ICE Core Concepts: Low Carbon Cements and Concrete for Construction

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Professor Monower Sadique CEng FICE

Published by Emerald Publishing Limited, Floor 5,
Northspring, 21-23 Wellington Street, Leeds LS1 4DL.

ICE Publishing is an imprint of Emerald Publishing Limited

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A catalogue record for this book is available from the British Library

ISBN 978-1-83608-477-8

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Commissioning Editor: Michael Fenton
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Books Production Lead: Benn Linfield

Typeset by: KnowledgeWorks Global Limited
Index created by: Lyn Nesbitt-Smith

Dedication

To the loving memories of my mother and father.

To Afrina, for her unreserved support.

To Sabique and Nahla, for their encouragement.

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Acknowledgements

I extend my heartfelt gratitude to my beloved wife, Afrina, my wonderful son, Sabique, and my sweet daughter, Nahla, for their unwavering support and encouragement throughout the writing of this book. Their love and understanding made this journey possible. I also wish to express my deep appreciation of my colleagues at Liverpool John Moores University, whose invaluable support and knowledge have greatly enriched my work.

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About the author

Professor Monower Sadique CEng FICE is Professor of Construction Materials at the School of Civil Engineering and Built Environment, Liverpool John Moores University, UK. Professor Sadique is a Fellow of Institution of Civil Engineers (ICE). He earned his first degree in Civil Engineering from Chittagong University of Engineering and Technology (CUET), Bangladesh. He began his professional journey in 1999 by joining the Bangladesh Civil Service as an Assistant Engineer in the Roads and Highways Department (RHD) under the Ministry of Communication. During his tenure, Professor Sadique contributed to the construction of various concrete girder bridges at national and regional highways across Bangladesh.

In 2009, he achieved an MSc in Road Management and Engineering with Distinction from the University of Birmingham. He went on to complete his PhD in 2012 at Liverpool John Moores University (LJMU), where his research titled ‘Development of Low Carbon Cement from Waste Biomass Fly Ash’ laid the foundation for his career in sustainable construction materials. In 2017, Professor Sadique joined LJMU as a Senior Lecturer, progressing to the rank of Professor due to his outstanding contributions to research, teaching, and industry collaboration.

Professor Sadique’s commitment to low-carbon construction materials is rooted in his unique career trajectory, which bridges practical industry experience and academic research. His transition from a highway engineer to an academic researcher has equipped him with a deep understanding of industry challenges and the scientific expertise required to develop innovative solutions.

Over the past decade, Professor Sadique has been at the forefront of pioneering research in industrial and academic settings. His work spans the UK highways sector, collaborating with public and private organisations, Small and Medium-sized Enterprises (SME), universities, and manufacturers. Professor Sadique’s diverse research portfolio includes cement and concrete innovation, low-carbon construction materials, highway design, and asset management. Within ten years of earning his PhD, he secured four patents, supervised six PhD projects, published over 50 journal papers, and generated external grant funding – all focused on addressing critical challenges in low-carbon construction.

Driven by a passion for transformative knowledge exchange, Professor Sadique is dedicated to creating practical and scalable solutions that address material security challenges posed by climate change. The publication of this book exemplifies his strategic approach to advancing research and knowledge exchange. It aims to equip both aspiring and practicing engineers with essential and up-to-date knowledge in the civil, construction, and materials sectors, fostering sustainable practices for the built environment.

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Monower Sadique
ISBN 978-1-83608-477-8
https://doi.org/10.1108/978-1-83608-474-720251001

Chapter 1
Cement

After completing this chapter, you should be able to

- understand the composition and properties of cement and Portland clinker
- identify various types of cement and their nomenclature
- comprehend the mechanical and physical requirements of common cement
- recognise the permitted clinker replacement materials specified in the standards
- assess the carbon emission challenges associated with cement production
- explore the mitigation strategies and pledges the cement and concrete sectors undertake to reduce emissions.

Introduction

The fabric of the infrastructure of our world depends to a high degree on traditional Portland cement. Cement is believed to be the world's second most consumed substance after water. Cement is termed the glue of progress as it is the fundamental material for building society's infrastructures. The availability of this raw mineral and its versatility play an important role in its wide acceptance, evidenced by the annual consumption of more than 4 billion tonnes of cement and 14 billion tonnes of concrete that will continue to revolutionise the built environment throughout the world. However, it comes at a cost to the environment because the huge heat and chemical changes that are essential in making cement also result in carbon emissions. Although the technology has changed greatly, Portland cement technology still relies on the same basic raw material of quarried limestone and on volcanic heat (around 1450°C). The construction sector is under huge pressure to develop climate solutions to meet targets of reducing carbon emissions. Accordingly, British Standards have already adopted various alternative materials to reduce dependency on Portland clinker. The design standards, designation, and allowable content of those cementitious additions are also in use.

Cement

In 1824, Joseph Aspdin patented 'Portland Cement', the modern hydraulic binder made from a calcined mixture of clay and limestone that, when ground to a powder, reacts with water to exhibit cementitious properties. The name 'Portland' was chosen for its resemblance to the widely used Portland stone of that era. Earlier, in 1790, James Parker developed and patented a version which was based on the calcined nodules of a calcareous clay.

British Standard BS EN 197-1 (BSI, 2019a), which specifies the confirmatory criterion for common cement (CEM), defines cement as a hydraulic binder that reacts directly with water and, through hydration reaction, forms paste or cementitious compounds that harden over time and retain strength and stability even under water. A cement conforming to BS EN 197-1 should be capable of producing grout/paste (binder only) or mortar (binder and fine aggregate) or concrete (binder, fine and coarse aggregate) after being mixed with water, and attain specified compressive strength after a defined curing period generally after 2 and 28 days. CEM consists of different materials and, based on their composition, BS EN 197 parts 1 and 5 have grouped the following five main cement types, under which there are 27 and 5 (total 32) types of cement products listed in the family of common cement. The compositional details of the 32 products are available in Table 1 in BS EN 197-1 & 5 (BSI, 2019a, 2021d).

- CEM I Portland cement
- CEM II Portland-composite cement
- CEM III blast furnace cement
- CEM IV pozzolanic cement
- CEM V composite cement.

Out of these groups, only CEM I consists of Portland cement clinker (95–100%). This was historically known as ordinary Portland cement (OPC); however, this does not exist anymore and it is no longer appropriate to use the term ‘OPC’. The other 26 family members of common cement (CEM II to CEM V) contain different proportions (additions) of either ground granulated blast furnace slag (GGBS), silica fume (SF), pozzolana, pulverised fuel ash (PFA) or fly ash, burnt shale, or limestone as additions to Portland clinker (5–80%). Each main group in CEM II–CEM V is sub-divided into various types based on the compositional content of clinker and respective addition. Given that blending ‘additions’ with Portland clinker is a standard industry practice, the term ‘binder’ (e.g. water/binder ratio or binder content in kg/m^3) is logically more appropriate than ‘cement’. The Global Cement and Concrete Association (GCCA) defines ‘binder’ in its policy document *Blended Cements and Supplementary Cementitious Materials*: ‘A binder is a material that sets and hardens by chemical reaction with water (hydration). The hydration reaction results in the formation of a hard solid mass’ (GCCA, 2024a).

Manufacture of Portland cement

Portland cement clinker is made by burning principally quarried limestone ($CaCO_3$) as a source of lime (CaO), small quantities of sand, shale, and clay as a source of silica (SiO_2), aluminium (Al_2O_3), and iron (Fe_2O_3) to a temperature around 1500°C. Nodules (size of a tennis ball) of clinker are produced through partial fusion. During this calcination, the carbonate component of limestone, which is a sedimentary rock, is converted to calcium oxide (CaO) and produces calcium silicates (which is the fundamental component of Portland cement) in addition to releasing carbon dioxide (CO_2) through the calcining reaction. Calcium aluminates and calcium aluminoferrites are also present in clinker. These principal chemical reactions during the clinker production in the kiln are shown in Equation 1.1 to Equation 1.4 (Lea *et al.*, 2019).

$$\mathrm{CaCO_3} \equiv \mathrm{CaO} + \mathrm{CO_2} \tag{1.1}$$

$$2\mathrm{CaO} + \mathrm{SiO_2} \equiv (\mathrm{CaO})_2 \cdot \mathrm{SiO_2} \tag{1.2}$$

$$3\mathrm{CaO} + \mathrm{Al_2O_3} \equiv (\mathrm{CaO})_3 \cdot \mathrm{Al_2O_3} \tag{1.3}$$

$$4\mathrm{CaO} + \mathrm{Al_2O_3} + \mathrm{Fe_2O_3} \equiv (\mathrm{CaO})_4 \cdot \mathrm{Al_2O_3} \cdot \mathrm{Fe_2O_3} \tag{1.4}$$

The cooled clinker is then pulverised to fine grey powder to produce cement; during this process a controlled minor portion of gypsum or calcium sulphate which influences the rate of set and acts as a grinding aid is also added. The PSD as well as the fineness (specific surface area (SSA)) of typical clinker, which are dependent on the clinker grinding process, are presented in Figure 1.1 and compared against conventional fly ash. The particle size of clinker generally ranges between 0.5 and 100 μm, with d_{50} around 50 μm, with a relative density of about 3.15. The PSD and fineness of cement (ground clinker) influence the workability (water demand) and reactivity (rate of strength gain) during the fresh and early age of concrete, respectively.

Chemical properties of Portland clinker

Depending on the source of the raw meal (limestone silica, and other minor minerals), the typical chemical composition of clinker is in the range of 62–66% CaO, 19–22% SiO_2, 4–6% Al_2O_3, and 2–4% Fe_2O_3, of which at least two-thirds by mass presents in the form of calcium silicate, which is a crucial component of Portland cement. Other minor oxides such as Mn_2O_3, MgO, Na_2O, and K_2O are also present. For convenience, in cement chemistry, instead of writing the full notation of elements and compounds, the following shorthand notation is widely used for principal oxides.

$C = CaO$

$S = SiO_2$

$A = Al_2O_3$

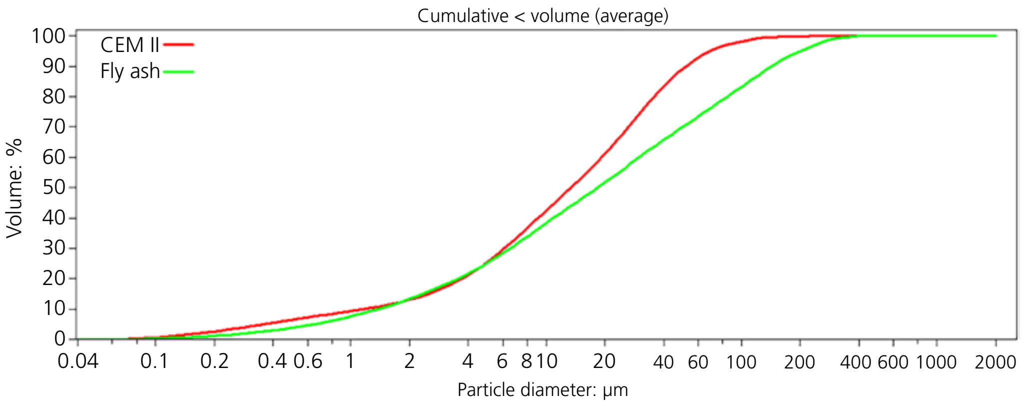
$F = Fe_2O_3$

$K = K_2O$

$M = MgO.$

All these oxides in Portland cement are present as compounds or phases. The four major phases, in shorthand form, are tricalcium silicate (C_3S) or alite; dicalcium silicate (C_2S) or belite; tricalcium aluminate (C_3A) or aluminate; and tetracalcium aluminoferrite (C_4AF) or ferrite. The relative

Figure 1.1 Comparative particle size distribution of cement and fly ash (author's own)



content of each compound in Portland cement depends on the source of limestone and the calcination technology used. Any variation in the composition of phases influences the hydration reaction (discussed in Chapter 3) and concrete and mortar's fresh and hardened properties. A typical general-purpose Portland cement, as reported by Soutsos and Domone (2018), has phases distributed approximately as follows: 48% C_3S; 24% C_2S; 13% C_3A; and 9% C_4AF. For cement applications requiring high early strength, such as emergency repair works, a clinker composition with a high content of C_3S and a lower content of C_2S is desirable. Conversely, for mass concrete structures with significant thermal cracking risk, a clinker with lower C_3S and higher C_2S content is preferred. In the case of sulphate-resisting cement, a general-purpose clinker with a very low C_3A content is essential to enhance durability against sulphate attack. During the production of cement, careful attention must be given to maintaining a consistent distribution of these phases to ensure uniform desirable properties in the final product. As discussed, the performance of cement is largely influenced by the phase composition of the clinker. However, its reactivity can also be significantly modified by adjusting the PSD of the clinker. This adjustment can be achieved through fine or coarse grinding, allowing for the tailoring of cement properties to suit specific applications. The typical PSD of cement is illustrated in Figure 1.1, providing a comparative analysis with fly ash. A comprehensive discussion of the physicochemical properties of cement is presented in Chapter 5.

Cement standards, types, and designation

As per the standard, all 27 types of distinct cement products have to meet defined mechanical, chemical, and physical properties. Different parts of BS EN 196 (BSI, 2011a, 2016a, 2020) specify the method of determining these properties under the general title 'Methods of testing cement'. The mechanical requirement includes the determination of standard mortar strength, while the physical requirement comprises initial setting time and soundness. BS EN 197-1 (BSI, 2019a) is dedicated to the evaluation of conformity of common cement: the ten requirements are strength, chemical analysis, setting times, soundness, determination of constituents, pozzolanicity, fineness, sampling, the heat of hydration by solution and semi-adiabatic method, and water-soluble chromium content. The physical and mechanical requirements specified in BS EN 197-1 (BSI, 2019a) are tabulated in Table 1.1.

As mentioned earlier, the unified current version of European and British standard BS EN 197-1:2011 (BSI, 2019a) recognises 27 types of CEM under the main five categories of cement group (CEM I to CEM V) following complex and rigorous procedures. BS EN 197 (BSI, 2019a) also specifies a standard designation protocol using letters and numbers to identify each CEM, indicating the main cement type (type I–type V), the proportion of clinker (higher to lower), second main constituent (addition), strength class (28-day strength) and type of strength gain at early stage (rapid or normal). The permitted second main constituent (addition) in 26 products in the family of common cements other than Portland clinker and their notations are listed in Table 1.2.

The first part of the nomenclature contains a designatory letter (either A or B or C) immediately after the Roman number (II to V) that indicates the main cement type. This letter indicates the level (A for higher, B for medium, and C for lower) of Portland clinker content in the cement. CEM I, which is historically OPC composed of only Portland clinker, does not contain any of these designatory letters.

The second part of the nomenclature contains an additional designatory letter for each second main constituent (addition) as mentioned above. The third part of the nomenclature contains a number that indicates strength class (compressive strength in megapascals, MPa) that will be achieved

Table 1.1 Mechanical and physical requirements set out in BS EN 197-1 (BSI, 2019a) for conformity of common cements

Strength class	Compressive strength: MPa Based on BS EN 196-1 (BSI, 2020)				Initial setting time: min Based on BS EN 196-3 (BSI, 2016a)	Soundness: mm Based on BS EN 196-3 (BSI, 2016a)
	Early strength		Standard strength			
	2 days	7 days	28 days			
32.5L	–	≥ 12.0	≥ 32.5	≤ 52.5	≥ 75	≤ 10
32.5N	–	≥ 16.0				
32.5R	≥ 10.0	–				
42.5L	–	≥ 16.0	≥ 42.5	≤ 62.5	≥ 60	
42.5N	≥ 10.0	–				
42.5R	≥ 20.0	–				
52.5L	≥ 10.0	–	≥ 52.5	–	≥ 45	
52.5N	≥ 20.0	–				
52.5R	≥ 30.0	–				

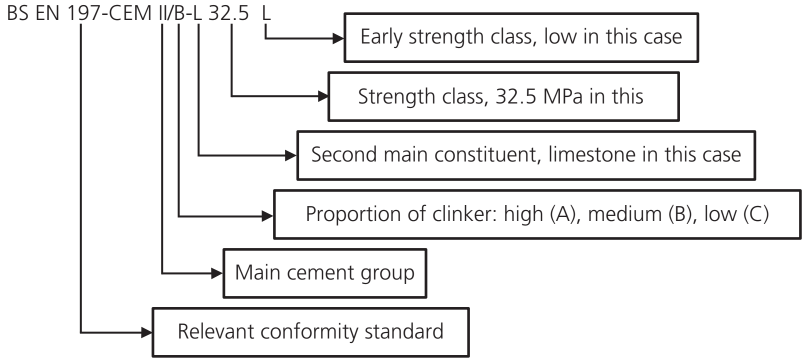
Table 1.2 List of permitted second main constituent and their notations specified in BS EN 197-1 (BSI, 2019a)

Permitted additions	Notation
Granulated blast furnace slag	S
Natural pozzolana	P
Natural calcined pozzolana	Q
Siliceous fly ash	V
Calcareous fly ash	W
Burnt shale	T
Limestone	L
Silica fume	D

by a 40 × 40 × 160 mm prism of mortar after 28 days under water curing. There are three strength classes: 32.5, 42.5, and 52.5; cement needs to achieve equal or more than the specified strength after 28 days according to BS EN 196-1 (BSI, 2020). The prism of mortar should be made of a cement to fine aggregate (sand) to water ratio of 1:3:0.5 by weight. This number in the nomenclature is then followed by a letter: either N (ordinary early strength), R (high early strength) or L (low early strength). This nomenclature is summarised in Figure 1.2.

For example, a cement denoted EN 197-1 CEM I 32.5 R is Portland cement conforming to EN 197-1, of strength class 32.5 with high early strength.

Figure 1.2 Cement designations/nomenclature proposed in BS EN 197-1 (BSI, 2019a)



A cement denoted EN 197-1 CEM III/B-S 42.5 N is blast furnace cement conforming to EN 197-1, containing between 66% and 80% by mass of granulated blast furnace slag (S), of strength class 42.5 with ordinary early strength.

According to BS EN 196-1 (BSI, 2020), strength conformity for any cement or cementitious binder needs to be conducted using 40 × 40 × 160 mm prism mortar; details of the test are discussed in Chapter 5.

Emission issues of Portland cement production

It is believed that concrete, which is a composite material, is the world's second most consumed substance after water. Depending on the intended use and mix design, in typical concrete (by mass), 70–85% is taken by aggregates (coarse and fine), 10–20% by cement or cementitious binder, and the rest, around 3–6%, by water. Cement is termed as the glue of progress as it is the fundamental material for building society's infrastructures. However, it comes at a cost to the environment because the huge heat and chemical changes that are essential in making cement also result in carbon emissions. Cement production is a carbon-intensive process from the viewpoint of the requirement of extraction of enormous amounts of natural resources (raw meal), burning fossil fuels at high temperatures (kiln), as well as process emission of carbon dioxide (CO_2) (Equation 1.1) during the calcination reaction. The total carbon emission arises from cement production through quarrying and preparing raw materials, calcination in kilns for clinker production, milling clinker, and transportation of the final product (cement). Based on the current version of the *Inventory of Carbon and Energy* (ICE) database (Jones, 2019), the embodied carbon content of cement (CEM I) is 0.912 kg CO_2/kg cement, of which 60% of CO_2 (0.55 kg) is released during the calcining reaction, which is necessary for clinker production and cannot be avoided, and 30% emission arises from fuel combustion. A more detailed discussion on approaches to reducing the embodied carbon of cement at the manufacturing level is presented in Chapter 5.

Concrete sector approach to reducing carbon emissions

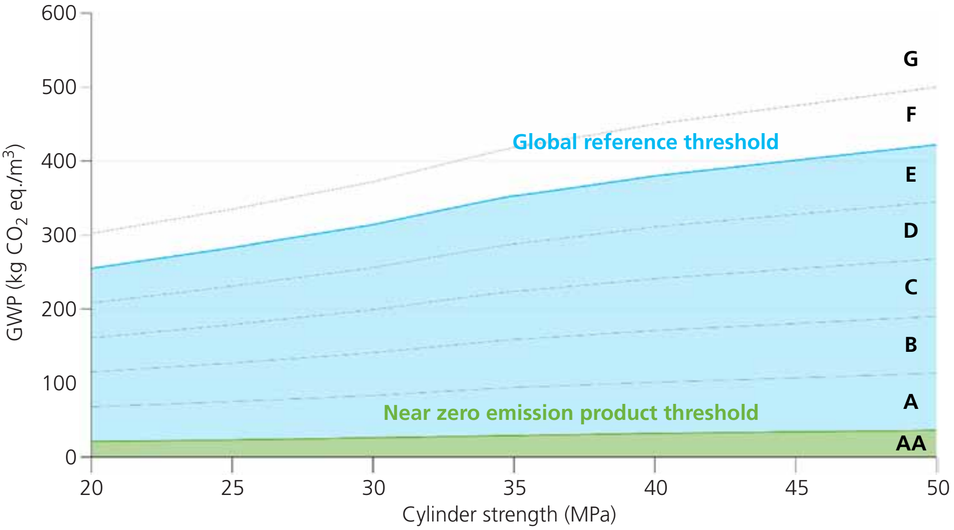
Globally in 2020, around 14 billion m^3 of concrete and over 4 billion tonnes of cement were produced (GCCA, 2021) to revolutionise the world's built environment. Up to 90% of the carbon emissions associated with the production of concrete are blamed on cement. In 2018, 7.3 million tonnes of CO_2 were emitted by the UK cement industry (MPA UK Concrete, 2020). MPA Cement, which is part of the Mineral Products Association (MPA), represents the six major UK

Portland cement manufacturers that adopted the concrete and cement industry roadmap to deliver net zero emissions by 2050 (MPA UK Concrete, 2020). This roadmap targeted a 39% carbon reduction per tonne of cementitious materials, of which 16% and 12% savings were aimed at the deployment of fuel switching (biomass waste, hydrogen fuel) and low carbon cement (alternative binder), respectively. Likewise, the Institution of Civil Engineers (ICE) in association with the Green Construction Board published the *Low Carbon Concrete Routemap* to roll out and transition to net zero concrete by 2050, recommending three decarbonisation routes, namely benchmarking carbon in concrete, improvement in using concrete, and improvement in making concrete (Low Carbon Concrete Group, 2022). The GCCA, which is a trade association for the cement and concrete sector across the world, pledged contributions in the following items as a pathway to reach the net zero target (GCCA, 2023).

- efficiency in design and construction
- efficiency in concrete production
- savings in cement and binders
- savings in clinker production
- carbon capture, utilisation, and storage at the cement plant
- CO_2 sink/recarbonation
- decarbonisation of electricity.

As a first step, standardised measuring, reporting, and benchmarking of the embodied carbon in concrete for different types of cement need to be established across the construction sector. In 2024 GCCA published global numerical definitions for low carbon and near zero emissions concrete (GCCA, 2024b) for procurement, reporting, and comparing progress between countries, as shown in Figure 1.3, where the band values in global warming potential (GWP) units (ECO_2e/m^3) are plotted against concrete compressive strength (MPa). The global definition of concrete products

Figure 1.3 GCCA global definition of low carbon and near zero emissions concrete. Reproduced with permission from Global Cement and Concrete Association (GCCA, 2024b)



(precast and ready-mix) comprises seven bands (near zero and A to F), including the near zero emissions and global reference thresholds.

To establish the global reference threshold for concrete, data from ten major cement-producing countries (except China) were used to determine carbon footprint thresholds for each country. To create a global threshold, country-specific thresholds were then combined and weighted by each country's cement output.

The International Energy Agency (IEA) proposed 125 kg of CO_2 equivalent per tonne (kgCO2e/t) of cement as the threshold for near zero emissions cement production using 100% clinker, compared to an IEA reference value of 850 kgCO2e/t for a conventional dry kiln (IEA, 2022).

Five equal bands (A to E) are defined after establishing the global reference threshold (top of E) and the near zero emissions threshold (band AA), as shown in Figure 1.3, for the global definition of low carbon and near zero emissions concrete.

The following assumptions were made by GCCA to estimate the near zero emission product threshold for concrete by 2050.

- clinker content in cement will be reduced to 0.52
- cement's carbon footprint will align with IEA's near zero definition
- cement usage per unit volume of concrete will decrease by 14% through advancements in admixtures
- shift to 56-day compressive strength and performance testing.

The unit of carbon intensity or carbon coefficient of concrete products is reported as kg CO_2e/kg, kg CO_2e/t, kg CO_2e/m^2, or kg CO_2e/m^3 by the different stakeholders such as suppliers and developers in the supply chain. Considering this, the ICE *Low Carbon Concrete Routemap* recommended using CO_2e/kg during calculation and CO_2e/m^3 for general reporting and comparison with concrete carbon benchmarks by taking concrete strength class into account (Low Carbon Concrete Group, 2022).

Questions to practice

1. List four major chemical compounds and their corresponding chemical elements commonly found in Portland clinker.
2. Briefly explain how Portland cement is manufactured using natural limestone.
3. Designate a blast furnace cement, conforming to BS EN 197-1 (BSI, 2019a), containing between 81% and 95% by mass granulated blast furnace slag (S) of strength class 32.5 with low early strength.
4. List a few strategies that can be adopted to reduce carbon emissions in the concrete sector.