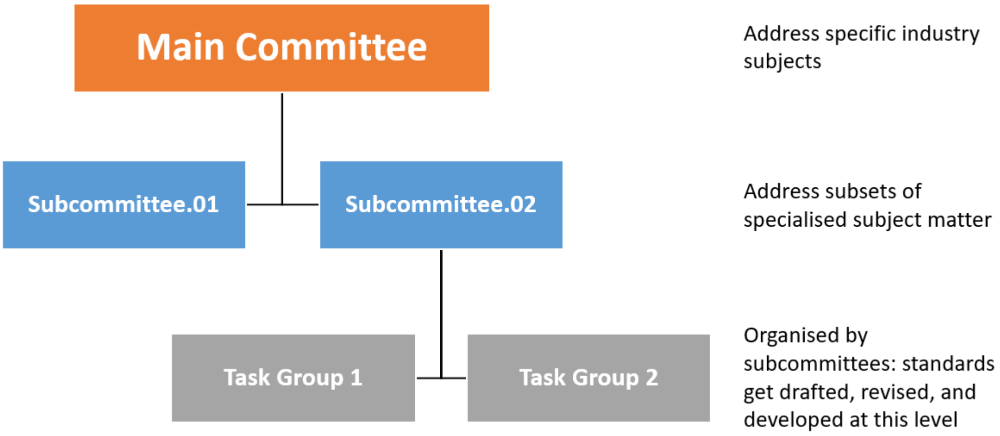

Figure 6-1: ASTM International technical committee structure organisation, adapted from[39].

1. New Need

Idea for a new standard of revision to an existing standard.

- Better test
- New specification
- Safer product
- Test performance of product

2. Task Group

If new activity is approved a task group is formed and a work item is registered to draft the standard.

Non-members are invited to participate in the task group.

No formal requirements

- Better test
- New specification
- Safer product
- Test performance of product

3. Subcommittee Ballot

Once a new standard or revision are drafted, a subcommittee ballot is initiated.

To initiate

- Subcommittee chairman approval or motion passed at a subcommittee meeting
- At least 30 days between issue and closing date
- Requires a Standard title, ballot action, work item, technical contact information and clear rationale explaining the reasons for ballot

To proceed to the next level

- 60% return required
- 2/3 affirmative of the combined affirmative and negative votes cast by voting members
- All negative votes considered and resolved via ASTM online negative resolutions systems
- None of the negative votes were considered persuasive

4. Concurrent Ballot

Revision and withdrawals, or new standards that have undergone at least one subcommittee ballot can be initiated concurrently.

To initiate

- Main and sub-committee chairman approval or motion passed by voting majority at main and subcommittee meeting
- Ballots for revisions and withdrawals or new standards that have undergone at least one sub-committee ballot

To proceed to the next level

- 60% return required
- 2/3 affirmative of the combined affirmative and negative votes cast by voting members
- All negative votes considered and resolved via ASTM online negative resolutions systems
- None of the negative votes were considered persuasive

5. Main Committee Ballot/Society Review

All standards are reviewed by the main committee/society.

To initiate

- All subcommittee ballot requirements completed
- Ballot items that successfully passed the subcommittee ballot process will automatically be included on the next main ballot
- Ballots for reapproval authorised by subchair or voting majority of subcommittee

To proceed to the next level

- 60% return required
- 2/3 affirmative of the combined affirmative and negative votes cast by voting members
- All negative votes considered and resolved via ASTM online negative resolutions systems
- None of the negative votes were considered persuasive

6. Committee on Standards Review

All not persuasive and not related actions for items passing main committee ballot shall be reviewed and approved by the Committee on Standards (COS).

To initiate

- Staff submits actions to COS after successful Main Committee Ballot/ Society Review

To proceed to the next level

- COS approves that procedures were followed correctly in resolving negative votes

7. Editorial Review

ASTM Editor sends a review copy to the technical contact for final review and approval before publication.

Figure 6-2: ASTM International standardisation process, adapted from[39].

6.1.2 ACI

To develop standards, ACI establish Technical Activities Committees (TACs) which form technical committees responsible for a specific knowledge area. Technical committees are classified into one of five groups based on their scope:

100 – General
200 – Material and properties of concrete
300 – Design and construction
400 – Concrete reinforcement and structural analysis
500 – Specialised applications and repair

ACI committees develop standards that are specific to an industry. The relevant ACI committees for building materials are 301 Specifications for Concrete Construction and 318 Structural Concrete Building Code.

The ACI standardisation process involves eight stages:[40]

1. Preparation of a new document or revision of an existing document.
2. If the document is to be proposed as an American National Standard (ANS), a Project Initiation Notification System (PINS) form must be submitted to the American National Standards Institute (ANSI).
3. Letter balloting of the draft document by the committee.
4. Submission of the committee-approved document for TAC review.
5. Revision of the document in response to TAC comments.
6. A 45-day public discussion period through ACI and ANSI. Staff notified ANSI of the public discussion.
7. Submissions of committee-approved responses to comments received during the public discussion period for TAC review. All views and objections on proposed ANS are addressed in accordance with ANSI Essential Requirements.
8. Submission to Standards Board and ANSI for final approval.

A commentary is often supplied alongside the code to provide supporting documentation for code provisions. The commentary is written in non-mandatory language so cannot be referenced by a code.

6.2 Europe

The European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Standards Institute (ETSI) are responsible for developing and maintaining European standards. Technical groups within the CEN National Standardization Bodies and CENELEC National Committees of the European Union (EU) and European Free Trade Association (EFTA) develop and maintain standards, coordinated by CEN-CENELEC. The relevant technical committees for building materials are CEN/TC 250 Structural Eurocodes, CEN/TC 104 Concrete and related products, CEN/TC 51 Cement and building limes and CEN/TC 154 Aggregates.

The European standardisation system for building materials is a comprehensive system of design and material standards comprising the EN Eurocodes, product, execution and test standards. The Eurocodes are umbrella codes that are developed and adopted by EU and other non-EU members as their national codes to promote common engineering and design practices, which is key for the European Single Market. National Annexes allow members to add additional requirements to the Eurocodes.

Figure 6-3 illustrates the relationship between the Eurocodes and product standards for concrete. Eurocode 2 is a four-part series of documents for the design of buildings and civil engineering works in plain, reinforced and prestressed concrete. EN 206 is a comprehensive umbrella standard for a broad range of EN materials standards, testing standards and assessments and serves as the basis for Eurocode 2.

CEN and/or CENELEC technical committees are assigned to revise an existing standard or create a new one once enough support is gained from CEN and/or CENELEC members. Mirror committees are formed for each member after the technical committee is established to determine their national contributions to the development of the standard. The European standardisation process involves six stages:[41]

1. Proposal – evaluation and decision
2. Drafting and consensus building
3. Public enquiry
4. Consideration of comments
5. Approval of the standard
6. Publication.

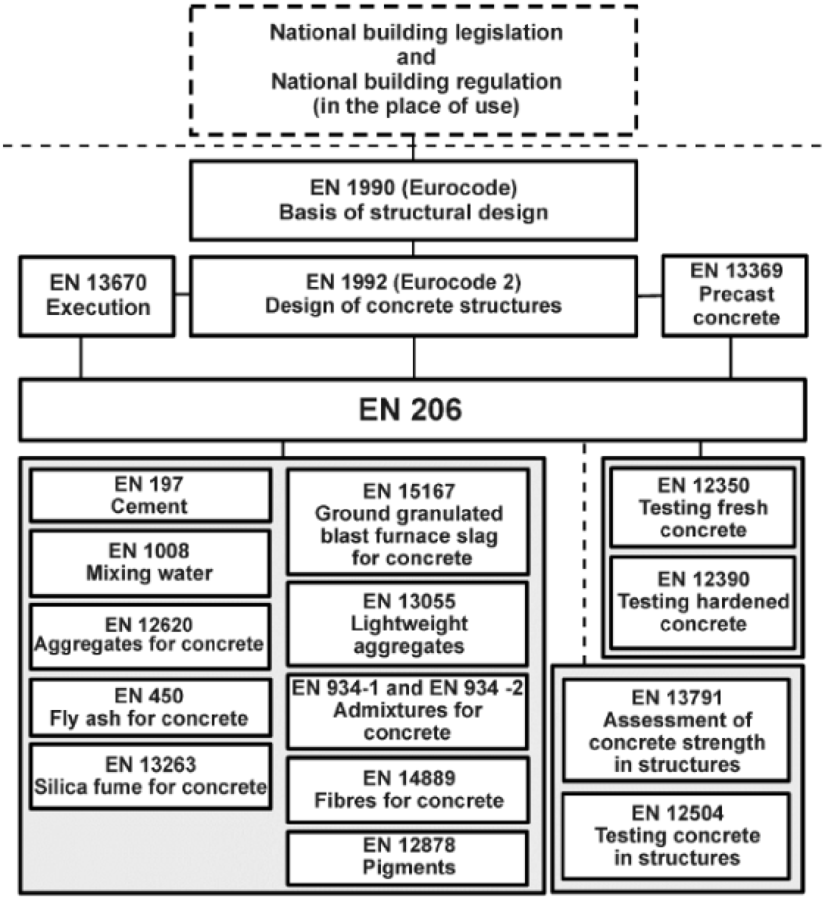

Figure 6-3: Relationship between EN 206 and standards for design an execution, standards for constituents and test standards.[42]

6.3 China

The Standardization Administration of China (SAC) is the main standards organisation in China and represents the country in major international standards groups. SAC assigns a standard to one of five broad categories: national standards, industry standards, local or regional standards, enterprise standards for individual companies, and association standards. National standards, also known as guobiao (GB), are the highest-level standards and the most relevant for building materials. These standards may be mandatory or voluntary, with "/T" representing voluntary standards (*i.e.* a voluntary national standard is represented by GB/T). However, GB/T standards can become mandatory if referenced in laws and regulations.

Technical committees are responsible for developing and maintaining standards within their respective technical area. The relevant SAC technical committees for building materials are TC184 National Cement Standardization Technical Committee and TC458 National Concrete Standardization Technical Committee**.** SAC has the authority to designate committee work to other agencies and organisations.

The standardisation process involves nine stages:[43]

1. Preliminary stage
2. Proposal stage
3. Preparatory stage

4. Committee stage
5. Voting stage
6. Approval stage
7. Publication stage
8. Review stage
9. Withdrawal stage

6.4 East Africa

(With sincere thanks to Mr Joseph Marangu of Meru University in Kenya, and Professor Karen Scrivener of EPFL).

Cement: In East Africa, for cement, the operating standard is the East Africa Standard (EAS) which is essentially a EN version adopted in the seven countries in East Africa: the Democratic Republic of Congo (DRC), Tanzania, Kenya, Burundi, Rwanda, South Sudan, and Uganda. It is cited as KS EAS 148 (1,2, 3 etc) for Kenya, UG EAS for Uganda, TZ EAS for Tanzania etc; Kenya is in the process of adopting the latest amendment EN 197-5 currently being spearheaded by the Kenya Bureau of Standards. There is a great opportunity for LC^3-50 cements in other East Africa countries, this lies in the fact that if it is adopted in Kenya as KS EAS, it can be used in the other seven countries in East Africa, this way it can bypass the path of country by country adoption.

Concrete: There is a low technicality in concrete as engineers are mostly only interested in the strength of concrete. Other items such as consistency and durability are rarely taken into consideration. Although Kenya adopted the Eurocodes on 14th September 2012, the use of Eurocodes is still quite low. The nomenclature of concrete is causing quite some confusion in the industry. For example, what is known as Class 25/20 is represented in the Eurocode as C20/25; Class 30/20 is C25/30. The understanding of this matter is improving among consultancies, it is almost unheard of among contractors. The strength is also based on the minimum allowable strength as opposed to the characteristic strength, although engineers wrongly use the two terms interchangeably. BS 8500, which is a complementary standard to EN 206, would be the best to use in Kenya moving forward.

Building/Structures: Kenya mainly uses BS for the design of structures. The most popular codes are BS 8110 for the design of concrete buildings, BS 5400 for the design of bridges, and BS 5950 for the design of steel structures. Kenya adopted the Eurocodes on 14th September 2012. Implementing the code has been a challenge. There is no legal basis to force a designer to use the code. The National Construction Authority sought to change this situation in the Draft Building Code (2022). The building code would mandate the use of the Euro-codes for all new structures. This proposal is facing some resistance but would be one of the best ways to standardise building designs in Kenya. The main point of resistance is that Kenya has yet to finalize and publish the National Annexes to the Eurocodes.

6.5 International Organization for Standardization

The International Organization for Standardization (ISO) is an independent non-governmental organisation that consists of members from the national standardisation bodies of 163 countries. ISO forms technical committees that develop and maintain standards in specific subject areas. The relevant technical committees for standardisation of building materials are ISO/TC 71 Concrete, reinforced concrete and pre-stressed concrete and ISO/TC 74 Cement and lime. At the start of the standardisation process, a track for the development of a standard is assigned. This track determines the timeframe of the project (18, 24, or 36 months) as it progresses through the stages to publication. The ISO standardisation process involves six stages:[44]

1. Proposal
2. Preparatory
3. Committee
4. Enquiry
5. Approval
6. Publication

ISO closely collaborates with CEN under the 1991 Vienna Agreement on Technical Cooperation between ISO and CEN.[45] The agreement aims to avoid the duplication of work at international and European levels, promote global economy and ensure rational use of back-office resources. While recognising the primacy of international standards, the agreement also acknowledges that specific needs, such as those of the Single Market, may require the development of standards not recognised at the international level. The agreement outlines two modes for collaborative standards development: ISO lead and CEN lead, in which documents developed within one organisation are simultaneously approved by the other.

7 Development of models for safe and reliable performance-based standards

This section addresses the following two questions from the Project Scope:

1. Is there an effective way to create performance-based standards without compromising safety and dependability?
2. Are there tools or models that can predict long-term performance and the effect of wide-scale application?

There are multiple key performance criteria for cement concrete which performance-based standards should include. They include at least:[2]

1. Compressive strength at a specified time of curing – indicating strength
2. Slump – indicating workability
3. Resistance to deterioration – indicating durability.

It is important to note here (as is discussed in the interviews, see section 8.2 for a summary) that the process of setting a standard can be expensive. A figure of £150,000 was suggested for the cost of setting up a BSI standard, and this is without the considerations of the large amount of time for highly qualified people to discuss the standard. In addition, the *testing* which is required to go in to the standard can take a significant number of years and be even more expensive than the cost to develop the standard. It is not possible to give a costing for the tests, since these are specific to the desired property being tested – a Vicat needle for testing the initial and final setting time of a cement paste can be obtained for £250, a Los Angeles abrasion testing machine can cost tens of thousands of pounds. As well as this, there is the variability in the number of tests required, and the time and staff required to conduct the tests to enable a realistic standard to be put together, and the costs can be very high. Since performance-based standards require more tests than prescriptive standards (see section 8.2), the testing process to produce a performance-based standard will be significantly higher (see also the interview in section 10.1.1). It was mentioned that well-calibrated models for current cement types can reduce the number of tests required to produce a standard, see 10.1.2).

Compressive strength and slump are simpler properties to incorporate into performance-based standards since: (i) they can be measured at relatively short times of curing, i.e., minutes to hours for slump, and days for compressive strength; (ii) the general inverse relationship between porosity and strength is well known in materials science and specific micromechanical models exist for cementitious materials;[1] and (iii) predictive models for slump exist, e.g. based on the relative paste volume in a concrete mix.[2] Durability, meaning the resistance to deterioration, is more challenging to incorporate because deterioration of concrete: (i) can occur over years to many decades, or centuries, (ii) proceeds via several physical and chemical pathways (e.g. abrasion, chloride-induced corrosion), and (iii) is affected by both intrinsic material composition and handling/manufacturing conditions (on-site placement or factory-based production). Therefore, no comprehensive or generalised model currently exists to quantify concrete durability, and the development of such a model is a research gap and focus in cement and concrete science. Here a short review of the state-of-the-art research in this area is presented, particularly highlighting recent and promising progress.

Most of the current concrete durability assessment methods are (semi) empirical.[46] For example, the ‘rapid chloride migration method’ is commonly used to characterise the performance of concrete cover to protect against chloride-induced steel reinforcing bar corrosion, which is arguably the most important durability issue for structural (reinforced) concrete (though in the future this may become less of a problem, owing to possible wide-scale adoption of carbon-fibre reinforced polymer rebar, which is not subject to similar corrosion degradation). Ion diffusivity is an important indicator for chloride-induced corrosion since it governs the transport of chloride from the external concrete surface to the steel reinforcing bar. The rapid chloride migration method uses the Nernst-Einstein equation to relate ion diffusivity (D) to the inverse of the electrical resistivity (ρ), $D = k/\rho$[47], where the parameter k is a constant dependent on the type of concrete. Hence assessment of the performance of concrete to protect against chloride-induced corrosion of its steel reinforcing bar requires chloride diffusivity and electrical resistivity values to be established at different times of curing, for each concrete type. This requires extensive experimental data collection, which is time- and resource-consuming, and thus impossible to complete comprehensively for the increasingly large number of emerging low-CO_2 concrete types being developed. This example also shows that the models to assess concrete durability depend on the specific deterioration mechanism being investigated. Different models are needed for different deterioration mechanisms.

Deterioration categories for concrete and embedded steel reinforcing-bar include sulphate attack, acid attack, alkali-silica reaction, and freeze-thaw for the former, and carbonation and chloride ingress for the latter. Progress on model development for each category varies: some are more reliant on empirical models (e.g. chloride-induced corrosion) than others (e.g. freeze-thaw attack), for which theoretical models have recently become available. Ultimately, comprehensive performance-based assessment of concrete deterioration require all of the important categories to be assessed simultaneously. This is not yet possible. However, current research is making progress towards this aim.

Leveraging efforts in conceptualisation and development of durability indicators for concrete deterioration mechanisms[48], Gao et al. (2023)[49] proposed that these indicators could be used as intermediate indicators for concrete performance in an analogous manner to how life cycle assessment uses midpoint indicators (e.g. 100-year global warming potential) to quantify environmental performance (Figure 7-1). This conceptualisation is useful since it clarifies the modelling task, which is to relate environmental pressures, such as climate and exposure condition, to the ‘durability indicators’, and then to relate these ‘durability indicators’ to the damage to concrete that should be avoided. It is important to choose durability indicators that can be readily measured so that the models can be validated. Fully general predictive modelling is then feasible if thermodynamic modelling is combined with a sound physico-chemical understanding of the deterioration mechanism to determine the effect of concrete type. Thermodynamic modelling has a long tradition in modelling cement and concrete chemistry. In this context, it refers to a method that predicts the composition of gaseous, aqueous, and solid phases in concrete from first principles at a given temperature, pressure, and material composition. The results can be directly used to determine key physical properties (e.g., porosity) that are closely related to concrete durability. Heeren and Myers (2020)[50] piloted coupling of thermodynamic modelling and life cycle assessment to model the relationships between the chemical composition and porosity of cement paste, and cradle-to-gate environmental impacts of concrete. Explicit and more detailed modelling of durability indicators was achieved by Bharadwaj et al. (2019)[51] for freeze-thaw attack. We briefly discuss this research below as an example for how modelling to predict long-term performance of concrete can be achieved.

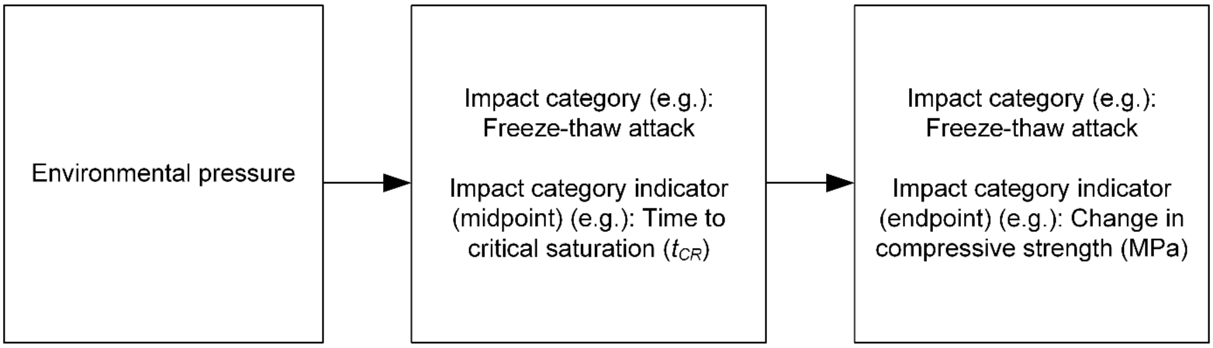

Figure 7-1. Life cycle assessment inspired framework for comprehensive prediction of concrete performance. Adapted from Gao et al. (2023).[49]

The environmental pressures for freeze-thaw attack include moisture ingress and temperature fluctuation around 0 °C. Freeze-thaw attack begins by ingressed water filling concrete pores. The degree of saturation (S [%]) of concrete is a measure of the amount of liquid in its pores, and is defined as the volume of its liquid-filled voids divided by the total volume of voids, multiplied by 100 to convert into a percentage. Freezing of this liquid (mainly water) to ice occurs at temperatures below 0 °C at atmospheric pressure. Since ice occupies 9% more volume than water, if there is no space for the expansion, ice formation will force the liquid within the concrete to transport into other empty pores, increasing capillary water pressure. Critical saturation (S_{CR} [%]) is the extent of pore filling above which the concrete becomes susceptible to freeze-thaw damage. Fagerlund[52] showed that concrete is not severely damaged when its water saturation degree is below a critical level (ranging from 83% to 91% for different material types[53]). However, if the critical saturation degree is exceeded, severe damage to mechanical properties will be observed upon the next freeze-thaw cycle[54], and damage to the physical properties of the cover layer of concrete would occur at a later stage.

Bharadwaj et al. (2019)[51] proposed a general theoretical model to assess the performance of concrete with respect to freeze-thaw attack by combining Fagerlund's critical saturation theory with thermodynamic modelling. In this model, the time to critical saturation is calculated using equation (1):

$$t_{CR} = \left(\frac{S_{CR} - S_{MATRIX}}{pS_2{}'} \right)^2 \tag{1}$$

Where S_{MATRIX} [%] is the degree of saturation of concrete when its cement paste pores (including the capillary, gel, and chemical shrinkage pores) are filled with liquid but the air voids contain only gas, S_{CR} [%] is the critical degree of saturation, p [–] describes the drying conditions that the concrete is exposed to (p = 0 for concrete cured in dry conditions, p = 1 for concrete in constant contact with water), and $S_2{}'$ [% $t^{-0.5}$] is the rate that the air voids in concrete are filled with liquid ('rate of secondary absorption'). The $S_2{}'$ parameter is a function of the apparent formation factor (F_{APP} [–], equation (2)), which describes the pore structure of concrete and is itself defined in terms of its porosity and pore connectivity:

$$S_2{}' = c_1 \sqrt{\frac{1}{F_{APP}}} \tag{2}$$

Where c_1 is a constant determined experimentally to be 0.581 [% $t^{-0.5}$]. The model proposed by Bharadwaj et al. (2019)[51] inputs parameters such as the raw material composition and curing condition of concrete to simulate (i) compositions and total volumes of gas, aqueous, and solid phases using thermodynamic modelling, and (ii) volumes of gel and capillary water using the Powers and Brownyard model[55]. They then relate these outputs of thermodynamic modelling to the time to reach critical saturation (t_{CR} [years]), which is the key performance indicator for freeze-thaw resistance in this model and is used to characterise the freeze-thaw resistance of concrete. The model was applied to calculate the time to critical saturation for ordinary Portland cement and a few composite Portland cement-fly ash concretes. Although the results require experimental validation, through their study Bharadwaj et al. (2019) demonstrated that a general theoretical modelling approach to quantitatively predict concrete deterioration for many concrete types is possible. Other limitations include the need to include the interfacial transition zone in the model, more reliable and complete thermodynamic modelling data and parameterisation for composite Portland cements, and more complete quantification of wetting/drying effects on concrete curing; notably its pore structure. Overall, this is a significant step towards rapid assessment of concrete durability, which is not yet possible in the current standardised approaches that rely on empirical measurement.

In a follow up paper, Bharadwaj et al. (2022)[2] showed how their predictive model for freeze-thaw resistance of concrete can be included in a performance-based design approach. Their proposed approach specifies certain values of key performance criteria, for strength (e.g. 56 days compressive strength), workability (e.g. slump), and durability (e.g. freeze-thaw resistance), and then predicts which concrete mix designs can meet them. The performance of selected concrete mix designs from the results are then validated using experimental testing. After validation, the concrete mix designs are suitable for use. Hence their work shows that it is feasible to develop a performance-based standard that specifies (i) the key performance criteria for concrete in different applications, (ii) models that should be used to determine feasible concrete mix designs to meet those criteria, and (iii) validation protocols for the feasible concrete mix designs (Figure 7-2).

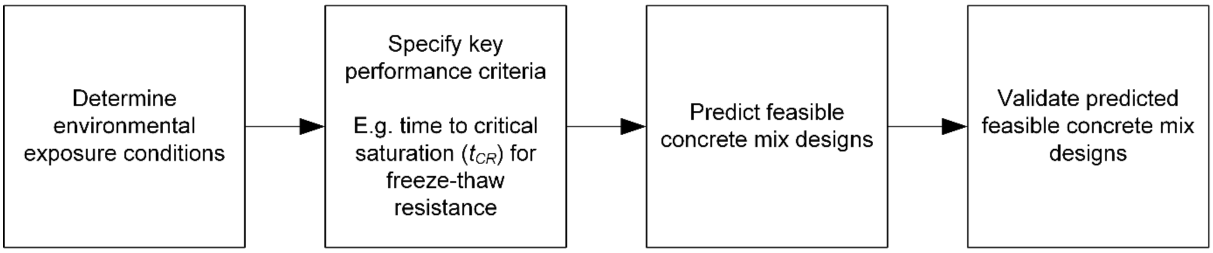

Figure 7-2. Framework for performance-based specification of concrete including emerging predictive modelling approaches.(e.g [2,49–51]).

The use of thermodynamic modelling in this framework is important since it captures long-term changes in materials and thus improves reliability in its results. An important example where thermodynamic modelling using data now currently available[56] could have avoided structural failure from concrete deterioration is the use of calcium aluminate cement concretes in the mid-late 20th century in Great Britain. These failures occurred from volume and solid phase changes that thermodynamic modelling can now reliably predict. With sufficiently complete thermodynamic data, it is unlikely that such issues will arise using the performance-based specification of concrete framework outlined here.

8 Discussion of Interviews

8.1 Interview structure

Interviews were conducted with a wide variety of industrial stakeholders, industry groups, and individuals. Each was approximately 1 hour long and followed a set format as below:

Meeting between IC and [organisation]
Date and time
In attendance: [Imperial attendees]
[organisation attendees]
[titles in organisation].
General introduction to the project, freeform discussion, exploration of areas of interest

followed by:
Question 1 "Is there and effective way to create performance-based standards with respect to not compromising safety and reliability"
[answer]
Question 2 "Have any external factors such as local policy or legislation helped new materials gain approval and adoption?"
[answer]
Question 3 "Are there tools or models that can predict long-term performance and the effect of wide-scale application?"
[answer]
Question 4 "Potential markets and business models for novel carbonaceous building materials? "
[answer]
Standards that we should look at:
standards already looked at
[suggested standards]
Question 5 "Is there anything we have missed? Any questions we should add?"
[answer]
Question 6 "Who else should we contact?"
[answer]

Minutes of each meeting were made, collated amongst the interviewers and then sent to the interviewees for fact checking. At this stage, the interviewees were also asked to confirm that they would allow their names and company affiliation to be used, or whether they would prefer their responses to be anonymised (or only to be used under Chatham House rules, or just to be used in aggregate form). One respondent chose to be anonymous, all others were happy for their responses and affiliations to be included – the interview notes are appended after this discussion. After the first round of interviews, the results were collated and analysed for consistent themes. The entire draft document was provided to each interviewee for further comment. A number of suggested further interviewees were provided during the interview process and follow-up interviews were arranged. We have not included the names of other people volunteered under Q6 in the final document unless they themselves gave an interview.

8.2 Key findings from Interviews

General Findings

The first and most important finding from almost all respondents is that climate change is an extremely important priority throughout the industries interviewed, with a number of interviewees stating that it is increasingly common for CO_2 intensity or another measure of climate change impact to be part of the tendering process. In particular, where government contracts were being sought, lower carbon intensity was seen as an important differentiator. Other interviewees stated that carbon lead markets and buyers clubs are potentially important, with companies both private and public increasingly aware of their climate responsibilities. Shareholder pressure to decarbonise was also mentioned. However, there was a large groundswell of opinion that safety is critical and that testing must remain rigorous, with interviewees representing suppliers to the construction industry, and also a member of the construction industry expressing very strongly that unless a material was within an existing and well respected code (the example of EN standards was made) it would not be specified except under exceptional circumstances. It was also mentioned that the ability to obtain insurance was a key question if novel materials were used. An interesting example was made that a cement products supplier might choose to take the risk themselves to build e.g. a new headquarters out of a new low-carbon product and commit to the monitoring and risk that that entailed. A number of respondents referred to the importance of developing confidence in new materials, using them at first in non-safety critical operations (e.g. retaining walls) to gain an understanding of how they behaved in real life situations. Looking forward to section 4 of Part II of this report, it is clear that a number of companies are conducting demonstration campaigns in exactly this manner. Others pointed out that such incremental development in use would lead to decades before full implementation occurred in more critical uses. Knowledge sharing across industry(ies) and countries was mentioned by a number of respondents as being very important – each company / country does not have to replicate what everyone else has done. Another interesting point which was raised during the interviews was that a large amount of infrastructure will be built in the developing world in the coming decades. The standards within some African nations are based on EN standards (though as discussed in section 10.1.7, there will need to be changes because of e.g. higher ambient temperature). However, there is a challenge that sometimes devices are specified within standards, that are not accessible to those validating compliance to a particular standard in such countries. Interestingly, Kenya is progressively switching from British Standards to EN standards for some applications (see section 6.4)[60].

In terms of support mechanisms to help with deployment of new materials, it was stated that in the UK the government was not providing a great deal of support – only barriers. There was a significant desire to push technologies forwards, in particular given the difficulty of enacting CCS in certain locations, but it was not seen that there was a level playing field in terms of CO_2 abatement technologies. Other jurisdictions are providing significant incentives for low-carbon construction : there are tax benefits in state procurement for using low CO_2 materials in New York (Low-Embodied-Carbon Concrete Leadership Act (LECCLA)).[61] New Jersey also provides similar tax incentives[62]. In Finland –

planning requires a demonstration that low carbon options have been seriously considered. It is necessary to have an assessment of the carbon footprint of your construction – EPD / Carbon footprint of your construction – local authorities require this, and it to be based on some form of life cycle assessment[63]. Companies can also apply for funding through the Low Carbon Built Environment Programme launched in 2021 to promote low-carbon building solutions.[64]

Findings Relating Specifically to Testing and Standards

A number of interviewees made the clear point that existing standards actually contain a mixture of prescriptive and performance-based elements. It was noted that performance-based standards take longer to develop, and that it was a challenge to include every possible combination of materials in a performance-based standard – the number of experiments would be huge. In particular, durability standards are more difficult to accelerate than some others, so that they can take a very long time to complete. Specifiers were stated to prefer a simpler prescriptive standard than a more complex performance-based standard, since it is easier to demonstrate compliance. An issue which was raised by numerous people was that the tests which have been developed for existing concrete and cements may not be suitable in practice for a new generation of cementitious materials – there is a plethora of potential tests, and a great incentive for testing houses to develop their own tests and have them incorporated into a standard – regardless of suitability. It was mentioned a number of times that it is substantially easier to add parts to an existing standard, rather than to develop a new standard from scratch – the time taken to develop a new EN standard was frustrating to some.

It was also a discussed by more than one member who was sitting on a standards committee that the process of setting a standard can take a very long (and unpaid) time. A number of respondents mentioned that LC^3 cement is important for the future, and it is noted that there is a RILEM committee working towards the development of a standard for its use.

Findings Relating Specifically to Measuring and Certifying the Performance of Carbonated Building Materials

Measuring the performance of novel building materials based on new formulations can be difficult due to the need for more relevant test methods. One example highlighted in the interviews was Alkali-activated cementitious materials (AACMs), which are currently at the development stage where demonstrations are being carried out and more durability testing is required. A publicly available specification (PAS) has been written on AACMs (PAS 8820:2016 *Alkali-activated cementitious material and concrete*) and the Green Construction Board is working with BSI to develop an accelerated performance test for AACMs but this will take 18 months at the fastest. A significant challenge is that some of the tests specified for AACM-based concrete are not relevant. For example, the Bauer test is not suitable because the product doesn't bleed but the test is mandated by the standard.

Another challenge discussed in the main report is that tests are designed for known issues. For example, the ASTM C151 autoclave expansion tests are designed to monitor volume instability due to the delayed hydration of MgO or CaO. Novel cement formulations may not contain these components but, instead, contain new components that could cause unknown instability issues. These issues must be understood to design test methods and set limits in the standards.

These testing challenges are evident when using ASTM C1157. The standard allows high flexibility in the composition of cements by only defining performance criteria. In the market, however, the standard does not find acceptance because there is limited confidence that the products meet the necessary performance. A 2001 survey on the acceptance and use of the standard found uptake was limited due to perceived barriers and concerns held by specifiers and manufacturers[26]. Barriers to adoption included a lack of interest and familiarity with the specification, lack of adoption in current standards and building codes, lack of commonly tested properties in other standards, concerns with the lack of appropriate performance test methods, and difficulties interpreting the standard, which was seen as complex. The responsibility for verifying the applicability of the cement is shifted to the customer. One interviewee believed that it is possible to use ASTM C1157 and that suppliers should do the testing and there would not be an issue. However, the necessary experiments can take a long time, may be hard to accelerate, or don’t give much useful information for new cement types/new materials.

The general consensus from the interviews was that designers would use lower-carbon materials as soon as the materials are included in the standard. However, the most common challenge identified from the interviews is that an extensive performance and testing history is required for new materials to be incorporated into a standard. To build confidence in the materials, testing them in non-safety-critical applications/trials for specifiers is crucial. Potential applications include paving and other non-structural applications and backfill in retaining walls. Major infrastructure projects were identified as key enablers as they often have targets on CO_2. The HS2 project in the UK was highlighted as having carried out trials to test new low-carbon concretes, including a number that relied less on ground granulated blast furnace slag and some involving calcined clays. These materials were used in low-risk applications such as culverts and retaining walls. New materials used in a large public infrastructure project can increase confidence as the performance of the materials can be continually analysed over time – satisfying the industry need for a 5 to 10-year period of demonstrated performance before they take on the risk.

Extensive demonstration of materials in non-safety-critical applications helps develop experience of how the materials perform in the field rather than in the lab. However, if the aim is to start using these materials in more challenging areas, developing them would take a long time by needing to continually “prove” them in less challenging areas. A list of companies developing carbonated building materials and a list of their most recent/largest commercial/demonstration projects are reported in the second part of this report.

9 Appendix

9.1 International standards and codes for building materials

Table 9-1. Exposure classes in international concrete standards.

Specification	**EN 206**	**ACI 318**	**ISO 22965**	**GB/T 50476**
Structure	Six exposure classes divided into 18 subclasses	Four exposure classes divided into 23 subclasses	Six exposure classes divided into 18 subclasses	Five exposure classes divided into 16 subclasses
Exposure categories	X0: No risk XC: Corrosion induced by carbonation Mild: XC1 Moderate: XC2 Severe: XC3 Very severe: XC4 XD: Corrosion induced by chlorides other than from sea water Mild: XD1 Moderate: XD2 Severe: XD3 XS: Corrosion induced by chlorides from sea water Mild: XS1 Moderate: XS2 Severe: XS3 XF: Freeze/thaw attack with or without de-icing agents Mild: XF1 Moderate: XF2 Severe: XF3 XA: Chemical attack Mild: XA1 Moderate: XA2 Severe: XA3	F: Freezing and thawing Negligible: F0 F1, F2, F3 (in order of severity) S: Sulphate Negligible: S0 S1, S2, S3 (in order of severity) W: In contact with water Negligible: W0 W1, W2 (in order of severity) C: Corrosion protection of reinforcement Negligible: C0 C1, C2 (in order of severity)	X0: No risk XC: Corrosion induced by carbonation Mild: XC1 Moderate: XC2 Severe: XC3 Very severe: XC4 XD: Corrosion induced by chlorides other than from sea water Mild: XD1 Moderate: XD2 Severe: XD3 XS: Corrosion induced by chlorides from sea water Mild: XS1 Moderate: XS2 Severe: XS3 XF: Freeze/thaw attack with or without de-icing agents Mild: XF1 Moderate: XF2 Severe: XF3 XA: Chemical attack Mild: XA1 Moderate: XA2 Severe: XA3	I: Atmospheric environment Slight: I-A Mild: I-B Medium: I-C II: Freeze-thaw environment Medium: II-C Serious: II-D Very serious: II-E III: Marine chloride environment Medium: III-C Serious: III-D Very serious: III-E Extremely serious: III-F IV: Chloride (excluding cryohydrate) environment Medium: IV-C Serious: IV-D Very serious: IV-E V: Chemical environment Medium: V-C Serious: V-D Very serious: V-E

Table 9-2. Review of prescriptive and performance-based specifications in international concrete standards.

Specification	**EN 206**	**ACI 318**	**ISO 22965**	**GB/T 50476**
Cement type	EN 197-1 EN 197-5 EN 14647 EN 15743	ASTM C150 ASTM C595 ASTM C1157	-	GB 175
Supplementary cementitious materials	Prescriptive maximum contents of: Fly ash Silica fume Ground-granulated blast-furnace slag	Prescriptive maximum contents of: Fly ash and natural pozzolans Silica fume Slag cement	Prescriptive maximum contents of: Fly ash Silica fume Ground-granulated blast-furnace slag	JTGT 3310 Prescriptive maximum contents of: Fly ash Ground-granulated blast-furnace slag
Contribution of supplementary cementitious material to water/cement ratio	Prescriptive k-value concept[A]	Entire content	Prescriptive k-value concept[B]	Entire content
Aggregate	EN 12620 EN 13055	ASTM C33 ASTM C330	ISO 19595	GB/T 14684 GB/T 14685
Maximum water/cement ratio	Prescriptive[C,D]	Prescriptive	-	Prescriptive
Minimum cement content	Prescriptive[C,D]	None	-	Prescriptive
Minimum compressive strength	Performance-based[C,D]	Performance-based	-	Performance-based
Chloride content	Prescriptive	Prescriptive	Prescriptive maximum limit	Prescriptive
Concrete cover depth	Prescriptive (EN 1992-1)	Prescriptive	Prescriptive (ISO 15673)	Prescriptive
Curing	Prescriptive and performance-based (EN 13670)	Prescriptive and performance-based	Prescriptive and performance-based (ISO 22965)	Prescriptive and performance-based (GB 50666)

[A] equivalent concrete performance concept can be applied but is not widely used

[B] only valid for specific cement classes in ISO 22965

[C] values are provided in informative annex F in EN 206 based on concrete producing using cements conforming with EN 197-1, normal weight aggregates and designed for a working life of at least 50 years.

[D] performance-based route possible

Table 9-3. Comparison of exposure categories for international concrete standards.

Exposure Type		**Standard**			
Corrosion source	**Severity**	**EN 206**	**ACI 318**	**GB/T 50476**	**ISO 22965-1**
No risk	-	X0	F0, C0, W0	I-A	X0
Carbonation	Mild	XC1	-	-	XC1
	Moderate	XC2	-	-	XC2
	Severe	XC3	-	-	XC3
	Very severe	XC4	C1	-	XC4
Chlorides other than from seawater	Mild	XD1	-	-	XD1
	Moderate	XD2	-	IV-C	XD2
	Severe	XD3	C2	IV-D	XD3
Chlorides from seawater	Mild	XS1	-	-	XS1
	Moderate	XS2	-	III-C	XS2
	Severe	XS3	C2	III-E	XD3
Freezing and thawing	Mild	XF1	-	II-C	XF1
	Moderate	XF2	F1	II-D	XF2
	Severe	XF3	F2	-	XF3
	Very severe	XF4	F3	II-E	XF4
Chemical attack	Mild	XA1	S1[A]	V-C	XA1
	Moderate	XA2	S2[A]	V-D	XA2
	Severe	XA3	S3[A]	V-E	XA3

Table 9-4. Comparison of limiting values minimum cement contents, maximum water/cement and compressive strength in international concrete standards[A].

Exposure Type		**Minimum cement content (kg/m^3)**			**Maximum water/cement ratio**			**Minimum compressive strength (MPa)**		
Corrosion source	**Severity**	**EN 206**	**ACI 318**	**GB/T 50476**[B]	**EN 206**	**ACI 318**	**GB/T 50476**[B]	**EN 206**[A]	**ACI 318**	**GB/T 50476**[B]
No risk	-	260	-	-	-	-	0.60	12	F0, C0, W0	25
Carbonation	Mild	260	-	-	0.65	-	-	20	-	-
	Moderate	280	-	-	0.6	-	-	25	-	-
	Severe	280	-	-	0.55	-	-	30	-	-
	Very severe	300	-	-	0.5	-	-	30	17	-
Chlorides other than from seawater	Mild	300	-	-	0.55	-	-	30	-	-
	Moderate	300	-	-	0.55	-	0.42	30	-	40
	Severe	320	-	-	0.45	0.40	0.42	35	34	40
Chlorides from seawater	Mild	300	-	-	0.5	-	-	30	-	-
	Moderate	320	-	-	0.45	-	0.42	35	-	40
	Severe	340	-	-	0.45	0.40	0.40	35	34	45
Freezing and thawing	Mild	300	-	-	0.55	-	0.40	30	-	45
	Moderate	300	-	-	0.55	0.55	0.50	25	24	35
	Severe	320	-	-	0.5	0.45	-	30	31	-
	Very severe	340	-	-	0.45	0.40	0.45	30	34	40
Chemical attack	Mild	300	-	-	0.55	0.50	0.45	30	31	40
	Moderate	320	-	-	0.5	0.45	0.45	30	31	40
	Severe	360	-	-	0.45	0.45	0.40	35	31	45

[A] reference exposure categories are shown in Table 9-1. Exposure classes in international concrete standards.

[B] limiting values for "board, wall, and other plate components" and a design working life of 50 years

[C] EN 206 states that w/c and min cement apply in all cases, while the requirements for concrete strength class may be additionally specified.

Table 9-5. Curing requirements in international concrete standards.

Curing Requirement	**ACI 318**		**EN 13670 and ISO 22965**[A]												**Chinese**				
															Exposure Class				
															I-A		**I-B, I-C, II-C, III-C, IV-C, V-C, II-D, V-D, II-E, V-E**		**III-D, IV-D, III-E, IV-E, III-F**
															OPC-based	**SCM-based**	**OPC-based**	**SCM-based**	**SCM-based**
Curing temperature (°C)	≥10	≥10	≥ 25			25 > and ≥15			15> and ≥10			10> and ≥ 5			≥10				
Strength development	Normal	High early strength	R[B]	M[B]	S[B]	R[B]	M[B]	S[B]	R[B]	M[B]	S[B]	R[B]	M[B]	S[B]	-				
Minimum curing period (days)	7	3 unless accelerated curing is used	1.5	2.5	3.5	2.0	4	7	2.5	7	12	3.5	9	18	1	3	7	7	7
Curing condition (% of minimum compressive strength)	-	-	≥50[C]	50> ≥30[C]	>30[C]	≥50[C]	50> ≥30[C]	>30[C]	≥50[C]	50> ≥30[C]	>30[C]	≥50[C]	50> ≥30[C]	>30[C]	-	-	50	50	50
Environment	Maintain in moist conditions	Maintain in moist conditions	Keep surface permanently wet												Natural curing	High moisture condition	Natural curing	High moisture condition	High moisture condition (until 50%) Continue natural curing 70% of 28-day strength

[A] minimum curing period for curing class 3 corresponding to a surface concrete strength equal to 50 % of the specified characteristic strength

[B] R, M and S are rapid, medium and slow strength development during curing, respectively.

[C] The ratio of mean compressive strength after 2 days to the mean compressive strength after 28 days, f_{cm2}/f_{cm28} for rapid, medium and slow strength development are $f_{cm2}/f_{cm28} \geq 0.5$ $0.50 > f_{cm2}/f_{cm28} \geq 0.3$ and $0.3 > f_{cm2}/f_{cm28} \geq 0.15$, respectively.

Table 9-6. Review of prescriptive and performance-based specifications in international cement standards.

Specification	**EN 197-1**	**EN 197-5**	**ASTM C150**	**ASTM C595**	**ASTM C1157**	**GB 175**
Amount of constituents, e.g. limestone, fly ash, pozzolans, slag, etc.	Prescriptive	Prescriptive	Prescriptive	Prescriptive	No requirement	Prescriptive
Chemical composition	Prescriptive	Prescriptive	Prescriptive	Prescriptive	No requirement	Prescriptive
Chloride content	Prescriptive	Prescriptive	Prescriptive	Prescriptive	No requirement	Prescriptive
Sulphate content	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Performance-based	Prescriptive
Air content	No requirement	No requirement	Prescriptive	Prescriptive	Prescriptive	Prescriptive (GB 50119-2013)
Loss on ignition	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Prescriptive
Compressive strength	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based
Setting time	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based
Expansion	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based
Heat of hydration	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based	Performance-based (GB 50496-2018)

Table 9-7. Cement types in international cement standards.

Specification	**EN 197-1**	**EN 197-5**	**ASTM C150**	**ASTM C595**	**ASTM C1157**	**GB 175**
Main cement types	CEM I (95-100% clinker) CEM II (65-94% clinker) CEM III (5-64% clinker) CEM IV (45-89% clinker) CEM V (20-64% clinker)	Additional CEM II types CEM VI (35-40% clinker)	Type I Type II Type III Type IV Type V (>95% clinker)	Type IP: pozzolan content ≤ 40 % by mass. Type IS: slag content ≤ 95 % by mass. Type IL: limestone content > 5 % and ≤ 15 % by mass. Type IT (P)(P): pozzolan content ≤ 40 % by mass. Type IT (S)(P): slag and pozzolan content ≤ 70 % by mass and pozzolan content ≤ 40 % by mass. Type IT (P)(L): pozzolan content ≤ 40 % by mass and limestone content ≤ 40 % by mass. Type IT (S)(L): - Type IT(S≥70) in which slag content ≥ 70 by mass is permitted to use hydrated lime where limestone content ≤ 15 % by mass. - Type IT(S<70) in which slag content < 70 by mass is permitted to use limestone content ≤ 15 % by mass.	General use Moderate sulphate resistance High early strength Low heat of hydration High sulphate resistance	P·I (100% clinker) P·II (95~100% clinker, 0~5% GGBS or limestone) P·O (80~95% clinker, 5~20% FA/GGBS/pozzolanic composite) P·S·A (50~80% clinker, 20~50% GGBS) P·S·B (30~50 clinker, 50~70% GGBS) P·F (60~80% clinker, 20~40% FA) P·P (60~80% clinker, 20~40% pozzolanic composite)
Total of cement types	34	5	8	16	6	7

[A] air entrainment and moderate sulphate resistance requirements can be specified

Table 9-8. Review of prescriptive and performance-based specifications in international aggregate standards.

Specification	**EN 12620**	**EN 13055**	**ASTM C33**	**ASTM C330**	**ISO 19595**	**GB/T 14684-2011 (fine aggregate)**	**GB/T 14685 -2001 (coarse aggregate)**
Geometrical							
Grading	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Prescriptive	Prescriptive
Fines content	Prescriptive [A]	Prescriptive [A]	Prescriptive	Prescriptive	Prescriptive [A]	Prescriptive	Prescriptive
Fines quality	Prescriptive or performance-based [A]	-	-	-	Prescriptive or performance-based [A]	-	-
Shape	Prescriptive [A]	Prescriptive [A]	-	-	Prescriptive [A]	-	Prescriptive
Shell content	Prescriptive [A]	-	-	-	Prescriptive [A]	Prescriptive	-
Physical							
Resistance to fragmentation	Performance-based [A]	Performance-based [A]	-	-	Performance-based [A]	-	-
Resistance to wear	Performance-based [A]	Performance-based [A]	-	-	Performance-based [A]	-	-
Density	Performance-based [A]	Performance-based [A]	Performance-based	Performance-based	Performance-based [A]	Performance-based	Performance-based
Water absorption	Performance-based [A]	Performance-based [A]	-	-	Performance-based [A]	Performance-based [A]	Performance-based [A]
Resistance to abrasion	Performance-based [A]	Performance-based [A]	Performance-based	Performance-based	Performance-based [A]	Performance-based	Performance-based
Water content	-	Prescriptive [A]	-	-	-	-	-
Freeze thaw resistance	Performance-based [A]	Performance-based [A]	Performance-based	Performance-based	Performance-based [A]	-	-
Magnesium sulphate soundness	Performance-based [A]	-	Prescriptive or performance-based	Prescriptive or performance-based	Performance-based [A]	-	-
Volume stability (drying shrinkage)	Performance-based [A]	Performance-based [A]	-	Performance-based	Performance-based [A]	-	-
Resistance to thermal shock	-	Performance-based [A]	-	-	-	-	-
Resistance to cyclic compressive loading	-	Performance-based [A]	-	-	-	-	-
Chemical							
Chloride content	Prescriptive [A]	Prescriptive [A]	-	-	Prescriptive [A]	Prescriptive	Prescriptive
Sulphate content	Prescriptive [A]	Prescriptive [A]	-	-	Prescriptive [A]	Prescriptive	Prescriptive

Coal, lumps, chert and friable particles	-	-	Prescriptive	Prescriptive	-	Prescriptive	Prescriptive
Organic impurities	Prescriptive	Prescriptive	Performance-based	Performance-based	Prescriptive	Performance-based	Performance-based
Loss on ignition	-	Prescriptive [A]	-	Prescriptive	-	-	-
Petrographic description	-	-	-	-	Prescriptive [A]	-	-
Alkali-silica reactivity	[B]	[B]	[C]	-	B	Performance-based	Performance-based
Mechanical							
Confined compressive strength	-	Performance-based [A]	-	-	-	-	-
Compressive strength	-	-	-	Performance-based	-	-	-
Splitting Tensile Strength	-	-	-	Performance-based	-	-	-

[A] when required

[B] in accordance with local provisions

[C] Guide C1778 provides information on identifying and preventing the deleterious alkali-aggregate reaction

Table 9-9. Source materials in international aggregate standards.

Specification	**EN 12620**	**EN 13055**	**ASTM C33**	**ASTM C330**	**ISO 19595**	**GB/T 14684-2011** **GB/T 14685 -2001**
Source materials	- Natural aggregate from mineral sources which has been subjected to nothing more than mechanical processing. - Manufactured aggregate of mineral origin resulting from an industrial process involving thermal or other modification. - Recycled aggregate from the processing of inorganic material previously used in construction.	- Natural aggregate from pumice, scoria, tuff. - Manufactured aggregate from natural sources including expanded clay, expanded shale, expanded slate, expanded perlite and exfoliated vermiculite. - Manufactured aggregate from industrial by-products or recycled products, including sintered fly ash, cold bonded fly ash, foamed blast furnace slag, expanded pelletized blast furnace slag, expanded glass, and foamed glass. - Aggregate from industrial by-products, including furnace clinker, furnace bottom ash and fly ash	- Fine aggregate: natural sand, manufactured sand, or other recycled aggregate. - Coarse aggregate: gravel, crushed gravel, crushed stone, air-cooled blast furnace slag, or crushed hydraulic-cement concrete, or other recycled aggregate.	- Aggregates prepared by expanding, pelletizing, or sintering products such as blast-furnace slag, clay, diatomite, fly ash, shale, or slate. - Aggregates prepared from processing natural materials, such as pumice, scoria, or tuff.	- Natural aggregate from mineral sources which has been subjected to nothing more than mechanical processing.	- Fine aggregate: natural sand, manufactured sand - Coarse aggregate: Pebble, crushed stone.

Table 9-10. List of international standards for building materials reviewed in this work.

Standard	**Description**
Concrete	
EN 206:2013+A2:2021	Concrete. Specification, performance, production and conformity
EN 1992-1-1	Eurocode 2. Design of concrete structures. Part 1-1. General rules. Rules for buildings, bridges and civil engineering structure
EN 13670:2019	Execution of concrete structures
ACI 301-20	Specifications for Concrete Construction
ACI 318-19(22)	Building Code Requirements for Structural Concrete and Commentary
ISO 22965-1:2007	Concrete. Methods for specifying and guidance for the specifier
ISO 22965-2:2007	Concrete. Specification of constituent materials, production of concrete and conformity of concrete
ISO 15673:2016	Guidelines for the simplified design of structural reinforced concrete for buildings
GB/T 50476-2019	Code for durability design of concrete structures
JTG/T 3310-2019	Code for Durability Design of Concrete Structures in Highway Engineering
GB 50666-2011	Code for construction of concrete structures
Cement	
EN 197-1:2011	Cement. Composition, specifications and conformity criteria for common cements
EN 197-5:2021	Cement. Portland-composite cement CEM II/C-M and Composite cement CEM VI
ASTM C150/C150M-22	Standard Specification for Portland Cement
ASTM C595/C595M-21	Standard Specification for Blended Hydraulic Cements
ASTM C1157/C1157M-20a	Standard Performance Specification for Hydraulic Cement
GB 175-2007	Common Portland cement
Aggregate	
EN 12620:2002+A1:2008	Aggregates for concrete
EN 13055:2016	Lightweight aggregates
ASTM C33/C33M-18	Standard Specification for Concrete Aggregates
ASTM C330/C330M-17a	Standard Specification for Lightweight Aggregates for Structural Concrete
ISO 19595:2017	Natural aggregates for concrete
GB/T 14684-2011	Sand for construction
GB/T 14685 -2001	Pebble and crushed stone for construction

10 Interviews

10.1.1 Meeting between IC and the Mineral Products Association (MPA).

Date: 28/11/22, 3 pm

In attendance PSF and MH (Imperial)

Diana Casey (Director, Energy and Climate Change, and Director, MPA Cement)

Colum McCague (Technical Manager, MPA Cement).

The interview started with a discussion about prescriptive standards – it was stated that there will always be some role for prescriptive cement standards. It is important to note that there are performance-based criteria **within** current standards – it's not an either / or.

Question 1 "Is there an effective way to create performance-based standards with respect to compromising safety and reliability"

It is not necessarily the case that specifying cementitious materials under a performance-based standard is not preferred by purchasing managers – there is also the issue of getting the building certified for insurance purposes, and some insurers may not prefer performance-based standards.

Purely performance-based standards can be difficult to enact because they require a LOT of testing, which comes at a cost (and takes time). We are fortunate with OPC that there has been a very long history and that we can predict how different replacements for clinker will work in reality. This allows good understanding of how cements will behave within a certain range of substitution. For entirely new cements this will not be the case.

There are performance elements in prescriptive cement and concrete standards, strength being the main example, and heat of hydration. The European commission is encouraging performance-based standards but retaining some prescriptive based elements in standards is important.

It is possible to either revise initial standards or to add new parts to an existing standard. It is much quicker to add new parts to an existing standard than to revise the original standard – revising an existing standard can get heavily delayed.

Standards are needed over new specifications. The specification PAS 8820:2016 was introduced for Alkali activated cementitious materials but it doesn't get used much because insurers and specifiers prefer standard BS 8500 (British EN 2016).

In the UK standard BS 8500 it is possible to go down a purely performance-based route, but people are reluctant to do this if a prescriptive route is there.

For NEW materials, where there is not such a huge volume of experience, it might be more sensible to go down the route of a performance-based standard.

BSI Flex is a performance-based standard for concrete, though CM was not certain how it was being put together https://www.bsigroup.com/en-GB/our-services/standards-services/flex/.

It is not just a case of wanting a particular standard, but (justified and sensible) aversion to risk – buildings or other structures have been built in a particular manner, and people know how to design something to a particular code, so are reluctant to change. There is a role for education here. It is also important for low carbon materials to be used in low risk applications initially, to develop confidence in them by the people specifying them. This is very important. Applications could include, for example, paving and other non-structural applications.

It is possible sometimes to engineer our way out of issues with new cements etc by changing the way a structure is built – for example waiting for longer between sections to allow strength to develop if the 1 day strength is lower, but the 28 day strength is the same. Essentially, it might be necessary to design the building and construction process to allow the use of the new materials.

Question 2 "Have any external factors such as local policy or legislation helped new materials gain approval and adoption?"

Important to note that there is no policy incentive in the UK currently for CO_2 captured from industry e.g. cement manufacture, to then be used e.g. in building materials [n.b. see section 10.1.5 where a number of initiatives are discussed]. Essentially, all of the current policy and financial support goes for geological storage, whereas there is significant potential for the use of cementitious materials to store CO_2. There is currently no funding for any use of low carbon materials – only barriers, and they need to be removed. CCU is a **real** benefit to MPA members, who may be situated a long way from a storage site, though admittedly the actual amount taken up in many circumstances is quite small – though potentially there is a big market in sustainable aviation fuels.

There is a new cement standard currently in production, based on using fines from End of life concrete that allows up to 35% clinker replacement and is prescriptive-based. This is based on the fact that currently limestone is allowed in cements in ISO 197-1:2011 up to 35 mass%, and fines from end-of-life concrete are expected to perform at least as well as limestone (they are approximately limestone since they are naturally carbonated during use and end-of-life management).

Major infrastructure projects often have targets on CO_2. HS2 have done some trials, and were looking to test new concretes – including a number that relied less on ground granulated blast furnace slag – some involving calcined clays. These are used in lower risk applications such as culverts and retaining walls. [CEMEX Vertua concrete was used in some parts of HS2].

Prescriptive standards are not so slow to develop as performance-based ones, but OPC does need a performance-based standard, which is being developed. New 'Exposure Resistance Classes' (ERCs) will be introduced into EN 206. Essentially this means that concrete can be classified by its durability performance using limiting values for performance e.g. chloride migration, rather than composition (e.g. cement type/content). BSI is also developing performance based guidance for PC and non-PC concretes which will draw upon the European ERC guidance. This will take the form of a BSI flex standard.

Question 3 "Are there tools or models that can predict long-term performance and the effect of wide-scale application?"

[further discussion / DC and CM will ask colleagues for their views]

Question 4 "Potential markets and business models for novel carbonaceous building materials? "

Current list of possible markets

- Cement from carbonated end-of-life cement paste
- Carbonated normal weight and recycled concrete aggregate
- Carbonated lightweight aggregate
- CO2-injected ready-mix Portland cement concrete

- Carbonated Portland cement concrete products
- Solidia

The interviewees also know about carbon cure and carbon8 systems.

Standards that we should look at:

EN197-1 is used a lot

BS 8615 (Calcined Clay)

BS 7979 – limestone fines

Cement EN 197-5 new low clinker cements

EN197-1 part 6 for recycled concrete fines

Parts are being added to European standards to overcome issues in revising harmonised standards - parts can be added quite quickly.

BS 8500 (British EN 2016)

PAS 8820:2016 (specification)

10.1.2 Meeting between IC and Heidelberg Materials

In attendance: PSF and MH (Imperial)

Dr Ing Reiner Haerdtl (Heidelberg Materials)

General introduction to the project, followed by:

Question 1 “Is there an effective way to create performance-based standards with respect to compromising safety and reliability”

Regarding performance-based standards. The aim is really to allow more flexibility in the existing standards and e.g., to allow more efficient introduction of cements containing new constituents– to avoid being prescriptive.

The requirements are twofold – there must be considered both product standards, and additionally usage standards (i.e. concrete codes defining how to use the products in situ (water ratio, etc).

Nearly all standards, product as well application, contain a mixture of both prescriptive and performance-based approaches. Depending on the type of cement and the SCMs used there may be a number of different standards. However, for the future the existing methods may be a little prescriptive.

In Europe, product standardization has also to follow the rules for market legislation according to Construction Product Regulation (CPR). Because of legal reasons, the European Commission is blocking any revision of existing or creating new “harmonized” standards. To overcome that blockage and to introduce cement types new compositions and components following the needs for further clinker reduction, CEN was obliged to develop new separate “non-harmonized” standards.

The application standards for cements and concrete additions (SCMs) must follow national concrete standards because the individual Member States are responsible for construction safety. Under these conditions, concrete standards on European level have more a framework and recommending character which needs to be amended at least by National Application Documents.

ASTM C1157 Performance Hydraulic cement (created 1992): the standard allows high flexibility in composition of cements by only defining criteria on the performance of cement. In the market, however, the standard does not find acceptance because there is missing confidence that the products really meet the necessary performance. The responsibility for verifying the applicability of the cement is shifted to the customer.

Prescriptive rules on the use of cements with regard to long-term parameters for durability give the concrete producers the possibility to apply the materials without the need of additional testing. Performance testing of these parameters would usually take a lot of time and needs special equipment (e.g. freeze-thaw chambers). Thus, more flexibility in cement standards does not mean automatically more flexibility in their application in concrete.

This was summarised in the statement “Flexibility isn’t for free”; i.e., additional testing or approval procedures need to be considered.

The European cement standards already cover a wide range of cement types enabling the reduction of the clinker content, but there is currently work going on to develop new, more performance-based standards. However, this takes time to find necessary acceptance by all stakeholders involved in standardization process. The aim is very much to have a more performance-based process.

Question 2 “Have any external factors such as local policy or legislation helped new materials gain approval and adoption?”

There needs to be better sharing of understanding and field knowledge across countries, to enable adoption of new cement types, SCMs etc. Cross-sharing of knowledge OF ALL TYPES is important. It may be valuable to have a new material or technology into an existing standard, but the key thing is to disseminate the knowledge that is extant – construction (materials) is a very conservative business!

Promoting aspects in tendering – requests for new “lower CO_2 material” in tendering have been observed.

On the other side – new developments are frequently blocked by conservative (e.g. environmental rules) – for example re-use of concrete waste, end of waste classification. For example – the material could have a tiny amount of asbestos and prevent any further use at all.

Question 3 “Are there tools or models that can predict long-term performance and the effect of wide-scale application?”

Accepted models, calibrated to the practical conditions of concrete in-situ, can avoid or minimize the required large-scale testing.– I The revision European concrete standard EN206 will include a performance concept on the durability of concrete currently under development. Defined performance limits are based on input from the FIB model code (according to the concept of exposure resistance classes). However, if you have a new material, you go away from the conditions of the existing materials, so you have to do a set of testing to demonstrate that the new material performs as per the existing codes. New cements will additionally have extra safety margins until proven that they do not need them – which leads to a push and pull effect in the environmental effects. Then you have to think about CO_2 emissions within the standards – at the moment it is separate.

Question 4 “Potential markets and business models for novel carbonaceous building materials? “

Governmental tendering – bonus on certain building supplies that are low carbon. The Netherlands has this. Under review, because in some cases durability concerns may have come about – speak to colleagues in the Netherlands.

Private lead markets – large contractors have more requirements for cement carbon costs – these will become more important over time. Over the lifecycle of a building the initial cement CO_2 (for example) is less important. Taxation of CO_2 release is important. Recycling of concrete is very important (fine materials, recarbonate, reuse in cement) – if you recarbonate it it can develp pozzolanic properties: the first and easiest measure is to prevent people from dumping concrete – you must reuse it. In principle the recycling rate is very high – however, using concrete in road base for example can be seen as downgrading it, there might be a better solution.

Standards that we should look at:

Some ones we know of below

EN197-1 – mandatory in all European countries, blueprint for many countries worldwidet

BS 8615 (Calcined Clay and natural pozzolans) – A European standard will be developed.

BS 7979 – limestone fines – European standard to come about this year.

Cement EN 197-5 new low clinker cements

EN197-1 part 6 for recycled concrete fines

Parts are being added to European standards to overcome issues in revising harmonised standards - parts can be added quite quickly.

BS 8500 (British EN 2016)

PAS 8820:2016 (specification / guideline) British guideline on alkali activated materials. Too open to define how people should use these.

CaSBelite cements not covered – a standard is needed.

Question 5 “Is there anything we have missed? Any questions we should add?”

Question 6” Who else should we contact?”

10.1.3 Meeting between IC and Construction Industry Supplier

5 / 01 / 23 10:00 – 11:00

In attendance: PSF and MH (Imperial)

Anonymous interviewee.

Suggests we should talk to Low Carbon working group – [contact]. They're looking to set up a BSI committee on performance-based approach for concrete specifying.

Important to ensure that there are not vast numbers of different approaches suggested – there is a potential for confusion and slow / contradictory outcomes unless people work together and don't ignore what has been done already. Industry players have already tried to ensure that there is a consistent approach around the world. Eurocodes have pushed ahead somewhat, some things have been included in the Eurocode and have gotten ahead of the standards. EN standards are a monster to move forward, they need strong agreement to change.

Some current debate is about removing minimum cement contents, though these are a protection mechanism to ensure concrete doesn't fail. Lots of different interested parties and conflicts – for example a test house might introduce a test that they have invented and that only they could do, which is little use to the wider community – but they will try hard to get it in to a standard (see also the discussion at the beginning of section 7).

Company works through the MPA, and have full time members that support / help BSI, and then push upwards to EN committees. BS 8500 concrete standard enacting EN 206 is in UK legislation – this stops people putting bad cement / failing cement in place and rushing ahead with something new (BS 8500 haven't adopted all the cement options in EN 197).

An example of new cement types that have been included in standards recently is Portland Limestone Cement Ternaries – Portland EN197 part 5 being taken into BS 8500 to allow limestone fillers to be used in place of / in harmony with GGBS cements. Interested parties are very much pushing forward on Portland Limestone Cement Ternaries, but still rely on slags. The carbon footprint of a filler is much less than a slag. However, people don't want to put new cement types in to concrete without a lot of testing – it has taken 7 years and the standard isn't published yet (expected mid 2023).

IF no bureaucracy 😊 then a standard could be possible within a 3 year cycle. But which test methods should be used? There are no common approach test methods across Europe. For example, Sulphate tests / carbonate tests there are no official test methods, which leads to time wasted. The company would then go to the best / most skilled recognised bodies (Dundee, Sheffield, BRE), knowing that the work is done properly – but it is a source of frustration how long it takes.

Winning projects now implies low carbon. However, designers will currently work ONLY within a standard – they won't specify something that is not in a standard, but are very happy to specify something once it is in a standard (see also section 10.1.7, which echoes this feeling). For example, a new type of cement - AACM high slag concrete – is at the stage where demonstrations are being done / durability testing / raw materials need testing. Everyone is on a patented solution with different types of activators etc – the processes are not fully scaled up, and all admixtures are bespoke to a particular solution. If companies are using slag – compositions change day to day / supplier to supplier. A publicly available specification (PAS) has been written on AACMs (PAS 8820:2016). The green construction board is working with BSI to try and get an accelerated performance test for AACMs – but this will take 18 months at the fastest – an issue is that some of the tests that are run are the wrong tests – for example the Bauer test won't work because the product doesn't bleed.

People need to be wary with AACMs – there is a lot left to understand. For example, how do you accelerate the testing without ending up in a calamity? One way of building confidence is through a lot of testing in non safety critical applications [a repeated theme through the interviews]. You might want different tests for some classes of concrete – some tests may not actually be appliable, which is frustrating when they are mandated in a standard.

As soon as the materials are included in the standard, the designers will start using the lower carbon materials, once trained.

General introduction to the project, followed by:

Question 1 "Is there and effective way to create performance-based standards with respect to compromising safety and reliability"

Use the existing framework, with people having a sense of urgency, but not rushing to do things – doing it properly – it is important to understand what different stakeholders want to do. Urgency is key – this can't take the usual 12 years – ternary cements were held up for 1 year due to not having a convener for the committee.

Question 2 "Have any external factors such as local policy or legislation helped new materials gain approval and adoption?"

Carbon tax / cost and shareholder pressure to the board. To stay in business you have to go low carbon – in recent years there has been more of a way forward – the blocker was the cost. Company has a specific approval process for low carbon innovation – with vastly reduced bureaucracy.

More intelligent ways of making buildings. Not only about technology revolution but also about changing peoples practices. 28 day strength is not always needed, why not a 56 day strength and remove some cement if you're not going to load a structure up (see also section 10.1.1).

National highways pushed for the early adoption of low carbon materials and pushed for the BS in low carbon materials (BS 8500). Need people to be lobbying (incl. tier 1 contractors).

There is a general move towards whole life carbon and cost.

Concrete is very durable if made properly – why not make mechano concrete.

Thermal mass is important and needs careful consideration.

Question 3 "Are there tools or models that can predict long-term performance and the effect of wide-scale application?"

[no answer]

Question 4 "Potential markets and business models for novel carbonaceous building materials? "

[no answer]

Standards that we should look at:

Some ones we know of below

EN197-1 is used a lot

BS 8615 (Calcined Clay)

BS 7979 – limestone fines

Cement EN 197-5 new low clinker cements

EN197-1 part 6 for recycled concrete fines

Parts are being added to European standards to overcome issues in revising harmonised standards - parts can be added quite quickly.

BS 8500 (British EN 2016)

PAS 8820:2016 (specification)

Question 5 "Is there anything we have missed? Any questions we should add?"

Question 6"Who else should we contact?"

Eurocodes – concrete centre, go direct to them – insight into how they are being pushed forward.

Things to consider – alternative fuels, recycled woods, hydrogen? Hubs to capture CO_2.

Calcined Clay very important.

10.1.4 Meeting between IC and GCPAT

4/1/23

In attendance: PSF, MH and RJM (Imperial)

Nathan Tregger : GCPAT (acquired by Saint Gobain)

Introduction – there has been a lot of movement in the environmental area, lots of interest in cement etc now. Nathan has a background in concrete research. Nathan now leads a group of data scientists – looking at sensors on concrete trucks, rheology of concrete etc.

Their company works in the area of untangling how to persuade people to "do the right thing" – and hence to reduce the total amount of cement required in concrete, by reducing the standard deviation of concrete strength and other qualities – allowing reduction of total amount of cement used / CO_2 produced. By tracking e.g. slump (workability) of the concrete, time to arrive, the amount of water added, rpm of the truck, it is possible to develop a better idea of what has happened to the concrete along its journey and to therefore ensure that some changes which may be made to the formulation post leaving the concrete production / batching plant are accounted for / are discouraged. For example the addition of extra water improves the workability of the concrete, but reduces the strength – and may take it out of specification. Since e.g. quality control people understand this, there is an incentive for them to over-specify the amount of cement added to the mix to ensure that strength will not be compromised – but everyone suffers because some people are adding water unnecessarily. Education is important here.

In addition, there are CO_2 savings in terms of fuel – GPS sensors allow understanding of such things (as well as time to site, etc).

Question 1 "Is there an effective way to create performance-based standards with respect to not compromising safety and reliability"

Having a large amount of information on properties of the concrete as it is delivered – from a US perspective, we can see when contractors are adding water at the site, which over the years has led producers to add more cement in the mix. If you don't know what is going on onsite you don't know what performance you are getting - there is a potential for people on site to significantly change the properties. So – the specifier specifies what is required but this can be changed by the site operators. There is a difference between what is prescribed and what happens on site – if you don't know what's going on at the site then you don't know what performance you're getting. In some cases you can clearly see that there is too much cement in the mix, but because at the level of the standards this has been taken in to consideration, you can't take it out because of the prescriptive specifications.

Question 2 "Have any external factors such as local policy or legislation helped new materials gain approval and adoption?"

Type 1L cements have been available in Europe for decades, but only recently has the US moved towards its use – risk aversion is very high in the US (maybe EU is less risk averse). In terms of the work that is being done by GCPAT, they are trying to increase the rate of knowledge transfer. Penetration relies on first movers to adopt materials and processes. If there were local changes to require measurement systems it would be a lot more quickly rolled out. Education / work required to do – BBV, who are working on HS2 are looking at specifying an in-transit measurement/management system – this push is coming from a contractor/producer rather than a regulatory requirement.

Liability / traceability is important to help the company. This helps to demonstrate that their concrete is fit for purpose.

There is actually a lot of concrete bought for slump testing – which can be avoided by managing the concrete water content properly.

Question 3 "Are there tools or models that can predict long-term performance and the effect of wide-scale application?"

We see a few AI companies popping up around concrete mix designs. It remains to be seen how accurate these can be in the long term. It is a difficult problem the variety of materials used in the field is typically way beyond the training lab data set. Example is the slump test data set from UCI. Producers may on a weekly basis use a different cement, and there are also interactions with chemical admixtures and variety of environmental conditions where the concrete is placed leading to a massive dimensionality of the problem.

Maturity / sensor type people would be worth talking to (Giatech, Maturix, Exact technologies).

Question 4 "Potential markets and business models for novel carbonaceous building materials? "

A lot more commercial LCA going on – very political area – lobbyists have a great deal of influence here. A lot of design tools are available to use ultra high strength materials.

To allow new materials to be used, there is a challenge – either experiments take a long time, are hard to accelerate, or don't give that much useful information for the new cement types / new materials being added.

People are currently thinking of new ways to do things, and there is a renewed push for CO_2 mitigation. Improved measurement of what's happening post going out of the cement factory gate will allow better standard deviation on cement quality – and higher uptake of novel materials. What is really important is to make the concrete properly.

Nathan sees a push towards precast… this does lead to significantly improved quality … all Wallmart, Amazon warehouses in US are precast … there is a difference between US where precast is growing, and developing countries with industrialisation of concrete value chain – educating specifiers that concrete products / precast are also possible and how they can be used (beneficially) – will potentially mean that they switch to precast earlier.

Standards that we should look at:

Some ones we know of below

EN197-1 is used a lot

BS 8615 (Calcined Clay)

BS 7979 – limestone fines

Cement EN 197-5 new low clinker cements

EN197-1 part 6 for recycled concrete fines

Parts are being added to European standards to overcome issues in revising harmonised standards - parts can be added quite quickly.

BS 8500 (British EN 2016)

PAS 8820:2016 (specification)

Question 5 "Is there anything we have missed? Any questions we should add?"

LC3 interesting – kilns popping up to do LC3. Cement companies in general. Saving cement is counterintuitive because the cement companies sell cement!

Educate specifiers to not use prescriptive standards that are 50 years old.

Question 6 "Who else should we contact?"

10.1.5 Meeting between IC and Carbon8 Systems

4/1/23 2 – 3 pm

In attendance: PSF and MH (Imperial)[63]

Paula Carey and Colin Hills – Carbon8 Systems, a purveyor of lightweight carbonated aggregates.

General introduction to the project, followed by general considerations about performance based-standards.

Performance-based standards were considered by the respondents to be the main route to allow materials to market. Currently, prescriptive standards EN 13055 (2016) specify which source materials can be used for lightweight aggregates. This is detrimental to the production of *new* materials – if you can prove that your current material behaves in the same way to the materials in the standard then why should you not be able to use them?

Carbon8 have engaged in the development of the standard – there is a general procedure for the incorporation of new materials in a clause in EN 13055, but people want to see a 25 year history, which makes it significantly harder to get a new material into use.

Prescriptive standards are easier for the user – they were, however, seen as a tick-box exercise. If a prescriptive standard exists then in order to get a new material in to a standard you have to do all of the testing in advance and then get it in to the standard, which can take a long time and a lot of effort – if a performance based standard exists you don't have to wait 10 years to get the material (as tested) into a prescriptive standard. There are already performance elements in existing standards such as accelerated durability test methods for freeze/thaw resistance (EN 1367-7) and magnesium sulphate resistance (EN 1367-2).

One of the big problems is that the construction industry is very conservative – they can use a prescriptive standard as an excuse to not use a particular material and not to innovate. There's a lot of potential for protecting existing interests as well.

Question 1 "Is there and effective way to create performance-based standards with respect to compromising safety and reliability"

The respondents suggested that "Is there a way to ensure fitness for purpose without going down the prescriptive standard route?" might be a better way to phrase this.

The existing standards methodology works, but it is slow.

There was a brief discussion about why people might not use a particular performance-based standard - with respect to ASTM 1157 (high performance cement) – the opinion of the interviewees was that it is entirely possible to use them, people supplying them should actually go out and do the testing and there would not be an issue.

Lightweight carbonated aggregates have already been used in lower performance applications – which will help them to gain experience with how they perform in the field rather than in the lab. However, if your aim is to start using these materials in more challenging arenas, it would take a long time to get them developed by continually "proving" them in less challenging areas. Carbon8 materials have been used as backfill in retaining walls and they meet performance criteria. New materials used in a HS2 type application can increase confidence as the performance can be continually analysed over time – industry want demonstrated performance for 5 to 10 years before they take the risk.

Question 2 "Have any external factors such as local policy or legislation helped new materials gain approval and adoption?"

New York: there are tax benefits in state procurement of using low CO2 mateirals in construction Low-Embodied-Carbon Concrete Leadership Act (LECCLA) Signed by New York Governor - New York Build 2023 (newyorkbuildexpo.com). New Jersey has similar legislation NJ Law Provides Tax Incentives for Concrete Products that Use Carbon Footprint-Reducing Technology | FORVIS. In Finland – planning requires a demonstration that low carbon options have been seriously considered. It is necessary to have an assessment of the carbon footprint of your construction – EPD / Carbon footprint of your construction – local authorities require EPD / LCA. Construction emissions may now be compared – new emissions database lays foundation for statutory guidance of low-carbon construction (valtioneuvosto.fi). Companies can also apply for funding through the Low Carbon Built Environment Programme launched in 2021 to promote low-carbon building solutions.

Question 3 "Are there tools or models that can predict long-term performance and the effect of wide-scale application?"

Accelerated performance tests exist in current standards. The tests include those for alkali silica reaction (BS 812-123) and aggregate resistance to freeze/thaw (EN 1367-7), fragmentation (Los Angeles testing; EN 1097-2) and wear (microdeval testing; EN 1097-1).

Question 4 "Potential markets and business models for novel carbonated (not carbonaceous) building materials? "

Yes – lightweight aggregates pubic procurement to build the market – return to question 2 – external policies required to be in place to push low carbon materials. Stakeholder drive is quite strong nowadays – large investment banks / green financing / green bonds – no green premium yet, but they are trying to reduce the carboon footprint of their material.

There is a lot of money around for investment and some of it is going into less well advised investments.

Standards that we should look at:

Some ones we know of below

EN197-1 is used a lot

BS 8615 (Calcined Clay)

BS 7979 – limestone fines

Cement EN 197-5 new low clinker cements

EN197-1 part 6 for recycled concrete fines

Parts are being added to European standards to overcome issues in revising harmonised standards - parts can be added quite quickly.

BS 8500 (British EN 2016)

PAS 8820:2016 (specification)

Question 5 “Is there anything we have missed? Any questions we should add?”

Question 6 “Who else should we contact?”

10.1.6 Meeting between IC and CarbonCure

2023/01/06

In attendance: PSF and RJM (Imperial)

External attendees: Sean Monkman, CarbonCure

CarbonCure takes the view that they are using CO_2 in the concrete processing pipeline as an admixture, just like any other chemical.

Admixture chemistries are already in the standards, but if we add in another type of admixture/chemistry then this can complicate matters. ASTM Type S. Europe has definition of admixtures that it is necessary to meet, if not then it is necessary to go through some technical assessment process. ASTM C494 can assist.

In terms of concrete plant operations, the water from concrete plants that has been used to wash trucks/stationary mixer and concrete slurry waste; in order to recycle this it can put in a drum (usually in US put in ponds and stuff settles out, usually in Europe it is put in tanks to recycle water). However, in a significant number of cases the cementitious solids are simply sent to landfill currently, but instead one can add in CO_2, and then produce aggregates. [these views are in sympathy with the views expressed in the interview under section 10.1.2].

General introduction to the project, followed by:

Question 1 "Is there and effective way to create performance-based standards with respect to not compromising safety and reliability"

Sean is involved in Canadian standards organisation. Optionality is important. If you want to specify w/c or normal materials then this makes sense, but if not then it is necessary to do particular tests to validate that the concrete is OK. Two options in Canadian standards is what is currently being worked on.

Do we have the right tests now, or do we need new tests? For long term performance

Question 2 "Have any external factors such as local policy or legislation helped new materials gain approval and adoption?"

The jurisdictions of Langley BC, New York State and California were mentioned.. Their local policies have helped with low carbon concrete.

CarbonCure have contributed to help get their product in the policy… e.g. concrete has to be included in the clean solution agenda… first it is necessary to define clean concrete, then encourage people to be even better than that! [This is a similar approach to that taken for the EU's Green Taxonomy].

Question 3 "Are there tools or models that can predict long-term performance and the effect of wide-scale application?"

They are not looking for new tests for CarbonCure cement since it is not a new material. It was necessary to assess the suitability of CarbonCure technology within an existing standard. With the US DoT they asked what would ASTM C494 (setting time, air content, shrinkage, etc.) imply? There are also additional things specific to CarbonCure, which could be examined – pH, calcium oxychloride impact, air voids analysis.

Measurement and verification is important. Proving the actual CO_2 uptake in the concrete from the technology is important. Efforts are underway by NIST USA, RILEM TC to address this – quantification of CO_2 in concrete in general is needed and needs to be done in a way that is accurate and verified.

Question 4 "Potential markets and business models for novel carbonaceous building materials? "

Carbon reduction of a project(LCA is a big component of) validating this … what is the baseline carbon vs new technology carbon?

CarbonCure did the first procedure for concrete materials, being used as an exemplar for the concrete materials industry.

Standards that we should look at:

Some ones we know of below

EN197-1 is used a lot

BS 8615 (Calcined Clay)

BS 7979 – limestone fines

Cement EN 197-5 new low clinker cements

EN197-1 part 6 for recycled concrete fines

Parts are being added to European standards to overcome issues in revising harmonised standards - parts can be added quite quickly.

BS 8500 (British EN 2016)

PAS 8820:2016 (specification)

For recycling of mix water and solid content: ASTMC1602, EN…934?

Question 5 "Is there anything we have missed? Any questions we should add?"

Traditional approach: For this exposure class need X.

But for sustainable approach: For this product we need this lifetime and thus this durability / performance.

Question 6 "Who else should we contact?"

10.1.7 Discussion with John Ballantyne

Date: 21/1/23, 17:00 pm

In attendance PSF (Imperial)

John Ballantyne,Technical Director (Energy, Security and Technology), Jacobs Engineering

Question 1 Standards – appropriateness of standards. How do you choose a standard you will operate under?

This depends on the structure that you are working on. There are a host of structural engineering standards. These range from BSEN1990 – 1996 / 7. BSEN 1990 is an overriding standard talking about reliability – they are looking for a level of reliability in the design. It is possible to go for a higher level of reliability (e.g. in the nuclear industry).

Durability is important – corrosion resistance, there are more onerous requirements if, for example the building is located in a marine environment (corrosion of steelwork and rebar). Chemical attack is important, it is necessary to test the ground to determine if there are issues with sulphate and other ground contaminants which may attack the foundations and other buried structures. Also, it could be important to know what the processes going on in the building are (for example if heavy chemical engineering is going on).

Question 2 Standards – appropriateness of standards. What would you do if you were building in (say) Africa or the Middle East.

You would apply the same standards, but apply different temperatures etc. You can use local standards but make sure that they are equivalent to the EN standards.

Question 3 Standards – If you were going to build under a very low CO_2 requirement, and needed to use a new cement, which wasn't under EN/BS, what would you do?

For structural design, you have to comply with EN. If you start deviating from the EN on the materials side you are cherry picking and run the risk of problems – the codes have evolved over many years and there is an awful lot of thought and expertise which have gone in to them. It is possible to deviate from a code, but you have to be extremely careful – you may end up having to demonstrate that your deviation has no detrimental effect – a very long and tedious process. You can bring in **more** onerous standards, but people would not be happy with working under "lesser" standards. It's been a long time for GGBS to be accepted – it didn't happen in 6 months, it was 40 – 50 years. You deviate from the standards at your peril!

There is a continuous process that has gone on over many years to develop a harmonious set of standards. The onus is on you to determine that there will not be an effect on the building. For example ,in the past, people used to use high aluminia cement, which set much quicker – the trouble is that many years (20) down the line the buildings were found to fall apart. If you specified some non-conforming material, which was subsequently shown to be deficient, then in all likelihood you would be sued / prosecuted for possible shortcomings in this material.

To demonstrate the appropriateness of a material, for example a cement manufacturer (as a client) may decide to build e.g. its new headquarters using a particular new material – then it takes the risk, sets up a program of regular inspections throughout the life of the structure to ensure that it is performing as intended – but will have to sign up to do this.

Question 4 Standards – Supposing that there was a new cement in the standards, when would you be happy to specify it?

Only after a long period of time, research, testing and monitoring to demonstrate its acceptability will it then be accepted in to the EN standards. If it is in the EN you would generally be happy that it has been well tested.

10.1.8 Meeting between IC and Karen Scrivener, EPFL

Date: 19/01/23, 9 am

In attendance PSF and MH (Imperial)

Karen Scrivener (Professor of Building Materials, EPFL)

European standards have allowed blended cements for a long time, EN had broad standards which allowed many different constituents to be added, but clinker substitution was limited to low values (around 35%, apart from slag cements where up to 90% could be substituted).

LC3-type cements can be produced under the current version of EN 197-1, as both limestone and calcined materials can be used in CEM II/B cements up to 35% clinker substitution. However, during the development of LC3 the developers realised that it was better to go to at least 50% substitution for environmental (increased CO_2 savings) and economic benefits (accelerated payback for clay calciner due to higher throughput). Lobbying efforts to increase the permitted substitution for LC3 are extant, but this was held up by a European cement association, due to due diligence and needing to test and examine changes to the standard. EN 197-5 was eventually added as a non-harmonised part to EN 197-5 a couple of years later.

There was a court case in Ireland: the European Court ruled that the EU should be legally responsible for the safety of all the materials it has standardised. Consequently, the EU hasn't published any harmonised standards in the construction sector since the ruling to avoid taking legal responsibility for the materials. It is possible to about this case at this link.

Question 1: Is there an effective way to create performance-based standards without compromising safety and dependability?

Discussion about a developing country. The current standard is complicated, producers can only use certain amounts of specific materials, but the standards authorities in many other countries do not have sophisticated analytical techniques to verify whether the concrete fits the description or not – the standard is very difficult to demonstrate compliance with. Producers want to use LC3 but don't have much local limestone, however most of the limestone in LC3 effectively acts as a filler so could theoretically be replaced with locally available basalt.

KS and Laurent Izoret (previous head of the EN committee for cement standardisation for many years) called a meeting on performance-based standards. Cement makers have become more receptive to performance-based standards recently. KS in the process of chairing a RILEM committee (~5 year duration) to consider approaches to the development of performance-based standards, which has now been approved and will start soon. KS to send the document when finalised. (briefing note attached)

RILEM committee proposed items for work:

1. Mechanical performance: two approaches
    - EN 196-1 fixes the water/cement ratio (one part cement, three parts sand, one half part of water)
        - Fixed water/cement ratio is the best approach as any cement can be used in any quality of concrete – the strength of a cement does not tell you what the strength of the concrete will be, therefore a fixed approach is best.
    - ASTM test includes a workability effect
        - Working in a mortar rather than a concrete exacerbates flow problems because the flow is strongly affected by the total surface area of the

        aggregate in contact with the paste – much higher total aggregate surface area for very fine sand than in a concrete
        - Unduly penalise materials like calcined clay

2. Dimensional stability: two criteria in standards, to avoid, 1. excess of free lime and 2. an excess of sulphate as these can led to uncontrolled expansion in humid conditions over time.
    - Tests for these factors are up to 100 years old, very out-of-date, complex and most organisations cannot do them, especially in the global south (soundness test)
    - Easy submerged mortar test exists → important that anybody can carry out without sophisticated apparatus
3. Minimum clinker or CSH content
    - The concrete industry has been using cements for 100 years that form CSH as the main hydration product. We will lose tried-and-tested experience gained if new cements with fundamentally different chemistries are used – don't know how they'll behave.
    - E.g. carbonation of alkali-activated or geopolymers could cause them to fall apart,.
    - E.g. magnesium silicate cements have given very poor results, poor protection of reinforcement, no buffer to carbonation.
    - The standards are for materials that will be used in ALL settings – a bag of cement should be a bag of cement and needs to be valid so that all people can just pick it up and use it in any context. It needs to be able to be presumed to be e.g. be used with reinforcement.
    - Not yet clear what will a test for CSH – because we can't necessarily guarantee the chemistry you need a prescriptive standard for this part, but you can go for a performance based standard for things that you CAN test.
4. Test for durability
    - The only form of durability currently in cement standards is sulphate attack (remove aluminate content → sulphate resisting cements).
    - Issues with reproducibility of tests
    - EU committee did a LOT of work, including round robins and couldn't come up with a test that people agreed with.
    - could be desirable to also have a chlorine diffusion test and resistance to carbonation, these aspects will be looked at.
    - Likely an intermediate standard developed. Will be a blend of performance and prescriptive standards.

There will be a possible move to an intermediate standard after a RILEM committee - blend of performance (strength and dimensional stability) and prescriptive (keep categories of cement based on clinker content as a test for CSH is not likely). No one is paying for/sponsoring the work (RILEM), committee members are participating on a voluntary basis. PF and MH are welcome to join the first RILEM meeting in March.

Do we continue with the two camps of standardisation – EN and ASTM? Or should we do it through ISO? Some tests are not cross-applicable. Alternative is just to do it through ISO. Indians are pushing to reactivate the ISO standards, but there are issues with bureaucracy. A lot of African countries are modelling their own standards on EN. However, the new additions to standards (i.e. EN 197-5) still need to be applied in the countries themselves (e.g. Egypt and Senegal).

- A lot of work is done on the cement level, but there are also the layers of concrete standards and building codes.

- Once the cement is in the standard it can be sold and demonstration buildings can be constructed and signed off by an engineer (building codes are used to govern buildings that don't have an engineer doing testing) → if the structure maintains performance for 5 or 10 years then designers will more inclined to use it.
- More flexibility at the concrete level.

Global warming accelerated the discussion on performance-based standards compared to two or three years ago – people seem to have changed their mind set hugely.

Question 2: Have any external factors such as local policy or legislation helped new materials gain approval and adoption?

Many countries are promoting low carbon solutions. For example, in the USA, the Inflation reduction act is pumping a huge amount of money into low-carbon solutions. However sometimes these funds are badly targeted, and favour solutions with high slag contents. As nearly all available slag produced (~95%) is already used. Using more slag in one project just takes it away from another project and there is not global reduction in CO2. Policy is easily taken in by particular special interests and "novelty" – "wonder solutions" but what will really make a difference is when people impose benchmarks at the building level – different materials can be used to overall make a building that is low carbon.

Policy measures will make a difference when benchmarks are imposed at the building level. RE2020 (https://www.bouygues-construction.com/blog/en/re-2020-frugalite/) in France sets criteria for different buildings.

Question 3: Are there tools or models that can predict long-term performance and the effect of wide-scale application?

A huge subject of research. Separate in to 2 parts.

1. The vast majority of concrete (~90%) is not subjected to any severe aggression.
    - The main form of degradation that *could* affect most buildings is carbonation that *may* lead to carbonation of the reinforcement.
    - Researchers have spent decades developing carbonation test methods, and the only test currently approved is 6-month natural carbonation test with extrapolation ($t^{0.5}$).
2. Minority of concrete (~10%) is used in aggressive environments.
    - The largest cause of concrete degradation is chloride-induced corrosion of reinforcing steel (90% of real cases in the field). The remaining 10% is split evenly between freeze-thaw and alkali-silica reaction (ASR), with sulphate attack being very small proportion.
        - Good tests exist for ASR - mainly to do with the aggregate.
        - For chlorides, the rapid chloride permeability test (RCPT) has been developed – a conductivity test, results have shown that measuring the conductivity of a block of concrete is a good indicator of its durability in an aggressive environment.

A large number of researchers in cement or concrete are working on durability testing which can exaggerate the extent of durability problems in the field (isn't an issue for 90% of concrete). Also need to proceed with caution.

For example – most of the new materials presented are producing blocks and the blocks can use very little concrete, so savings minimal.

Question 4: Review of the potential markets and business models for novel carbonaceous building materials?

Question 5: Is there anything we have missed? Any questions we should add?

Globe Consensus is working at the building level. Globe Consensus is an initiative of the liason committee which co-ordinates the work of 6 professional societis (FIB, RILEM, CEB, IABSE, ECCS, ISS). It issues a polic note last year and will not co-ordinate a intiative to have an internationally recognised protocol for collecting data on CO2 in buildings. "Benchmarking of Resource Use and Embodied CO_2 in Buildings". Trying to bring together building designers / software engineers / people collecting data to ensure that buildings are being harmonised – not all pressure is on the cement manufacturers to improve sustainability.

Question 6: Who else should we contact?

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International Standards and Testing for Novel CO_2-Containing Building Materials (IEAGHG/CON/22/291)

Part II – Market Entry of CO_2-Containing Materials into Construction Industry

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2 Executive summary

In this part of the project, we assessed a number of different companies which are currently producing carbonated building materials for use in the construction industry. We then assessed, from a mainly supply-side basis, the market potential and total sequestration capacity of such materials. Additionally, three companies were examined in more depth in case studies, and interviews were conducted. The companies were chosen to span those that are producing carbonated aggregates (Carbon8systems), those carbonating the cement within concrete (CarbonCure, also the market leader in the carbonation of building materials space) and a company that develops pre-cast concrete products (CarbonBuilt). Judgment was utilised as to which companies were most representative. Also, Carbon8systems and CarbonCure were mentioned by a number of interviewees (see section 8 of Part I).

The aggregate market has been estimated to be 46 Gt per year. Owing to both environmental pressures and regional lack of resource, recycled aggregates and aggregates produced as industrial byproducts, including those utilising CO_2 within their production are becoming more prevalent. Additionally, to aggregates, there are other ways to use CO_2 in the production of building products: accelerated CO_2 curing of concrete and the use of alternative cement chemistries produced using CO_2. Finally, some materials such as carbonated concrete slurry waste can act in a complex manner (as a supplementary cementitious material / pozzolan) within cement, allowing reduction of the total amount of cement clinker. Previous work has shown that there is a large potential resource of concrete slurry waste and that it could be profitably used.[1]

Table 4-1 shows the different companies which were investigated as part of this project. Company names in bold face were interviewed and their responses used to develop the case studies.

Table 4-1: Overview of companies producing carbonated build materials

Company	**Product**	**Technological Approach**	**CO_2 source**	**Process conditions**	**Field application/ demonstration**	**Product commercially available?**
CarbonCure Technologies	Carbonated ready mix concrete	Injection of CO_2 during the delivery of ready mix concrete	Pure CO_2	Ambient pressure and temperature	2022: General Motors Spring Hill Assembly Plant, USA (20 800 m^3 of concrete)[2] 2022: Amazon HQ2, Arlington, Virginia, USA (106 600 m^3 concrete)[3]	Yes
	Carbonated precast concrete	Injection of CO_2 during the production of precast concrete	Pure CO_2	Ambient pressure and temperature	2020: Retrofit of Coreslab Structures (TEXAS) Inc facilities, USA[4] 2016: MGM National Harbor, USA (195 000 units)[5]	Yes

Company	**Product**	**Technological Approach**	**CO_2 source**	**Process conditions**	**Field application/ demonstration**	**Product commercially available?**
	Carbonated reclaimed water	Injection of CO_2 to create ultrafine CO2-stabilised suspended solids in reclaimed water which can be recycled for use as binder in new concrete mixes	Pure CO_2	Ambient pressure and temperature	2018: Trio Ready mix Commercial Pilot, Canada[6]	Yes
Solidia	Carbonated pre-cast concrete based on alternative cement	CO_2 curing of pre-cast concrete containing low lime calcium silicate clinker-based cement with a low kiln burning temperature	Flue gas	Ambient pressure and moderate temperature (30[7] to 60 °C[8])	2015: Demonstration in Pecs, Austria (6000 tonnes of cement)[9] 2014: Demonstration in Whaiutehall, USA (5000 tonnes of cement)[9]	No
CarbonBuilt	Carbonated pre-cast concrete with partial cement replacement	CO_2 curing of concrete containing partial replacement of OPC with portlandite and fly ash	Flue gas	Ambient gas pressures and flue gas temperatures (<75 °C[10]	2021: Field demonstration at the National Carbon Capture Center, USA (>15 000 concrete masonry units)[11]	Yes
Carbstone (VITO / Orbix)	Carbonated pre-cast concrete based on steel slag cement	Autoclave CO_2 curing of concrete produced using steel slag (after metal recovery for recycling) as an alternative cement	Flue gas	Autoclave conditions, i.e. high pressure (20 bar) and temperature (140 °C)[12]	2020: Construction of a footpath[13] 2013: Construction of pilot plant in Wallonia, Belgium[14]	No
CO_2-SUICOM (Kajima Corporation, The Chugoku Electric Power Company, Denka Company, and Landes Corporation)	Carbonated pre-cast concrete based on special additions	CO_2 curing of pre-cast concrete with reduced cement content using special admixture (γ-C_2S) and fly ash	Flue gas	Ambient pressure and moderate temperature (50 °C)[15]	2012: Brillia ist Nakano Central Park, Japan (apartment block for balcony ceilings) [16] 2011: Fukuyama Solar Power Plant, Japan (75 boundary, 40 fence foundation, and 5500 paving blocks)[16]	No
Carbicrete	Carbonated pre-cast concrete based on steel slag cement	CO_2 curing of pre-cast concrete containing steel slag as an alternative cement	Pure CO_2	Ambient temperature and CO_2 partial pressure equal to 1.5 bar[17]	2021: Pilot plant under construction (target of 2400 blocks/day in 2022, 25 000 blocks/day in 2023) at Patio Drummond, Drummondville, Canada[18]	"Available soon" on seller website, over 500 000 units reserved[19]
Fortera (IP acquired from Calera)	Carbonated SCMs	Process involving the dissolution/ reprecipitation of calcined limestone (source of Ca ions and calcined at a lower temperature than OPC) which react with dissolved CO_2 to produce reactive calcium carbonate cement	Flue gas	n/a	2021: Small commercial plant planned for 2022 in collaboration with Lehigh Hanson (HeidelbergCement subsidiary)[20]	No

Company	**Product**	**Technological Approach**	**CO_2 source**	**Process conditions**	**Field application/ demonstration**	**Product commercially available?**
Carbon8 systems	Carbonated construction products, e.g. carbonated aggregates	Accelerated carbonation technology demonstrated using the CO_2ntainer (carbonation of materials within a converted shipping container)	Flue gas	Ambient pressure and temperature	2021: Commercial deployment with Vicat Cement Group, France[21] Pilot demonstration projects in the Netherlands (2020), UK (2019) and Canada (2018)[21]	Yes
Blue Planet	Carbonated aggregates	Process involving the dissolution/ reprecipitation of waste/end of life concrete (containing calcium ions), which react with dissolved CO_2 to produce $CaCO_3$ coated aggregates and remediated recycle concrete aggregate	Flue gas	Ambient temperature and close to ambient pressure[22] Dissolved CO_2 solution with sufficient pH[22]	2016: San Francisco International Airport specified minimum 5% of lightweight coarse aggregate to be provided by Blue Planet. Aggregates were used for 40 yards of concrete (15 kg of Blue Planet coated aggregate and 280 kg of non-coated aggregate)[23] 2016: Commercial plant under construction in Pittsburg, USA. (Blue Planet subsidiary San Francisco Bay Aggregates)[24]	No
O.C.O Technology	Carbonated aggregates	Manufactured limestone aggregate from air pollution control residue (APCr)	Pure CO_2 Flue gas	Ambient temperature and pressure	2018: Plant established in Leeds, UK 2016: Plant established in Avonmouth, UK 2012: Plant established in Brandon, UK The three plants produce >200,000 t/y carbonated aggregate (>100 000 t/y APCr)[25]	Yes
Mineral Carbonation International	Carbonated building materials	Wet carbonation of crushed low-grade alkaline minerals and wastes	Pure CO_2 Flue gas	Higher than ambient pressure and temperature[26]	2016: Operation of pilot plant[27]	No
Greenore	Carbonated building materials	Wet carbonation of crushed low-grade alkaline minerals and wastes	Flue gas	Ambient temperature[28]	2022: Construction of 100 000 tonne/year steel slag plant[29] 2018: Operation of 3000 t/year steel slag pilot plant[29]	No
Cambridge Carbon Capture	Carbonated building materials	Wet carbonation of magnesium silicate from mine tailings	Pure CO_2 (from direct air capture)	n/a	2022: GBP 3 M awarded for pilot[30]	No

The overall CO_2 capture potential for the main markets found for carbonatable industrial materials is found in table 7 – 1 below.

Table 7-1: Global production and CO_2 capture potentials of carbonatable industrial materials in 2020.

Industry	Carbonatable material	Global production (Gt)	CO_2 capture potential (Gt)
Construction	End-of-life binder (concrete)	1.1	0.052
	End-of-life binder (mortar)	0.25	0.012
	Cement kiln dust	0.24	0.082
	Concrete slurry waste	0.23	0.058
Power	Coal ashes	0.70	0.093
Iron and steelmaking	Steel slag	0.55	0.16
Fertiliser	Phosphogypsum	0.38	0.10
Aluminium	Bauxite residue	0.20	0.0056
Total		3.6	0.56

Footnote: The CO_2 capture potentials were determined by assuming 100% of the CaO content of the materials could be carbonated and that half of the loss on ignition (LOI) is due to the release of CO_2 from $CaCO_3$

It is clear that there is a significant potential market for carbonatable materials, but it is important to note that lifecycle emissions, and commercial factors will potentially reduce the CO_2 savings and the total market available.

Research found that when substituting for other materials, savings of CO_2 between 0.01 and 0.49 kgCO_2-eq per kg material substituted were found. The greatest emissions reduction was found for carbonated lightweight aggregate. One study found that cement from carbonated end-of-life cement paste had the lowest CO_2 avoidance cost (€22/tCO_2-eq) and was the sole material to have a lower CO_2 avoided cost than applying CCS to a cement plant at a cost of 80 – 100 €/tCO_2-eq.

It is therefore strongly suggested that the term “low carbon” must be significantly better classified in the production of building products; materials that could reduce the CO_2 emissions associated with the material with which they are substituting by 5% should not be in the same category as those that reduce CO_2 by 50%, for example.

3 Introduction

The Global Cement and Concrete Association (GCCA) estimate that the 2020 global cement and concrete product market was valued at around USD 440 billion, with 14.0 billion m^3 of concrete and 4.2 billion tonnes of cement produced.[31] Ready mix concrete production uses the largest majority of cement, with 55% in the EU, 70 to 75% in the USA and 40 to 50% in China.[32] The second largest industrial market for cement is precast concrete production, accounting for 28% in the EU, split evenly between reinforced and non-reinforced products,[33] and 11% in the USA.[34] Other applications of cement include mortars and plasters. The demand for both ready mix concrete and precast concrete products is expected to increase in emerging markets due to population growth and urbanisation, while the demand in developed countries is expected to stabilise or contract.[35] The future market share of ready mix concrete and precast products will depend on a range of factors, including technological advancements, cost competitiveness, and local construction practices. Part I of this report has dealt with the relevant standards which are used for cements and aggregate materials. Here, we discuss the different companies entering this market.

The aggregates market is estimated to produce around 46 Gt of aggregate each year, comprising of crushed rock, sand, gravel, recycled and secondary materials.[36] Roughly 2/3 of aggregates is used for concrete, with 1/6 for road base and coverings and other uses making up the remaining 1/6.[37] However, this broad breakdown of the aggregates market can disguise local markets which may rely on specific sources of aggregate due to local availability and demand for certain products.[38] Infrastructure development, driven by population growth and urbanisation, is expected to increase the demand for aggregates. The reduction of quality and availability of natural aggregates in some regions has led to higher transportation costs and the need for alternative sources of aggregates, driving greater demand for recycled and alternative materials.[39,40]

Carbon capture utilisation and storage (CCUS) features as an essential component, and often the largest reduction measure, in the decarbonisation roadmaps of many major cement and concrete manufacturers and associations.[31,41–44] For example, a roadmap issued by GCCA found that CCUS was the measure with the highest CO_2 reduction potential (36%) to decarbonise the cement and concrete industry by 2050.[31] However, the relative contributions toward the reduction of CO_2 emissions intensity from CO_2 storage and utilisation are often not stated in these decarbonisation roadmaps.

Over the past two decades, an increasing number of companies have emerged with a focus on developing innovative materials that utilise CO_2 to lower the carbon emissions intensity of construction products. We begin this report with an analysis of companies currently developing novel carbonated materials, before considering supply and demand factors for the commercialisation of the materials. The three main technologies for CO_2 utilisation to produce carbonated building materials are:

- **CO_2 curing of concrete.** This process injects CO_2 into the concrete mix during curing process, accelerating the natural carbonation process. The binder stores CO_2 as it hardens.

- **Carbonated aggregates (inert additives).** This technology mineralises low-value alkaline solid industrial wastes, such as end-of-life cement-based materials, iron and steel slag, fly ash, lime mud, and red mud, using CO_2. The carbonated materials can then be used to substitute aggregates in the mortar and concrete.
- **Alternative cements (reactive additives).** Alternative cement chemistries have been developed that use CO_2 as a feedstock during production and can be used to substitute Portland cement clinker.

4 Companies developing carbonated building materials

A list of companies developing technologies to produce carbonated building materials is given below. The companies primarily develop technologies based on CO_2 curing of concrete, carbonated aggregates or the development of alternative cements.

Table 4-1 provides an overview of the technology, process conditions, CO_2 source and largest scale demonstration projects for each company and whether their product is currently commercially available.

CarbonCure Technologies is a concrete technology developer founded in 2012 and headquartered in Halifax (Canada). The company operates mainly in North America, although has expanded internationally, with hundreds of systems across dozens of countries and increasing installations in Asia Pacific, Central and South America, Europe and the Middle East. Originally developed for the precast market, CarbonCure currently offers four technologies and a carbon credit program. The technologies are 'CarbonCure Ready Mix', 'CarbonCure Precast', 'CarbonCure Masonry', and 'CarbonCure Reclaimed Water'. By targeting ready mix, precast, and masonry products, CarbonCure technologies are applicable to nearly the entire concrete market. CarbonCure technologies all involve injection of CO_2, either during concrete curing permitted under ASTM C494, or during treatment of concrete wash water. During injection, CO_2 reacts to form $CaCO_3$. Importantly, there is a risk of loss of the CO_2 during the injection and curing process (though this is mitigated where CO_2 is injected on the mixing truck).

Solidia is an alternative cement and SCM technology developer. Founded in 2008, the company is headquartered in San Antonio (USA) and mainly operates in North America and Europe. Solidia has patented a carbonatable calcium silicate clinker-based cement (Solidia Cement) that reacts with CO_2 during the curing process. The production of the alternative cement clinker occurs at lower temperatures than the conventional clinkering process. As a result, the company claims that the production of Solidia Cement requires less energy and emits less CO_2 emissions than ordinary Portland cement (OPC).[45] Recently, the company has developed Solidia SCM by directly reacting Solidia Cement with CO_2 in a wet or semi-wet condition. Solidia mainly offers precast concrete products such as paving slabs that are cured in a curing chamber. However, Solidia are also targeting the larger ready mix concrete market with Solidia SCM, following further testing and demonstration. As Solidia Cement does not use OPC (the most widely used cement), its applications in the construction industry may be limited due to the risk-adverse nature of the industry, and the fact that none of the standards developed for Ordinary Portland Cement can be utilised directly (see Part I). Performance-based standards will still contain prescriptive limits on concrete composition and chemistry, and rely upon decades of understanding of OPC cement chemistry and behaviour. The most important standards in this context are the EN 197-1 to EN 197-6 series.

In 2020, Solidia signed an agreement with Lafarge Holcim to continue to collaborate to develop Solidia technology, initially in non-safety-critical applications such as paving, but aiming to develop knowledge in reinforced concrete technologies also. Such a demonstration pathway is entirely consistent with the results of the interviews conducted in Part I of this project (section 8.2). Solidia claims several advantages, such as the use of conventional concrete manufacturing techniques and equipment, faster curing times and material characteristics and performance that is at least equal to or better than conventional concrete, including compressive strength, abrasion resistance and freeze-thaw resistance.[8]

CarbonBuilt is a concrete technology company formed in 2020 to commercialise the technology developed at the UCLA Samueli School of Engineering. The company is headquartered in Los Angeles, California (USA) and mainly operates in North America. CarbonBuilt's technology replaces most or all of the OPC in concrete with an OPC substitute made using calcium-rich industrial by-products and waste materials, such as fly ash or blast furnace slag. Following concrete batching, mixing, and forming, the precast concrete components are placed into a carbonation chamber where dilute CO_2 (flue gas) is injected at ambient pressure and near ambient temperature. The materials solidify after reacting with CO_2, strengthening the concrete and permanently storing the CO_2. CarbonBuilt states that the concrete blocks that they produce were designed to comply with existing industry standards. As their technology is compatible with existing concrete production facilities, the company do not see significant challenges to market entry in terms of technology adoption (supply) or the customer (demand). The cement within the blocks has a high proportion of slag from steelmaking as an SCM and would fall under ASTM C595 (see Table 9-7 of Part I of this report).

Carbstone is a precast concrete product that has been developed by a collaboration between Vito, a research and development organisation based in Belgium, and Orbix, a Belgium-based company specialising in sustainable construction materials. The concrete is produced using an alternative cement produced from steel slag obtained after metal recovery and is carbonated using autoclave CO_2 curing. While the product has been demonstrated in small-scale construction projects, such as footpaths,[13] the need for high temperatures and pressures during manufacture may limit its commercial viability. A non-safety-critical demonstration project such as paving is consistent with the results of the interviews conducted in Part I of this project (section 8.2) to help measure and certify the performance of carbonated building materials.

CO_2-SUICOM low-carbon concrete was developed in 2008 by Chugoku Electric Power Company, Denka Company and Kajima Corporation in Japan. Precast products are produced by CO_2 curing of concrete with reduced cement content containing a special admixture (γ-C_2S) and fly ash. According to the developers, the product is carbon negative and has been demonstrated in construction projects such as sidewalk curbs, foundation blocks for solar panels, concrete paving blocks and other precasting formwork (**Table** 4-1).[16] CO_2-SUICOM is not currently available for sale to the public and is limited to demonstration projects. Early demonstration in non-structural and non-safety-critical applications is a key recommendation from the interviews (see Part I, section 8.2).

Carbicrete is an alternative cement developer founded in 2016 and headquartered in Quebec (Canada). The company operates in North America and licenses the use of its technology, first developed at McGill University, to precast concrete manufacturers. Carbicrete uses a process termed 'carbonation activation' to replace OPC in concrete with ground steel slag. The concrete is then cured using CO_2 to produce precast concrete products. Carbicrete claims to offer carbon negative cement, although it should be noted that the emissions produced during the production of the steel slag must be assigned to the steelmaking process. The company also claims that their precast products are up to 30% stronger than OPC-based products and develop strength much faster.[46] In late 2021, CarbiCrete announced a partnership with Patio Drummond to produce concrete masonry units for the commercial market; the product currently has an 'available soon' status on the Patio Drummond website, with over 500 000 units reported to be reserved.[19]

Fortera is an alternative cement developer founded in 2019 after acquiring the technology IP from Calera. The company is based in California (USA) and operates in North America and Europe. Fortera has developed a low CO_2 emissions cement produced through the dissolution and reprecipitation of calcined limestone. The limestone is calcined at a much lower temperature than to produce OPC and the calcined limestone reacts with dissolved CO_2 to produce reactive calcium carbonate cement. This product can be co-blended with OPC and used by ready mix concrete producers as a SCM, or used entirely as the cement for precast products, such as bricks and blocks (i.e. 0% OPC). In 2021, Fortera announced a collaboration with Lehigh Hanson, a subsidiary of HeidelbergCement in the USA. The companies plan to construct and operate a small commercial plant at Lehigh's Northern California cement facility.[20]

Carbon8 Systems is a UK-based company that spun out of the University of Greenwich in 2008. The company patented a process called Accelerated Carbonation Technology (ACT) that enables the conversion of industrial waste residues with CO_2 to produce carbonated lightweight aggregates (CircaBuild) that can be used as substitutes for traditional aggregates in the construction industry. In 2018, Carbon8 systems launched the CO_2ntainer, a modular CCUS unit with an annual capacity of up to 12,000 tonnes of waste residues.[47] The company mainly operates in Europe but the CO_2ntainer has also been demonstrated in North America. Carbon8 Systems claim that CircaBuild can be optimised depending on client needs for use in concrete blocks, ready mix concrete, pipe bedding and road construction.[48] However, it is important to note that lightweight CircaBuild aggregates are not suitable for all building applications, such as those requiring normal weight aggregates. In 2019, Carbon8 systems announced its first commercial licensing agreement with the Vicat Group, a major French cement manufacturer, to deploy the ACT technology at Vicat's Montalieu-Vercieu cement plant.[49] Further discussion of the applicability of lightweight aggregate standards (for example EN 13055 and ASTM C330) is found in Part I, section 5.3.1.

Blue Planet is a carbonated aggregate technology developer. The company was founded in 2013 and is headquartered in California (USA), with operations primarily in North America. Blue Planet have developed a process for producing carbonated aggregates via the dissolution/reprecipitation of waste/end-of-life concrete. The waste concrete is used as a source of Ca ions which are reacted with CO_2 to produce $CaCO_3$ aggregates. Blue Planet aggregates could provide a low-carbon alternative to traditional aggregates used in the construction industry. In 2016, the product was used in a small section of the construction work at San Francisco airport.[24] Such use helps to develop confidence in the technology in a non-safety-critical application, which was a key recommendation / finding from the interviews conducted in Part I of this project (see section 8.2). Indeed, it was further noted within the interviews that the most difficult tests to accelerate are those related to durability, which is also discussed in Part I, section 5.1.3, so that an early real-world test is of significant benefit. In particular, as discussed in 5.3.2 even if aggregates such as those produced by Blue Planet are not covered in ASTM C33 or C330, it is possible to use them under ACI 318 (the building code for structural concrete) if concrete produced from them has been demonstrated by test or actual service to produce strength of acceptable strength and durability.

The company has recently partnered with Holcim North America to further develop the technology.[50]

O.C.O. Technology (formerly Carbon8 Aggregates) is a UK-based carbonated aggregates developer that uses the ACT technology developed at the University of Greenwich and initially commercialised by Carbon8 Systems. The ACT technology is used to contact a variety of waste materials with CO_2, producing pellets of carbonated materials which can then be used as aggregates in the construction industry. The company currently operates three factories in the UK, located in Avonmouth, Leeds and Suffolk. The three plants produce more than 500,000 tonnes of 'carbon negative' aggregate per year, mainly from air pollution control residues, and have been used in the equivalent of 21 million building blocks.[51] The company has also announced partnerships with clients around the world, including Petronar SA, Alba and Repsol SA in Spain and the Maryvale Energy from Waste facility in Australia.[52,53]

Mineral Carbonation International is a carbonated aggregate product developer, which was founded in 2013 as a joint venture between the Canberra-based GreenMag Group, the University of Newcastle and Orica. The company is headquartered in Canberra, Australia and focuses on using CO_2 to produce carbonated aggregate products from alkaline mining waste through wet carbonation. The process involves the reaction of alkaline mining waste with CO_2 in the presence of water to form stable carbonates, which can be used as a substitute for traditional aggregates in the construction industry. Limited technical information is publicly available.

Greenore specialises in carbon mineralisation technology to produce calcium carbonate and carbonated steel slag through wet carbonation. The company was founded in 2016 as a spin-off from Columbia University. Greenore is headquarted in Shanghai (China) and mainly operates in China and North America. Following successful pilot demonstration, Baosteel is currently constructing the first commercial plant using Greenore technology, due to finish construction in April 2023 with a planned annual processing capacity of 500,000 tons of steel slag and 100,000 tons of CO_2.[29] In addition, Greenore is also co-operating with CRH to process steel slag using Greenore's carbon mineralisation technology to produce SCMs to be used in CRH's cement facilities.

Cambridge Carbon Capture is a carbonated aggregate developer founded in 2010 and headquartered in Cambridge, UK. The company have patented a process called CO_2LOC to sequester CO_2 through a two-stage mineralisation process of digestion followed by carbonation. Cambridge Carbon Capture use magnesium silicates as the feed material. This mineral can be recovered from mine tailings and converted to $MgCO_3$. In 2022, the company was awarded GBP 3 million by the UK Government through Phase 1 of the Direct air capture and greenhouse gas removal programme to construct a pilot plant to demonstrate the process.[30]

Table 4-1: Overview of companies producing carbonated build materials

Company	Product	Technological Approach	CO_2 source	Process conditions	Field application/ demonstration	Product commercially available?
CarbonCure Technologies	Carbonated ready mix concrete	Injection of CO_2 during the delivery of ready mix concrete	Pure CO_2	Ambient pressure and temperature	2022: General Motors Spring Hill Assembly Plant, USA (20 800 m^3 of concrete)[2] 2022: Amazon HQ2, Arlington, Virginia, USA (106 600 m^3 concrete)[3]	Yes
	Carbonated precast concrete	Injection of CO_2 during the production of precast concrete	Pure CO_2	Ambient pressure and temperature	2020: Retrofit of Coreslab Structures (TEXAS) Inc facilities, USA[4] 2016: MGM National Harbor, USA (195 000 units)[5]	Yes
	Carbonated reclaimed water	Injection of CO_2 to create ultrafine CO2-stabilised suspended solids in reclaimed water which can be recycled for use as binder in new concrete mixes	Pure CO_2	Ambient pressure and temperature	2018: Trio Ready mix Commercial Pilot, Canada[6]	Yes
Solidia	Carbonated pre-cast concrete based on alternative cement	CO_2 curing of pre-cast concrete containing low lime calcium silicate clinker-based cement with a low kiln burning temperature	Flue gas	Ambient pressure and moderate temperature (30[7] to 60 °C[8])	2015: Demonstration in Pecs, Austria (6000 tonnes of cement)[9] 2014: Demonstration in Whaiutehall, USA (5000 tonnes of cement)[9]	No
CarbonBuilt	Carbonated pre-cast concrete with partial cement replacement	CO_2 curing of concrete containing partial replacement of OPC with portlandite and fly ash	Flue gas	Ambient gas pressures and flue gas temperatures (<75 °C[10]	2021: Field demonstration at the National Carbon Capture Center, USA (>15 000 concrete masonry units)[11]	Yes
Carbstone (VITO / Orbix)	Carbonated pre-cast concrete based on steel slag cement	Autoclave CO_2 curing of concrete produced using steel slag (after metal recovery for recycling) as an alternative cement	Flue gas	Autoclave conditions, i.e. high pressure (20 bar) and temperature (140 °C)[12]	2020: Construction of a footpath[13] 2013: Construction of pilot plant in Wallonia, Belgium[14]	No
CO_2-SUICOM (Kajima Corporation, The Chugoku Electric Power Company, Denka Company, and Landes Corporation)	Carbonated pre-cast concrete based on special additions	CO_2 curing of pre-cast concrete with reduced cement content using special admixture (γ-C_2S) and fly ash	Flue gas	Ambient pressure and moderate temperature (50 °C)[15]	2012: Brillia ist Nakano Central Park, Japan (apartment block for balcony ceilings) [16] 2011: Fukuyama Solar Power Plant, Japan (75 boundary, 40 fence foundation, and 5500 paving blocks)[16]	No

Company	Product	Technological Approach	CO_2 source	Process conditions	Field application/ demonstration	Product commercially available?
Carbicrete	Carbonated pre-cast concrete based on steel slag cement	CO_2 curing of pre-cast concrete containing steel slag as an alternative cement	Pure CO_2	Ambient temperature and CO_2 partial pressure equal to 1.5 bar[17]	2021: Pilot plant under construction (target of 2400 blocks/day in 2022, 25 000 blocks/day in 2023) at Patio Drummond, Drummondville, Canada[18]	"Available soon" on seller website, over 500 000 units reserved[19]
Fortera (IP acquired from Calera)	Carbonated SCMs	Process involving the dissolution/ reprecipitation of calcined limestone (source of Ca ions and calcined at a lower temperature than OPC) which react with dissolved CO_2 to produce reactive calcium carbonate cement	Flue gas	n/a	2021: Small commercial plant planned for 2022 in collaboration with Lehigh Hanson (HeidelbergCement subsidiary)[20]	No
Carbon8 systems	Carbonated construction products, e.g. carbonated aggregates	Accelerated carbonation technology demonstrated using the CO_2ntainer (carbonation of materials within a converted shipping container)	Flue gas	Ambient pressure and temperature	2021: Commercial deployment with Vicat Cement Group, France[21] Pilot demonstration projects in the Netherlands (2020), UK (2019) and Canada (2018)[21]	Yes
Blue Planet	Carbonated aggregates	Process involving the dissolution/ reprecipitation of waste/end of life concrete (containing calcium ions), which react with dissolved CO_2 to produce $CaCO_3$ coated aggregates and remediated recycle concrete aggregate	Flue gas	Ambient temperature and close to ambient pressure[22] Dissolved CO_2 solution with sufficient pH[22]	2016: San Francisco International Airport specified minimum 5% of lightweight coarse aggregate to be provided by Blue Planet. Aggregates were used for 40 yards of concrete (15 kg of Blue Planet coated aggregate and 280 kg of non-coated aggregate)[23] 2016: Commercial plant under construction in Pittsburg, USA. (Blue Planet subsidiary San Francisco Bay Aggregates)[24]	No
O.C.O Technology	Carbonated aggregates	Manufactured limestone aggregate from air pollution control residue (APCr)	Pure CO_2 Flue gas	Ambient temperature and pressure	2018: Plant established in Leeds, UK 2016: Plant established in Avonmouth, UK 2012: Plant established in Brandon, UK The three plants produce >200,000 t/y carbonated aggregate (>100 000 t/y APCr)[25]	Yes
Mineral Carbonation International	Carbonated building materials	Wet carbonation of crushed low-grade alkaline minerals and wastes	Pure CO_2 Flue gas	Higher than ambient pressure and temperature[26]	2016: Operation of pilot plant[27]	No

Company	**Product**	**Technological Approach**	**CO_2 source**	**Process conditions**	**Field application/ demonstration**	**Product commercially available?**
Greenore	Carbonated building materials	Wet carbonation of crushed low-grade alkaline minerals and wastes	Flue gas	Ambient temperature[28]	2022: Construction of 100 000 tonne/year steel slag plant[29] 2018: Operation of 3000 t/year steel slag pilot plant[29]	No
Cambridge Carbon Capture	Carbonated building materials	Wet carbonation of magnesium silicate from mine tailings	Pure CO_2 (from direct air capture)	n/a	2022: GBP 3 M awarded for pilot[30]	No

5 Case studies

Case studies were produced for three leading companies producing carbonated building materials, CarbonCure Technologies, CarbonBuilt and Carbon8 Systems. The case studies were used to assess the market entry of carbonated materials into the construction industry, in particular from companies that were offering a commercial or semi-commercial product in different markets (CO_2 injection, aggregate production, and low-carbon cement production), and were produced from a combination of literature review and interviews with the companies. The questions asked at each interview were the same. Initially there was a general discussion about the project and the aims, followed by

When did your company start?
What scale is your company at in terms of people?
How much material have you sold?
What do you see as the main challenges to market entry?
At what scale do you realistically see your company in ten years?
Who do you think are the competition?
What other things can you make?
Should we speak to any other people in particular about novel building materials?
Any thoughts on prescriptive vs performance-based standards? Could you provide a background of your technological approach?
What is the most limiting issue relating to standards for your company ?
Have any policy measures (or other measures) helped you navigate market entry into the construction sector?
What policy support does your company currently make use of?
What additional policy support do you think should be made available, and why?

All interviews were conducted on a confidential basis to allow more frank discussion of market potential, etc. This is in contrast to the interviews in Part I, which were conducted on a more open basis (see sections 8 and 10 of Part I).

5.1 CarbonCure Technologies

CarbonCure Technologies is a concrete technology developer founded by Robert Niven in 2012 and headquartered in Halifax (Canada). It operates mainly in North America, although has expanded internationally, with hundreds of systems across dozens of countries and increasing installations in the Asia Pacific, Central and South America, Europe and the Middle East. CarbonCure has achieved global recognition, winning awards such as the grand prize in the USD 20 million NRG COSIA Carbon XPRIZE and being inducted into the Cleantech Hall of Fame after ranking among the Global Cleantech 100 seven consecutive times between 2016 and 2022.[54]

CarbonCure develops and deploys concrete technologies that utilise captured CO_2. They supply equipment and know-how for concrete producers to retrofit existing concrete plants with CarbonCure's technologies. CarbonCure currently offers four technologies and a carbon credit program.[55] The technologies are 'CarbonCure Ready Mix', 'CarbonCure Precast', 'CarbonCure Masonry', and 'CarbonCure Reclaimed Water'. By targeting ready mix, precast, and masonry products, CarbonCure technologies are applicable to nearly the entire concrete market, which was approximately 10 Gt globally in 2020.[36] As of 2023, CarbonCure has licensed more than 700 systems to concrete producers around the world.

CarbonCure technologies all involve injection of CO_2, either during concrete curing, or during treatment of concrete wash water. During injection, dissolvedCO_2 reacts to form $CaCO_3$. $CaCO_3$ is a very stable mineral at Earth surface conditions. Therefore, by using some of the CO_2 that would have otherwise been emitted, e.g. in industrial flue gas streams, CarbonCure's technologies are able to permanently store CO_2 emissions. It is important to note that there will be a fraction of the CO_2 which is injected emitted. CarbonCure technologies can also use industrially produced CO_2. In this case, life cycle CO_2 emissions can be reduced if the CO_2 injected concrete can achieve an overall significant reduction in cement content relative to the comparable conventional mix. It can achieve this since injected CO_2 mineralises and acts as a strength accelerator in fresh concrete. Therefore, injected CO_2 is regarded as an admixture, similar to chemicals like superplasticisers that can also be used to increase strength (in this case via reducing water content). The amount of avoided CO_2 emissions through applications of CarbonCure's technologies can be readily calculated and verified. This is a key basis of their carbon credit program. Previous work indicates that the majority of the emission reduction is caused by the increased strength (i.e. indirectly rather than by the CO_2 captured). A figure of 5 % overall reduction in CO_2 associated with concrete block production has been suggested, though this is likely to have been subject to continual improvement. [56]

CarbonCure has published several peer reviewed journal papers on their technologies (e.g. [57,58]) and regularly participates in international cement and concrete research events (e.g. 15th International Congress on the Chemistry of Cement, Prague, 2019) and industry networks (e.g. Global Cement and Concrete Association, Innovandi Network).

5.2 CarbonBuilt

CarbonBuilt is a concrete technology company formed in 2020 to commercialise the technology developed at the UCLA Samueli School of Engineering by Professor Gaurav Sant. The principal research and development for the technology began around 2013. The company is headquartered in Los Angeles, California (USA) and mainly operates in North America, although it aims to expand globally. CarbonBuilt has received recognition for its technology, winning the NRG COSIA Carbon XPRIZE, a global competition aimed at identifying solutions for converting CO_2 emissions into viable products.

CarbonBuilt's technology replaces most or all of the OPC in concrete with an OPC substitute made using calcium-rich industrial by-products and waste materials, such as fly ash or slag. Following concrete batching, mixing, and forming, the precast concrete components are placed into a carbonation chamber where dilute CO_2 (flue gas) is injected at ambient pressure and near ambient temperature. The materials solidify after reacting with CO_2, strengthening the concrete and permanently storing the CO_2. CarbonBuilt claims its technology can enable manufacturers to produce ultra-low carbon concrete products with 70-100% lower embodied carbon intensity. CarbonBuilt also offers a Carbon Removal Service that provides carbon credits to customers for each ton of CO_2 removed from the atmosphere through the use of CarbonBuilt technology. The credits can be used to offset emissions or sold in carbon markets.

Carbonbuilt's products were designed to comply with existing industry standards for concrete blocks, thereby ensuring seamless market entry for the company. As their technology is compatible with existing concrete production facilities, the company do not see significant challenges to market entry in terms of technology adoption (supply) or the customer (demand). Additionally, CarbonBuilt state that their technology can be installed at existing concrete manufacturing plants within one year at a low capital expense.

As of 2021, CarbonBuilt has expanded to a team of around 25 people and has secured more than USD 14 million in funding. The company has recently completed its first retrofit at the Blair Block concrete block manufacturing plant in Alabama.[59] The facility is now producing ultra-low carbon concrete blocks on a commercial scale. By reducing the use of OPC and employing CO_2 curing, the embodied carbon intensity of the concrete products produced at Blair Block is expected to decrease by at least 70% in comparison to traditional OPC-based concrete blocks. A final accounting of the embodied carbon intensity of the blocks is expected to be available in 2024 when the facility obtains an Environmental Product Declaration (EPD) which requires one full year of operational data. In addition, CarbonBuilt have also sold thousands of tonnes of carbon avoidance and removal credits to buyers, including Stripe, Shopify and the University of California.

CarbonBuilt recently announced it has secured funding from the Four Corners Carbon Removal Coalition to boost the development of a carbon capture-to-concrete project.[60] The project includes AirCapture, that will install modular, small-scale Direct Air Capture technology on site at the Block-Lite concrete block plant in Flagstaff, Arizona to feed atmosphere-derived CO_2 into the CarbonBuilt process.

5.3 Carbon8 Systems

Carbon8 systems patented a process called Accelerated Carbonation Technology (ACT) that enables the conversion of industrial waste residues (for example, cement kiln bypass dust, air pollution control residues, bottom ashes from power stations and a host of other possibilities – for further information see a previous IEAGHG report[1]) with CO_2 to produce carbonated lightweight aggregates that can be used as substitutes for traditional aggregates in the construction industry. The use of carbon negative aggregates has the potential to reduce the emissions intensity of building materials (please refer to a previous IEAGHG report for details of the amounts possible[1]) and contribute to a circular economy by diverting waste from landfills. Based in UK, Carbon8 Systems was formed as a spin out from the University of Greenwich and mainly operates in Europe, although the ACT technology has also been demonstrated in North America. The company's founders have authored over 40 scientific papers since 1997, which are frequently published in scientific journals.[61]

Carbon8 systems introduced the CO_2ntainer in 2018 as a modular CCUS unit designed to reduce the timescale of the naturally slow carbonation reaction from years to around 15 to 20 minutes.[47] The CO_2ntainer resembles a shipping container in size and has been demonstrated at pilot scale by integration into an existing industrial process. In the

CO_2ntainer, calcium and/or magnesium containing industrial waste residues are treated with CO_2 from the industrial process flue to form carbonates. The carbonation process primarily involves the reaction of CO_2 gas with metal oxides, hydroxides and silicates.

Industrial waste residues can be valorised through carbonation. The process stabilises heavy metals and immobilises trace elements, making waste remediation a significant application. Sources of wastes include: ashes produced from energy from waste incinerators (ACT also stabilises the heavy metals in the ashes), ashes produced from biomass combustion, cement bypass dust (CBD) produced by the cement industry, slag produced from steelmaking and ashes produced from biomass boilers for the pulp and paper industry.[48]

Carbon8 systems manufactures their lightweight aggregate, CircaBuild, by combining CO_2 with industrial residues in the CO_2ntainer. The amount of CO_2 permanently stored in the material depends on the reactivity of the waste residues and ranges between 10 to 30 wt%.[48] The company claim that their CircaBuild products can be optimised for client needs for use in concrete blocks, ready mix concrete, pipe bedding and road construction.[48] However, lightweight CircaBuild aggregates are not suitable for all building applications, such as those requiring normal weight aggregates (concrete based on light weight aggregates is not as strong, in general). Despite this limitation, CircaBuild aggregate provides a low-carbon alternative to traditional aggregate for use in the construction industry.

In 2018, Carbon8 Systems demonstrated its first CO_2ntainer project at a Cement Roadstone Holdings cement facility in Ontario, Canada.[47] The mobile CO_2ntainer has an annual capacity of up to 12,000 tonnes of waste residues and has since been demonstrated in pilot projects in the UK and the Netherlands.[21] In 2019, Carbon8 systems announced its first commercial licensing agreement with the Vicat Group, a major French cement manufacturer, to deploy the ACT technology.[49] The CO2ntainer was installed at Vicat's Montalieu-Vercieu cement plant in September 2020, where it captures CO_2 directly from the flue gas to convert cement bybass dust (CBD) into lightweight aggregates.[62] Carbon8 systems also partnered with CEMEX in 2021 to evaluate the suitability of saleable aggregates produced from by-products from CEMEX's Rüdersdorf cement plant in Germany and Rugby cement plant in the UK using ACT.[63]

6 Decarbonisation potential of carbonated building materials

Carbonatable by-products from industrial processes offer significant CO_2 emissions reduction potential through CO_2 mineralisation.[64] The global production rates of carbonatable by-products from the construction, power, iron and steel, fertiliser and aluminium industrial sectors were estimated to determine their CO_2 capture potential (**Table 6-1**).

The following carbonatable materials were considered:

End-of-life concrete and mortar comprises of secondary aggregate and end-of-life binder and is produced from the demolition of buildings and infrastructure. Shah et al. estimated that the amount of end-of-life binder in concrete and mortar in 2018 was 1050 Mt and 250 Mt, respectively.[65] To calculate the CO_2 capture potential of end-of-life binder it was assumed that concrete contains 15% end-of-life binder, 60% of which is CaO, 50% of the CaO is carbonated,[65] and the carbonation process converts 100% of the uncarbonated CaO to $CaCO_3$.

Concrete slurry waste (CSW) is produced during the production and application of concrete due to logistical, design and technical errors. Waste concrete is often washed to reclaim coarse aggregate leaving behind wastewater that contains hydrated cement and fine aggregates. This wastewater is then dewatered *via* sedimentation to produce a more concentrated slurry. The potential resource of CSW is estimated to be 0.8% of global concrete production, should all sedimentation and washing facilities have such technologies added[66] which equates to an annual production rate of 230 Mt in 2020. This estimate assumes that concrete contains 15% cement and that the annual production of concrete is 19.5 Gt.

Cement kiln dust (CKD) is a by-product of the cement manufacturing process and is composed of partially calcined meal that is collected from exhaust gases *via* bag filters and electrostatic precipitation. The annual production of CKD was estimated to be 480 Mt assuming an annual cement production of 4.2 Gt and an average CKD production rate of 11.5%.[64] CKD can be partly reused in the cement plant, therefore, the amount of CKD available for carbonation in 2020 was taken to be 50% of the annual production (240 Mt). This is distinct from cement bypass dust (CBD), which comes from cooling and extracting a fraction of the material recycled in a cement kiln, to prevent the build-up of contaminants and degradation of kiln efficiency, and is a significantly smaller resource (see a previous IEAGHG publication). [1]

Coal ash is produced in significant quantities as a by-product of coal-fired power generation. An estimated 700 Mt of coal ash was produced in 2020 assuming a global coal use of 6.85 Gt.[64] Around 85-95% of this coal ash is fly ash with the remainder termed bottom ash.[67] The specific chemical, physical and mineralogical properties of coal fly ash can depend on the type of coal and combustion conditions. The median ash compositions of class C and F fly coal ashes were used to predict the CO_2 capture potential of coal ash (Table 6-2).

Iron and steelmaking slags are produced by the iron and steelmaking processes. Renforth estimated that the annual production rate of iron and making slags in 2020 is approximately

550 Mt.[64] This estimate assumes that the steel industry produced 1.7 Gt steel in 2020, which creates approximately 185 kg of blast furnace slag and 117 kg of steel slag/tonne of steel.

Phosphogypsum is a by-product that arises from the production of phosphoric acid, which is a key feedstock in the production of phosphate fertilisers. To estimate the annual production of phosphogypsum, it was assumed that 4.5 tonnes of phosphogypsum was produced per tonne of phosphoric acid.[68] Based on a global phosphoric acid production of 83 Mt in 2021,[69] the annual production of phosphogypsum was estimated to be 380 Mt.

Bauxite residue is produced from the digestion of bauxite ore to produce alumina for the production of aluminium. Renforth estimated that the annual production of bauxite residue in 2020 to be 200 Mt.[64] This estimate assumes a global aluminium production of 58 Mt and the generation of 3.45 tonnes of bauxite residue per tonne of aluminium.

According to the data in **Table 6-1**, an annual supply rate of 3.6 Gt of carbonatable materials from five different industrial sectors could capture up to 0.56 Gt of CO_2 emissions each year through CO_2 mineralisation. However, key demand-side factors for market entry of carbonated building materials must also be considered as they can significantly limit the commercialisation of the technology. These factors include market sizes, suitable material properties, and economical production.[36]

Driver et al. calculated the life cycle CO_2-eq emissions of eight carbonated building materials that can be used as substitutes for conventional materials in the construction industryError! Reference source not found..[36] Their research found that the emissions reduction potential of the materials varied between 0.01 and 0.49 kgCO_2-eq per kg material substituted. The greatest emissions reduction was found for carbonated lightweight aggregate, while CO_2 curing technologies had relatively small reduction potentials at the product scale. However, the large size of the concrete industry means that large decarbonisation potentials could be achieved at market scale using CO_2 curing.

Driver et al. also carried out a technoeconomic analysis to compare the increased production costs of the carbonated building materials relative to the conventional materials and CO_2-eq avoidance costs of the technologies.[36] Cement from carbonated end-of-life cement paste was determined to have the lowest CO_2 avoidance cost (€22/tCO_2-eq) and was the only carbonated building material to have a lower avoidance cost than CCS (€80-100/tCO_2-eq). Cement from carbonated end-of-life cement paste was determined to be cost-competitive with conventional composite cement (CEM II). Other technologies analysed here, such as CO_2-injected ready-mix concrete, were also found to be cost-competitive with conventional ready-mix concrete production, which is consistent with the commercial success of CarbonCure. This research also found that carbonated lightweight aggregates cost substantially more to produce than conventional expanded clay aggregate, which may be restricting the commercial deployment of this material.

Table 6-1: Global production and CO_2 capture potentials of carbonatable industrial materials in 2020.

Industry	Carbonatable material	Global production (Gt)	CO_2 capture potential (Gt)
Construction	End-of-life binder (concrete)	1.1	0.052
	End-of-life binder (mortar)	0.25	0.012
	Cement kiln dust	0.24	0.082
	Concrete slurry waste	0.23	0.058
Power	Coal ashes	0.70	0.093
Iron and steelmaking	Blast furnace slag	0.34	0.10
	Steel slag	0.21	0.07
Fertiliser	Phosphogypsum	0.38	0.10
Aluminium	Bauxite residue	0.20	0.0056
Total		3.6	0.57

Footnote: The CO_2 capture potentials were determined by assuming 100% of the CaO content of the materials could be carbonated and that half of the loss on ignition (LOI) is due to the release of CO_2 from $CaCO_3$ (**Table 6-2**).

Table 6-2: Composition and potential CO_2 capture of carbonatable industrial waste materials

Material	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	P_2O_5	SO_3	LOI	Potential CO_2 capture ($g_{CO2}/g_{material}$)
End-of-life binder[70]*	64.7	19.4	4.4	3.0	0.9	0.5	0.2	-	2.2	2.4	0.50
Cement Kiln Dust[71]	53.3	9.5	2.5	2.6	1.7	3.1	1.8	0.2	4.4	15.1	0.34
Concrete slurry waste[66]	37.4	32.5	8.5	6.7	1.3	1.6	-	-	2.7	9.0	0.25
Fly ash (Class C)[72]	32.1	32.4	15.8	3.4	3.4	0.8	1.8	2.9	3.6	-	0.25
Fly ash (Class F)[73]	3.3	54.1	26.4	6.1	1.6	1.6	0.5	0.8	1.0	2.7	0.012
Average fly ash	17.7	43.3	21.1	4.8	2.5	1.2	1.2	1.9	2.3	2.7	0.13
Basic oxygen furnace slag[74]	37.9	37.2	8.7	0.4	11.4	0.4	0.4	-	2.7	0.8	0.29
Steel slag[75]	42.1	16.5	3.5	21.7	6.7	-	-	-	-	0.2	0.33
Phosphogypsum[76]	33.6	6.3	0.6	0.3	-	-	-	0.7	56.9	-	0.26
Bauxite residue[77]	13.3	19.1	23.4	15.7	1.3	-	9.4	-	-	15.3	0.028

Footnote: * composition of the cement clinker was not used for the calculation of CO_2 capture for end-of-life binder. To calculate the CO_2 capture potential of end-of-life binder it was assumed that concrete contains 15% end-of-life binder, 60% of which is CaO, 50% of the CaO is carbonated[65] and the carbonation process converts 100% of the uncarbonated CaO to $CaCO_3$.

The results in this section highlight the importance of focusing on the deployment of carbonated building materials with high environmental and/or economic performance. The current poorly defined approach for classifying carbonated building materials may lower the overall CO_2 emissions reduction benefits of low carbon materials if purchasers can get the same credit (financial or reputational) by specifying a material whose CO_2 emissions benefit is fractionally smaller than the conventional material. As discussed in Part I, section 10.1.6, lifecycle analysis is important to quantify the actual emissions reduction, and in Part I, section 10.1.8 it is important to not be taken in by "wonder" solutions that do not seriously reduce the overall CO_2 emissions when considered holistically. Therefore, the implementation of a standardised grading system for low carbon building materials could improve the deployment of the materials in the construction industry.

7 Measuring and certifying the embodied carbon content of carbonated building materials

An important step for the market entry of novel carbonated building materials is to have an appropriate methodology for assessing their carbon content. When considering carbon as a funding criterion, it becomes imperative to be able to compare and contrast bids transparently. This involves calculating the carbon content, also known as the embodied carbon, which is achieved through the implementation of life-cycle assessment (LCA) methodologies.

LCA methodologies, as defined in ISO 14040 *Environmental management—Life cycle assessment—Principles and framework*, examine the environmental aspects and potential impacts of a product throughout its entire life cycle, from raw material extraction, manufacturing, utilisation and end-of-life disposal. By conducting LCAs, valuable insights are gained into the environmental footprint of these materials and can be used to make informed decisions when selecting products based on their environmental impacts. This enables decision makers to allocate funding appropriately to support environmentally sustainable building materials in the market.

Life cycle assessment use various metrics to measure environmental impacts, including global warming potential (GWP), acidification potential, eutrophication potential and ozone depletion potential. Among these metrics, GWP is used to measure and report the embodied carbon of a material. GWP is expressed in kilograms of CO_2 equivalent (kg CO_2e), where the term "CO_2e" signifies the inclusion of other greenhouse gases, which are normalised relative to CO_2 based on their radiative forcing potentials. This ensures a comprehensive evaluation of the overall greenhouse gas impact of the materials.

Based on EN 15978 *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method.* and ISO 21930 *Sustainability in buildings and civil engineering works. Core rules for environmental product declarations of construction products and services*, the life cycle of buildings and building materials can be divided into four key stages: (i) product (ii) construction (iii) use (iv) end-of-life. Environmental product declarations (EPDs) are the typical means of communicating product- or material-level life cycle assessments. These EPDs are based on product LCAs that encompass the impacts of extraction, transportation, and manufacturing (stages A1-A3 as per ISO 21930).

EPDs serve as standardised documents presenting the LCA results for a specific material or product. To ensure credibility and accuracy, EPDs are third-party-verified and adhere to product category rules (PCRs). PCRs are sets of guidelines for particular product categories, dictating how LCAs should be conducted for EPDs in line with EN 15804 *Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products*, EN 17472 *Sustainability of construction works - Sustainability assessment of civil engineering works - Calculation methods*, ISO 14025 *Environmental labels and declarations—Type III environmental declarations—Principles and procedures*, ISO 14040, ISO 14044 *Environmental management—Life cycle assessment—Requirements and guidelines*, and other relevant international standards. By following these regulations, EPDs effectively capture the environmental impacts associated with A1-A3 life cycle stages and can be used to specify and procure lower-impact products.

The interviews held during the first part of this report identified two measures currently used to increase the use of low-carbon materials in the construction industry: (i) the Low Embodied Carbon Concrete Leadership Act (LECCLA)[78] aimed at reducing the carbon footprint of concrete materials acquired by public agencies in New York and New Jersey, and (ii) the Low-carbon Built Environment aid scheme, an integral part of the Finnish Sustainable Growth Programme under the EU's Recovery and Resilience Facility (RRF).[79] This aid scheme seeks to bolster economic recovery post-pandemic while simultaneously promoting the green transition.

Under the LECCLA, concrete vendors are required to conduct LCAs and disclose the carbon content of their products. The reporting tool used for this purpose is a standardised LCA methodology known as a Type III environmental declaration or EPD. To assist with compliance, the state offers a one-time tax credit to subsidise the cost of conducting these analyses. When concrete producers bid on public projects, their rankings are influenced not only by cost but also by the GWP value indicated in their EPDs. Those with the lowest GWP score receive a 5% price reduction applied to their bid, making their offers more competitive.[80] Additionally, concrete producers using CCUS technology in their manufacturing process are eligible for an extra 3% discount on their bids.[80] These incentives further promote the adoption of low-carbon practices and technologies, contributing to the overall reduction of carbon emissions in the construction industry.

The primary goal of the Low-carbon Built Environment aid scheme is to address climate change by identifying and implementing low-carbon solutions in the built environment. The program is set to conclude at the end of 2024 with a total of 57 supported projects, funded with €4.3 million.[81] In the application guidance, applicants are required to outline their plan for monitoring and assessing the project's impact on CO_2 emissions in the real estate and construction sector, as well as its ability to adapt to climate change. However, the guidance lacks a standardised methodology or specific instructions for calculating the project's CO_2 emissions impact. As a result, direct comparisons between bids becomes challenging, potentially undermining confidence in the scheme. The guidance highlights that grants are discretionary, and the selection of applications will be based on an overall assessment of the following criteria:[82]

a. Feasibility: The project can be implemented as planned, within the schedule and with the resources available.

b. Impact, scalability: The project relates to a challenge that is central to the realisation of a low-carbon built environment. Good practices can be scaled for as many other actors as possible.
c. Availability, openness: The results of the project are also available and open to other actors.
d. Innovation, creativity: The project or a solution presented within the project is new and special or implemented in a novel way

The assessment and allocation of funding based on the four criteria in the Low-carbon Built Environment aid scheme remain unclear, with no specified scoring or weighting system provided. This lack of clarity is further complicated by the wide range of eligible technologies as demonstrated by the three projects awarded the highest grant funding in the final funding call: "Innovative low-carbon recycled aggregate concrete", "MIKKI - Sustainable circular economy of the city of Mikkeli" and "Database of material statement information and material statement preparation tool" (project titles translated from Finnish to English).[81] The diverse array of technologies that can apply for funding, along with the discretionary nature of award criteria and non-standardised LCA requirements, makes assessing and comparing bids significantly more challenging than in the case of the LECCLA. The LECCLA, with its narrower focus, aims to increase the use of concrete with lower embodied emissions, calculated using a standardised LCA methodology verified by a third party. In contrast, the Low-carbon Built Environment scheme encompasses a broader scope of technologies and objectives, creating complexities in evaluating and selecting projects for funding. A clearer and more standardised assessment framework could enhance transparency and confidence in the scheme's decision-making process.

7.1 Challenges in measuring and certifying the embodied carbon content of carbonated building materials

LCAs across all applications commonly face scrutiny for their robustness and reliability.[83] Although the calculation methodologies for LCAs have continued to improve, any uncertainties in these calculations can create challenges in directly comparing materials and may undermine confidence in their accuracy and application for specifying and procuring lower-impact products.

There has been a growing interest in the USA in using EPDs for public procurement. The Buy Clean California Act of 2017 set a precedent for incorporating EPDs in the public procurement of building materials.[84] In 2021, federal initiatives demonstrated increased interest in using EPDs and fostering demand for materials with a lower carbon impacts. The Executive Order on Federal Sustainability aimed to achieve net-zero Federal Procurement, with support from the Federal Buy Clean Act.[85] Concerning EPDs, there have been debates between the bottom-up and top-down approaches for their implementation.[85] While the bottom-up approach, largely initiated by manufacturers, led to intensive producer involvement and promoted environmental awareness in the industry,[86] it also resulted in discrepancies among programs, questioning the use and comparability of EPDs due to a lack of transparency and harmonisation.[87] To address these challenges, ongoing efforts are being made to enhance the consistency and harmonisation of EPDs through updates to the EN 15804 standard and policy documents at both the state[88] and federal[85] levels in the USA aimed at establishing a more transparent and standardised approach to the use of EPDs for sustainable procurement practices.

Several research papers have drawn attention to the inconsistencies and challenges related to LCAs of building materials.[89,90] These challenges encompass functional unit definitions and product lifetimes. One of the primary issues with LCAs is the lack of transparency in reporting results and assumptions, which hampers comparisons among results and undermines the reliability of benchmarking. To establish a suitable and realistic benchmark for comparing the emissions avoidance of alternative products, specific considerations must be taken into account. For instance, when comparing the carbon intensity of different concretes, performance factors such as the concrete strength, workability and durability need to be considered. Additional limitations and benchmarking advice are provided in the Low Carbon Concrete Group's Low Carbon Concrete Routemap, which is supported by information from AMCRETE, Byrne Bros, Price and Myers, Ramboll, and WSP on the carbon intensity of recent concrete mixes, along with input from the British Ready-mixed Concrete Association.[91]

PCRs for materials and products aim to standardise LCA methodologies concerning functional units, system boundaries, and data collection and quality requirements. It is essential to use robust and fair approaches when measuring embodied carbon and striving for credible reductions. However, the use of different LCA software and life cycle inventory (LCI) databases complicates the task of making valid comparisons of the environmental impact of alternative materials. Notably, significant discrepancies in LCA results have been observed when different sources use the same database, for example, a variation of ozone depletion potential by as much as 100% due to different assumptions.[92] To address these challenges, it is imperative that embodied carbon values for concrete include a clear summary of the data sources and methods used in the calculation, as well as information on whether the values are self-determined or independently verified. This transparency enhances the reliability and credibility of the reported embodied carbon values, enabling stakeholders to make more informed decisions when selecting materials for sustainable construction practices.

8 Conclusions

This report reviewed companies currently developing technologies to produce carbonated building materials. As the 2nd most produced material on earth, mitigation of concrete CO_2 emissions is critical in the coming decades. The primary technologies under development were CO_2 curing of concrete, carbonated aggregates, alternative cements and some combination of these technologies. The report assesses the technological approaches adopted by each company, considering the process conditions and the feasibility of using flue gas directly in their process. In addition, the largest demonstration projects for each company were also outlined, as well as the commercial availability of their products.

Of the 13 companies investigated, four currently offer commercial products. Three companies, CarbonCure Technologies (CO_2 curing of concrete), CarbonBuilt (CO_2 curing of concrete with OPC fully or partially substituted) and Carbon8 Systems (carbonated aggregates), were selected for further study. Among these three companies, CarbonCure has achieved the highest level of commercialisation, having licensed more than 700 systems to concrete producers around the world. CarbonBuilt has recently finished its first retrofit project at a concrete block manufacturing plant in the USA, with commercial production of concrete blocks using its technology already underway. While the first commercial deployment of Carbon8 Systems' CO_2ntainer technology is currently in progress at a cement facility in Europe.

The main challenges that the companies commercialising technologies are the conservative nature of the industries, and challenges in getting the materials into the design codes (EN codes being a particular issue). It is not just a case of developing a new code though, until small-scale demonstrations have taken place in non-safety-critical applications, developing comfort and familiarity for specifiers (and importantly ensuring that findings are shared widely), large-scale applications will be unlikely. For companies whose products are compliant with existing codes, market pull is important, with buyers clubs and government departments in particular able to take a leading role.

An analysis of the CO_2 capture potential of industrial by-products from five industrial sectors found that up to 0.56 Gt of CO_2 emissions could be captured by 3.6 Gt of carbonatable materials each year using CO_2 mineralisation. A combination of lifecycle assessment and technoeconomic analysis was used to compare the increased production costs of the carbonated building materials relative to their conventional counterparts and the CO_2-eq avoidance costs of the mineralisation technologies. Of the eight carbonated building materials investigated, cement from carbonated end-of-life cement paste was determined to have the lowest CO_2 avoidance cost and was the only carbonated building material to have a lower avoidance cost than CCS. The CO_2 injected ready mix concrete and cement from carbonated end-of-life cement paste products were found to have cost-competitive production costs with their conventional counterparts, while the significantly increased production cost for lightweight aggregates is likely to be a barrier to commercialisation. The results in this section highlight the importance of focusing on the deployment of carbonated building materials with high environmental and/or economic performance. The current "one-size-fits-all" approach for classifying carbonated building materials, i.e. assigning the same 'low-carbon' label to material that reduce the overall CO_2 emissions of the product by

5% versus 50%, may need to be reassessed to improve the decarbonisation of the construction industry.

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