

Pathways Call for Evidence Submission

18 July – 14 August 2026

Submission type	Upload
Submitter	SmartCrete CRC
Response ID	382665

Disclaimer

This document is a submission to the Net Zero Commission’s 2026 Pathways Call for Evidence. As part of the consultation process, the commission has committed to publishing the submissions it receives. Submissions do not represent the views of the commission.

29 July 2026

SmartCrete Cooperative Research
Centre
3 Innovation Road
Wallumattagal Campus
Macquarie University NSW 2109

Decarbonisation Pathways Evidence Submission
NSW Net Zero Commission

Dear Commissioners,

Re: Submission to the NSW Net Zero Commission – Decarbonisation Pathways Call for Evidence

Please find attached SmartCrete CRC's submission to the NSW Net Zero Commission's *Decarbonisation Pathways Call for Evidence*. The attached report, undertaken by Prof. Stephen Foster and Charlotte Wang of UNSW entitled '*Low Carbon Concrete Research and Insight Report*' presents an evidence-based assessment of the barriers and opportunities associated with accelerating the uptake of lower-carbon concrete in Australia, with a particular focus on the role of standards, specifications, procurement and engineering governance.

Concrete is responsible for a significant proportion of embodied emissions in the built environment, but it also represents one of the most immediate opportunities for cost-effective emissions reduction. The report concludes that the principal barriers to further decarbonisation are no longer primarily technical; rather, they relate to the systems that govern how innovation is translated into engineering practice. As such, the report focuses on practical reforms that can accelerate deployment while maintaining the high standards of safety, durability and performance expected of Australian infrastructure.

Several recommendations contained within the report align closely with the objectives of the Commission's inquiry, including:

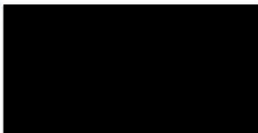
- **Transitioning to performance-based standards and specifications** that enable multiple low-carbon technologies to compete on demonstrated performance rather than prescriptive material requirements.
- **Strengthening engineering governance and standards development processes** to accelerate the translation of validated research into practice while maintaining public confidence in infrastructure performance.
- **Developing nationally consistent approaches to embodied carbon measurement and benchmarking**, providing government and industry with reliable metrics to assess progress.
- **Embedding decarbonisation objectives within procurement and infrastructure delivery**, allowing project owners to specify lower-carbon outcomes while preserving value, durability and resilience.
- **Supporting technology-neutral pathways** that encourage innovation across the supply chain without favouring particular products or manufacturers.

These recommendations reflect extensive consultation with government agencies, asset owners, Standards Australia, consultants, researchers and industry representatives, together with a detailed review of Australian regulatory frameworks and practical case studies.

SmartCrete CRC and our partners would welcome the opportunity to assist the Commission further. Should the Commission wish to explore any aspect of the report in more detail, we would be pleased to make members of the project team available to discuss the findings, methodology or their application to New South Wales policy and infrastructure delivery.

Thank you for the opportunity to contribute to this important process. We commend the Commission for its leadership in identifying practical pathways to decarbonise the NSW economy and would welcome the opportunity to support this work further.

Yours sincerely,



Clare Tubolets
Chief Executive Officer
SmartCrete CRC



THE UNIVERSITY OF
NEW SOUTH WALES

STUDIES FROM
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Low Carbon Concrete Research and Insight Report: May 2026

BY

Stephen J Foster *BE (Hons) MEngSc PhD FTSE FIEAust Ffib*

and

Charlotte Wang *BE (Hons 1) BA*

ACKNOWLEDGEMENTS

This project was commissioned and funded by SmartCrete CRC, a Commonwealth Government initiative, with support from Standards Australia and VIDA Rail, a project delivery organisation of the Victorian Infrastructure Delivery Authority.

Section 2 of this report reflects ongoing research and presents preliminary findings from the doctoral studies of Charlotte Wang. The author acknowledges and thanks her supervisors – Prof Richard Stuetz, Prof Robert F. Care AM, Prof Matthew Kearnes and Dr Ruth Fisher – and funding sources – an Australian Government Research Training Program (RTP) Scholarship doi.org/10.82133/C42F-K220 and a UNSW Engineering Top-up Award from the School of Civil and Environmental Engineering.

Section 3 draws on discussions by the lead author with professionals from government business enterprises, councils, Standards Australia, asset owners, consultants, and industry. Their input into the development of the author's thinking is duly acknowledged.

Section 6 of this report presents a case study based on data provided by the VIDA Rail Low Carbon Concrete Project team. We acknowledge and appreciate the information and data shared in the preparation of this chapter.

Finally, we would like to acknowledge the members of the Steering Committee:

Miles Dacre, AECOM

Estela Oliari Garcez, GHD

Vute Sirivivatnanon, University of Technology, Sydney

Adam Stingemore, Standards Australia

Clare Tubolets, SmartCrete

for their guidance, oversight, and commitment to the success of this project. Their strategic insight and leadership have been instrumental in shaping the direction and ensuring strong governance throughout.

ABSTRACT

This report examines the barriers to and opportunities for reducing greenhouse gas emissions from cement and concrete in Australia, in the context of state, territory, and federal commitments to substantial emissions reductions by 2035 and net zero by 2050. It considers how policy and regulatory settings – including standards, specifications, and procurement – shape the uptake of low-carbon concrete products, and how these settings interact with the technical, organisational, and cultural dynamics of the community of practice for concrete structures. The study draws on a review of relevant legislation, standards, and regulatory frameworks, supported by conversations with professionals across government business enterprises, councils, Standards Australia, asset owners, consultants, and industry.

The analysis shows that current barriers are not solely technical but are embedded in complex and fragmented engineering governance environments characterised by multiple authorities for engineering policymaking, competition between the established and emerging aims of engineering work, prescriptive requirements, inconsistent jurisdictional settings, and slow pathways for the incorporation of innovation into practice. A historical and institutional review highlights how these arrangements have shaped the aims of engineering practices over time. It suggests that decarbonisation is best understood not simply as a product-substitution challenge but as a broader transition of coordinated practices. The review identifies that the Engineers Committee Method for voluntary, consensus-based, standard-setting is recognised as a critical enabler of past transitions in engineering practice and remains a strong catalyst for current and any future transition(s). In this context, standards and specifications are reframed not as barriers in themselves, but as key instruments for enabling legitimate, coordinated, and scalable change.

The report further examines the relationship between lower-carbon materials and lower-carbon structures through design-based examples and case studies of embodied-carbon measurement and reduction in infrastructure delivery. The findings indicate that emissions reductions have been driven, thus far, mainly by the substitution of supplementary cementitious material within legacy frameworks, while deeper decarbonisation will require more adaptive rules, standards and processes, clearer performance pathways, validated test methods, and stronger upstream integration of technical and sustainability objectives. A series of recommendations is proposed to strengthen standards, specifications, regulatory and procurement mechanisms, and engineering governance in support of a coordinated national transition to lower-carbon concrete and infrastructure.

TABLE OF CONTENTS

Acknowledgements	2
ABSTRACT	3
1. INTRODUCTION	7
1.1 Background	7
1.2 Scope	11
2. CONTEXT AND PROBLEM DEFINITION	13
2.1 Questioning the Problem Definition: Standards as a ‘Barrier’?	13
2.2 Regulatory Context: Buildings, Infrastructure, and Industry	14
2.3 Historical Context: The Engineers’ Committee Method	17
2.4 Political Context: Engineering Leadership for Engineering Governance	20
2.5 Practice Context: What Makes a Standard a Standard	22
2.6 Proposed Problem Definition: A Transition of Practice	24
3. TECHNOLOGY DIVERSITY, COMPETITION AND SUPPLY-CHAIN EQUITY	27
3.1 Industry Context and Current Market Practice	27
3.2 Supply-Chain and Technology Considerations	28
3.3 Implications for Standards and Specifications	29
4. AUSTRALIAN STANDARDS AND TECHNICAL SPECIFICATIONS	30
4.1 Addressing Structural Limitations in the Standards Revision Process	30
4.2 Prescriptive Clauses within a Performance-Based Design Framework	32
4.3 Supporting NCC Performance Pathway through Development of Performance-Based Technical Specifications	34
4.4 Developing a Structured Framework for Test Method Validation	36
4.5 What is Cement and the Importance of its Definition	38
5. RELATIONSHIP BETWEEN LOWER CARBON PRODUCTS AND LOW CARBON STRUCTURES AND PROJECTS	40
5.1 Introduction	40
5.2 Evolution of Building and Infrastructure Rating Tools Addressing Embodied Carbon	40

5.2.1	Green Star.....	40
5.2.2	Infrastructure sustainability (IS) rating	41
5.2.3	NABERS and the emergence of embodied carbon for buildings	42
5.2.4	CCAA/GCCA and MECLA low carbon ratings for concrete.....	42
5.2.5	Other data sources for assessing cement and concrete emissions intensity	45
5.3	Evolving Australian Approaches to Embodied Carbon Measurement	45
5.3.1	Introduction	45
5.3.2	Cradle-to-gate (A1–A3) embodied carbon and embodied energy for typical Australian normal-class ready-mix concretes	46
5.3.3	Embodied carbon and embodied energy of Australian GP cement	48
5.4	Example 1: Cyclonic Drain Retaining Wall – Comparison of Conventional, Geopolymer and UHPC Structural Forms.....	50
5.4.1	Introduction	50
5.4.2	Project description.....	50
5.4.3	Material characteristics	52
5.4.4	Sustainability-focused design framework	53
5.4.5	Environmental impact calculation (EIC)	53
5.4.6	Performance and environmental impact.....	55
5.4.7	Conclusions from example 1	56
5.5	Example 2: Infrastructure of Different Structural Forms for a 40 metre Long Prestressed Concrete Girder Bridge	56
5.5.1	Introduction	56
5.5.2	Project description.....	57
5.5.3	Materials assumptions	59
5.5.4	Performance and environmental impact.....	60
5.5.5	Absolute 100-year GWP – superstructure total	65
5.5.6	Component-level breakdown – girders	66
5.5.7	Component-level breakdown – deck slab and ancillary elements	66
5.5.8	Structural carbon floor and system implications.....	67
5.5.9	Conclusions from example 2.....	68

5.6	Example 3: Three Bay-by-Three Bay Flat Slab Floor	68
5.6.1	Introduction and project description	68
5.6.2	Materials assumptions	69
5.6.3	Performance and environmental impact.....	72
5.6.4	Conclusions from example 3	74
5.7	Conclusions	74
6.	CASE STUDY: VIDA RAIL LOW-CARBON CONCRETE PROJECT.....	76
6.1	Introduction	76
6.2	Theme 1: Setting Targets for Embodied Carbon.....	77
6.3	Theme 2: Collaborating Between Sustainability and Engineering Functions.....	79
6.4	Theme 3: Contributing to a Reset of Engineering Governance	81
6.5	Addressing Structure-Level Decarbonisation – Study 1: Transport Interchange Car Park Structure	82
6.5.1	Background	82
6.5.2	Baseline definition and structural optimisation approach	83
6.5.3	Industry benchmark datasets	84
6.5.4	Results and discussion.....	87
6.5.5	Conclusions from the example.....	89
6.6	Addressing Structure-Level Decarbonisation – Study 2: Railway Bridge Application	90
6.6.1	Background	90
6.6.2	Material benchmark basis and assessment cases	91
6.6.3	Basis of the calculations.....	92
6.6.4	Results and discussion.....	93
6.6.5	Conclusions from the example.....	96
7.	CONCLUDING REMARKS.....	98
8.	REFERENCES.....	102

1. INTRODUCTION

1.1 Background

Australia's transition to lower-carbon construction materials is accelerating, driven by emerging policy commitments, industry-led innovation, and growing demand for decarbonised infrastructure. Concrete, as one of the most widely used construction materials, presents both significant challenges and major opportunities for carbon reduction. While the technical potential of low-carbon concretes – enabled primarily through alternative binder systems and supplementary cementitious materials – is increasingly recognised, their widespread adoption remains constrained. This report investigates the barriers to widespread adoption, focusing on the impact of standards frameworks, regulatory settings, procurement practices, and uncertainties regarding material performance and structural reliability.

As the planet continues to warm, the global community faces increasing urgency to limit and adapt to the escalating impacts of climate change. For more than three decades, scientists and engineers have consistently highlighted that without a coordinated international effort to reduce greenhouse gas (GHG) emissions, global mean temperatures will continue to rise, thereby increasing average ocean temperatures and atmospheric moisture and energy content. Indeed, in 2025, the World Meteorological Organisation reported that in 2024, the global average temperature increase over the pre-industrial baseline of 1.5 degrees C had been exceeded in a single year for the first time, with the period 2015–2024 being the 10 warmest years on record [1]. Figure 1 plots yearly spot mean global temperature every 10 years from 1860, relative to the pre-industrial baseline period 1861–1890. Seen this way, the acceleration in the rise in temperature from the 1970s to today is immediately apparent.

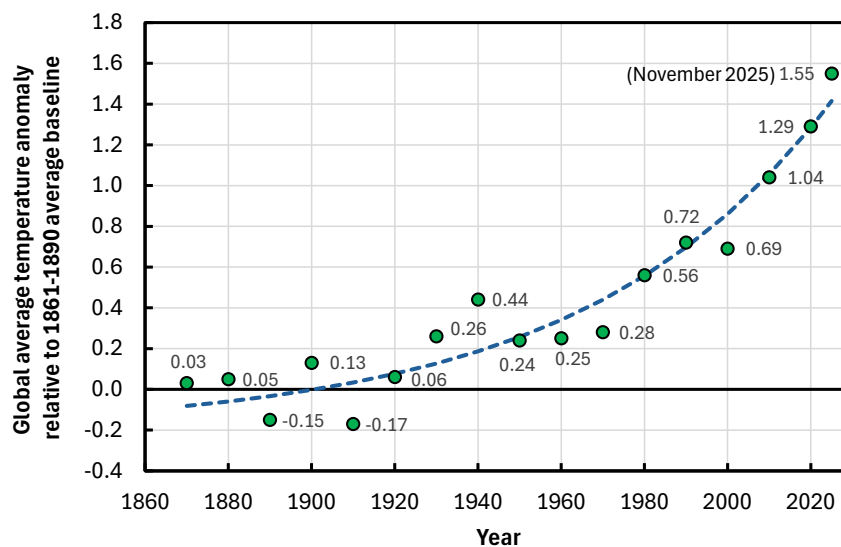


Fig. 1. Spot 10-yearly values for global temperature anomaly relative to the 1861-1890 baseline versus time (1860 – present). Data from [2].

The Brundtland Commission’s 1987 report *Our Common Future* [3] introduced what remains the most widely cited definition of sustainable development: meeting present needs without compromising the ability of future generations to meet their own. The Engineers Australia Code of Ethics [4] reflects this principle by requiring engineers to promote environmental sustainability and consider the long-term impacts of engineering decisions on society and future generations. However, current practices indicate that the Brundtland Commission benchmark is not being met; environmental stewardship remains insufficient for those who will inherit the built environment we create.

Within that environment, concrete – particularly its cement component – is a significant source of GHG emissions. Although some materials used in modern technologies, such as high-purity silica for electronics and photovoltaics, may be more carbon-intensive per unit mass, the sheer volume of concrete produced worldwide makes it a major contributor to carbon emissions. Indeed, as a material in its own right, concrete may not be defined as a high-carbon product. As seen in Table 1, it lies at the lower end of carbon dioxide emissions intensity among construction materials, second only to timber. It is the versatility and demand for concrete that make it so significant, with an estimated 4.2 billion tonnes of cement being transformed into 11 billion cubic metres of concrete (estimate based on 85% of total cement being used for the manufacture of concrete, with the remainder for mortars, renders, screeds, grouts, fibre-cement, soil-cement, etc.).

Table 1. GHG emissions from common construction building materials

Building Material	CO ₂ -eq per tonne	CO ₂ -eq per m ³	Notes
Steel (Blast Furnace)	2.3	18	High emissions due to coal-based production.
Steel (Electric Arc Furnace)	0.68	5.4	Lower emissions using recycled scrap and electricity.
Aluminium (Primary)	15	41	Very high emissions from energy-intensive smelting.
Clay Masonry (Fired Bricks)	0.48	0.86	Based on 0.48 kg CO ₂ -eq/kg.
Glass	0.1	0.25	Energy-intensive production.
Timber	-1.8	-0.90	Sequesters carbon; net negative emissions.
Concrete	0.13	0.29	Based on 14% cement content by mass

As engineers, concrete technologists and sustainability specialists, we have an essential role not only in broader advocacy for effective climate policy, but also – and more directly – in identifying, evaluating and implementing pathways to reduce emissions from concrete structures and construction systems within our professional domain. As previously stated, the

Engineers Australia *Code of Ethics and Guidelines on Professional Conduct* [4] commits engineering professionals to promoting sustainability in their practice. In its *Position on Climate Change* [5], Engineers Australia recognises the crucial role of engineers in managing the climate transition, stating:

“Engineering leadership and multi-disciplinary problem solving is crucial to achieving the necessary step change toward a sustainable society... Engineers must be at the forefront in policy formulation and decision-making affecting the scoping, planning, design, delivery and operation of systems for climate change mitigation and adaptation.”

The contribution of cement and concrete to global CO₂ emissions has been widely debated, with estimates often cited as 6–9%. This has fuelled attention-grabbing statements such as the Guardian’s 2019 characterisation of concrete as “*the most destructive material on earth*”. Such claims, while effective as headlines, are largely unhelpful unless accompanied by realistic alternatives to ordinary Portland cement concrete. Despite decades of research into alternative binders – notably geopolymers and other alkali-activated systems – their penetration into mainstream construction remains limited. This is due in part to the slow evolution of the chemical admixtures required to meet modern workability, pumpability, and controlled-setting requirements, and in part to the lag in developing robust design standards and specifications. In this space, Standards Australia is uniquely placed to lead change by strengthening its processes for translating validated research into practical design models and provisions, and by ensuring these are progressed in a timely manner from drafting, through robust committee deliberation and public scrutiny, to adoption in new and revised standards. Equally important is the way standards are structured – performance-based requirements stated clearly up front, followed by well-documented prescriptive, deemed-to-satisfy solutions – so that innovative, low-carbon materials and systems can be accommodated without being constrained by legacy prescriptive rules.

As noted above, there is considerable confusion around the actual share of global emissions attributable to cement and concrete. The Working Group III contribution to the IPCC Sixth Assessment Report [6] estimates that process emissions from cement manufacture accounted for 2.6 % of the 59 Gt of CO₂-equivalent (CO₂-eq) emissions in 2019, including both direct and indirect sources. These figures align with the data compiled by Andrew [7], which is updated annually, showing that in 2019, total fossil CO₂ emissions were about 44 Gt, of which calcination in cement production contributed 1.6 Gt. Combustion of fossil fuels for kiln and related energy added roughly another 1.0 Gt CO₂, giving 2.6 Gt in total – approximately 5.9 % of global CO₂ emissions in that year, with comparable values reported for 2023. When all GHGs are included, and emissions are expressed in CO₂-eq terms (59 Gt in 2019), cement

production accounts for about 4.4 %. The intention here is not to minimise the significance of emissions from our sector, but to accurately represent them.

Recent assessments underscore the scale and urgency of the decarbonisation challenge. The United Nations Emissions Gap Report [8] concluded that, if global mitigation efforts aligned with a 2°C or 1.5°C pathway were to begin in 2024, emissions would need to fall by an average of 4 per cent and 7.5 per cent per year, respectively, through to 2035. If enhanced action is deferred until 2030, the required annual reductions increase substantially to around 8 per cent for a 2°C pathway and 15 per cent for a 1.5°C pathway. By contrast, under currently announced policy settings, global emissions are projected to show no net decrease to 2035, highlighting the widening gap between existing commitments and the trajectories required to achieve agreed climate goals.

Roughly three-quarters of global GHG emissions originate in G20 countries, which collectively bear the most significant responsibility and capacity to act, yet effective, concerted action remains inadequate. Given current trends, overshooting 1.5 °C is effectively locked in, and a rapid acceleration of ambition and implementation will be required to move credibly towards a net-zero future.

From an Australian perspective, the decarbonisation challenge in cement and concrete reflects global trends, albeit at a smaller absolute scale. Globally, achieving net-zero emissions in the sector is estimated to require approximately US\$1.42 trillion in cumulative investment by 2050, with around 69% of this investment undertaken directly by plant owners and the remainder enabled by ecosystem actors, including clean power, hydrogen and CO₂ transport and storage infrastructure [9]. While Australia's share of this capital requirement is proportionally lower, the domestic task remains significant given the capital intensity of kiln upgrades, clinker substitution strategies and new capture-ready facilities. Investment in cement-making equipment and increased use of supplementary cementitious materials (SCMs) are expected to account for a substantial share of capital expenditure, alongside major investment in carbon capture, utilisation and storage (CCUS) infrastructure [10].

Recent emissions performance shows limited but measurable progress. Globally, absolute CO₂ emissions declined by approximately 4% between 2019 and 2023, largely due to reduced demand rather than structural decarbonisation [9]. Emissions intensity has remained broadly flat in recent years, reflecting the slow uptake of SCMs and the limited deployment of breakthrough technologies [9]. Low-emission clinker production remains at or below 1% of global output, and low-emission fuels account for only a small fraction of total thermal energy use [9]. In the Australian context, where production volumes are modest but process characteristics are comparable, these trends highlight the need for structural abatement measures rather than reliance on demand fluctuations. Taken together, high capital intensity,

technology-readiness constraints, and the requirement for coherent policy and market signals present a substantial implementation challenge for the Australian cement and concrete sector.

Against this backdrop, this work examines strategies for reducing GHG emissions associated with concrete in Australia, while recognising its central role as the primary structural material in the built environment.

1.2 Scope

In February 2026, Austroads released its report, *Carbon Reduction and the Use of Low Carbon Concrete* [11], which examines several pathways to reduce the embodied carbon of concrete in transport infrastructure across Australia and New Zealand. The report focuses on accelerating the adoption of low-carbon concrete, identifying opportunities through increased use of supplementary cementitious materials (SCMs), optimisation of mix designs, and improved material efficiency at the asset level. It also highlights several systemic barriers to uptake, including reliance on prescriptive standards and specifications, inconsistent carbon measurement methodologies, limited long-term performance data, rigid procurement practices and risk aversion.

The report proposes a series of coordinated reforms to address these constraints, centred on transitioning to performance-based frameworks. Key recommendations include introducing measurable embodied-carbon targets, standardising carbon-assessment methods, expanding the allowable SCM content, and enabling alternative binders, such as geopolymer concrete, through performance testing. Supporting measures include implementing pilot programs, revising constructability requirements (such as maturity-based strength assessment), and integrating carbon considerations into procurement processes. A phased implementation roadmap is outlined, underpinned by the establishment of a national taskforce to align stakeholders, drive specification reform, and support the widespread adoption of low-carbon concrete.

This study looks deeper into several aspects of these recommendations and examines the issues outlined above through a program of work encompassing five key components.

First, it reviews the Australian Standards governing concrete materials and structural design, focusing on how these standards shape the use of cement and alternative binders, and the extent to which current performance tests and design methodologies support the adoption of low-carbon concretes. The review also addresses technical considerations, including durability, time-dependent behaviour, fatigue, and the assurance level required across different structural failure modes.

Second, the report examines stakeholder engagement with government agencies, industry leaders, asset owners, architectural practices, and Standards Australia, providing insights into current pathways toward net-zero, existing barriers, and expectations for future regulatory and market developments. Industry projections and anticipated policy directions are examined alongside the broader policy and legislative environments that shape the uptake of lower-carbon products. This includes analysis of national and state regulatory mechanisms and ratings systems, guided by recognised life cycle assessment methodologies.

Third, the report analyses the relationship between lower-carbon concrete products, structural design requirements, and whole-of-project carbon outcomes. This includes assessment of material-level carbon reductions, implications for structural efficiency, interactions with existing standards, and gaps in testing methods, modelling tools, and design guidance. The analysis considers how decisions at the material, structural, and project levels collectively influence embodied and operational carbon.

Fourth, the report presents a case study of the Victoria Infrastructure Development Authority (VIDA) Rail Low Carbon Concrete Project, which is ongoing, with project information provided by VIDA Rail and its Technical Advisor, a joint venture of AECOM and GHD. This study provides a practical context for understanding how low-carbon concrete products are currently specified, evaluated, and implemented in a real project environment.

Finally, the report synthesises findings from each component to provide recommendations for enhancing national standards and technical specifications, as well as state-based specifications. These recommendations aim to facilitate the rapid, reliable adoption of alternative binder concretes within the Australian construction industry, aligning with the needs of suppliers, materials testers, designers, developers, and asset owners.

2. CONTEXT AND PROBLEM DEFINITION

2.1 Questioning the Problem Definition: Standards as a ‘Barrier’?

Decarbonisation policy is frequently oriented toward identifying and removing barriers to the widespread adoption of low-carbon products. This orientation reflects a policy framing rooted in technology-adoption models and economic theories of innovation [12], [13]. However, this framing may itself constrain the kinds of responses to climate change capable of producing widespread changes in practice – i.e. a decisive shift from business-as-usual [14].

When decarbonisation is conceptualised primarily as *product innovation*, standards are sometimes viewed as obstacles [15]–[17]. In the language of innovation theory, it can be argued that standards constrain product ‘experimentation’, understood to be essential for the emergence and scaling of ‘niche innovations’ within established ‘socio-technical regimes’ [18], [19]. In an Australian construction context, pathways for products to depart from standards – such as the Building Code of Australia’s Performance Solution pathway or seeking dispensation from specifications developed by states and territories – can be experienced as costly, time-consuming, complex, or opaque, leading to a perception of standards as barriers to innovation. This, in turn, presents an opportunity for Standards Australia and state and territory specification owners to facilitate dialogue and documentation that better enable the use of these existing pathways for innovation.

A similar problem framing – of standards as a ‘barrier’ – arises when decarbonisation policy is viewed as a matter of regulating greenhouse gas emissions and setting net-zero targets. From this perspective, standards may be seen as politically unaccountable policy instruments that prevent environmental policy and legislation from being fully realised [20].

This section critically re-examines the prevailing problem definition by asking why standards come to be framed as a barrier, what is meant by this, and how such barriers – real or perceived – might be addressed. It does so by situating standards within broader regulatory, historical, political, and practice contexts, arriving at a more systematic framing and problem definition. Here, decarbonisation is conceptualised as a *transition of practice* rather than *product innovation*. Decarbonisation policy is reoriented from the problem of *removing barriers to innovation* to that of enabling transitions in *practice*. Under this problem definition, ‘standards’ arising from voluntary, consensus-based methods of standard-setting are reframed as a key enabler rather than a barrier. The analysis in this section is informed by ongoing research at the University of New South Wales investigating transitions of engineering practice, with a particular focus on the Australian community of practice for concrete structures [21].

2.2 Regulatory Context: Buildings, Infrastructure, and Industry

Australian Standards underpin technical policy across the Australian building, infrastructure, and industrial sectors – yet they are also embedded within a complex regulatory structure. Understanding the effects of this regulatory structure on engineering practice is key to unlocking systemic barriers to decarbonisation. In other words, while first-hand experience may point to ‘standards’ as a source of inertia, meaningfully addressing this requires studying the structural effects of our regulatory approach as a whole. In this section, we review the policy and legislative instruments beyond Australian Standards, including procurement policies, that bear upon our progress toward decarbonisation.

The regulatory structure for buildings, infrastructure, and industry in Australia is multi-level, multi-domain, and multi-agenda. It comprises a complex array of policies and legislation enacted at different levels of government (e.g., federal, state, territory), within different domains of organisation (e.g., project, agency, corporate, professional), and across diverse policy agendas (e.g., safety, employment, industry, environmental). From the perspective of an engineering project team, there exist:

- International standards (e.g. ISO standards) and overseas national standards (e.g. British Standards) that are referenced in contract specifications and/or corporate systems, processes, and protocols;
- Federal regulations (e.g., the Building Code of Australia) and nationally recognised documents (e.g. Australian standards, Austroads guidance) that are specified in contracts, shape expectations of good practice, and/or are referenced in corporate systems, processes, and protocols;
- State- or territory-based technical specifications that are designed to be referenced across contracts for public works but are also regularly referenced for private works and adopted in corporate systems, processes, and protocols; and
- Additional asset-owner-specific, project-specific, corporation-specific, or agency-specific contract specifications, management systems, and operational protocols.

Such policy and legislative instruments can be further reinforced by tendering and procurement processes, professional codes of conduct, registration and accreditation schemes, and insurance policies, and enforced through criminal, tax, market, and contractual incentives and penalties. The instruments listed above are typically considered ‘technical’ in nature – requiring technical expertise to produce and interpret – and address established engineering aims, such as cost efficiency, reliability, and quality.

However, over the last five decades, an environmental policy agenda has sought to introduce broader aims such as environmental stewardship and sustainability. The pursuit of this agenda has led to the introduction of dedicated policy and legislative instruments, further deepening the regulatory complexity for buildings, infrastructure, and industry in Australia. These instruments include:

- Environmental impact assessments and development conditions;
- Environmental labels, certifications, and rating schemes (e.g. NABERS, Green Star, IS Rating, Living Building Challenge, EPDs, GECA, Climate Active, SBTi);
- Contract sustainability requirements and procurement specifications;
- Energy and climate legislation (e.g. the Safeguard Mechanism) and corporate sustainability reporting legislation (e.g. the National Greenhouse and Energy Reporting Scheme, climate-related financial disclosures); and
- Guidance documents (e.g. the Infrastructure and Transport Ministers Embodied Carbon Measurement for Infrastructure: Technical Guidance [22], the CCAA/GCCA and MECLA guides to low-carbon concrete [23], [24]).

The diversity of instruments listed above indicates the breadth and intensity of efforts to pull every possible lever in pursuit of this well-intentioned agenda. However, this broad, parallel set of policy and regulatory instruments, developed largely independently of the technical ones listed above, has encountered multiple points of tension with established technical aims. As an indirect attempt to redefine the established aims of engineering work to encompass a broader public policy agenda and to be accountable beyond the physical infrastructure asset, it has introduced competing pressures on engineering work that engineers must resolve.

While these pressures, expectations, and aims have been received by individual engineers in a variety of ways, they have also encountered systemic barriers to their meaningful resolution and integration. At the project level, engineers often lack the means and authority to adequately address what is experienced as intractable contradictions between technical and environmental requirements [25]. Even well-meaning, motivated practitioners default to the status quo, pragmatically prioritising technical quality and expedient project delivery where they lack options to viably integrate environmental aims. At the portfolio level and beyond, the degree and manner of integration is at the discretion of engineer-policymakers (e.g., contract and specification owners) and subject to their prioritisation of aims. The net result is often slow and arduous progress on environmental aims – predicated on highly motivated individuals – that remain subordinate to, rather than integrated within, strict technical rules.

We can understand this phenomenon structurally by examining it through the lens of engineering practice. From this perspective, our pursuit of well-intentioned policy agendas – technical and environmental alike – has increased the external, non-engineering oversight and control of engineering work. Regulatory achievements over the last half-century have come at the expense of professional autonomy [26], capacity for self-knowledge and appreciation for self-regulation [27], and opportunities for cultivating engineering judgement within a no-blame culture that encourages the responsible risk-taking that lies at the heart of engineering [28]. It has transformed the way engineering is perceived and practised in Australia, from a creative endeavour that manages risk through the exercise of good engineering judgement to a

routinised endeavour that avoids risk through adherence to established rules. Overall, the regulatory structure erected over the last five decades has disconnected and degraded engineering governance in Australia, in terms of quality, transparency, and consistency, making widespread, fundamental changes in engineering practice difficult or practically impossible.

The trade-off between regulatory control and engineering autonomy bears on the overall economic productivity and social licence of Australian engineering. In terms of its reception of innovation agendas (e.g., digitalisation, automation, robotics) and its responsiveness to public priorities (e.g., net-zero, affordable housing). Certain favoured approaches to regulating engineering work can constrain the profession's ability to respond to regulatory aims and lead to poor engineering outcomes across both traditional and emerging measures of success. Understanding these effects on how engineering is perceived and practised can enable us to better achieve important technical and environmental agendas.

Regulatory Context: Key Takeaways
Concrete decarbonisation policy: 1. Follows an approach consistent with policy implementation over the last five decades for buildings, infrastructure, and industry, which has seen greater regulatory oversight and top-down control of engineering work. 2. Both reduces the freedom of action in engineering work and increases the expectations on engineers and engineering policymakers (e.g. specification owners within government transport authorities). The former through an externally defined compliance approach, and the latter by introducing ill-integrated sustainability objectives into the traditional set of product and asset performance requirements. 3. Has widened the range of expertise, consequences, and stakeholders involved in engineering decision-making. Raising urgent questions requiring systematic thought as to how technical assurance, risk ownership, and accountability should be defined and coordinated under such changed circumstances. 4. Relies on the institutions and mechanisms of engineering governance, such as prescribed standards, approval pathways, avenues for collaboration, assurance methods to manage risk, alongside expectations that professional judgement continues to play a role in the deployment of emerging materials and practices. Taken together, these challenges underscore the need to review and strengthen governance arrangements for concrete structures practice in Australia, to align expectations with capabilities, and accountability with responsibility, while maintaining public trust and industry confidence in governance arrangements.

Recommendation 1: A reset of engineering governance to enable a smooth transition of engineering practice in concrete structures

Recognising that decarbonisation depends upon our capability for governing engineering practice through periods of transition, Standards Australia to work with key professional engineering bodies and learned societies – including Engineers Australia (EA), the Australian Academy of Technological Sciences and Engineering (ATSE), and the Concrete Institute of Australia (CIA) – as well as relevant government agencies, to establish shared principles for governing a practice-wide transition to low-carbon binders in Australia. These principles should ensure that enduring values such as safety and durability are maintained while new values are systematically integrated in a way that is responsive to public expectations and responsibly evolves engineering expertise.

2.3 Historical Context: The Engineers’ Committee Method

To understand what best practice engineering governance looks like, we need only consult our history. By the late nineteenth century, engineers had institutionalised the committee method – a voluntary, consensus-driven process of deliberation among technical experts representing the various interests at stake. This mechanism enabled a form of collective self-regulation oriented toward the public interest, particularly where neither markets nor state authorities could establish standard specifications in a timely or credible manner [29]. Long before standards were imposed through law, embedded in contracts, or settled through competition among proprietary systems, these engineering committees had assembled the largely invisible foundations on which networked, modern industries came to depend [30].

While there are various methods for standard-setting, the historical record demonstrates that the engineers’ committee method is central to effective democratic governance of engineering. Democratic engineering governance, in turn, is central to effective democratic governance in a modern industrial society. The Engineers’ Committee Method exhibits “the legitimacy and superiority of decisions hammered out in uninhibited discussions between equals who represent a variety of interests” [31]. Through this process, democratic engineering governance enshrines “the national standards body’s unique role, not just in national economic and technological development, but in Australian civil society and governance” [31].

The smooth and total transition of Australian engineering practice from an imperial system of weights and measures to the international metric system is a key example¹. This transition had lasting economic and geopolitical consequences for our nation, opening the door to international trade and participation outside of the Anglophone sphere of influence. Importantly, it was delivered by the Standards Association of Australia’s (SSA) voluntary,

¹ Notably, the Australian experience of metrication was a unique success when compared to the experience of similar jurisdictions, e.g. the United Kingdom and the United States of America.

consensus-based standard-setting process, which encompassed activities both inside and outside the committee room [31]. As an example of the latter, SAA published (what was openly termed) ‘propaganda’, advancing a narrative for action on metrication, and organised conferences in which the objections of different industries (notably the timber industry) could be aired, and industry leaders cajoled. Importantly, representatives of the engineering profession played a leading role in framing deliberations in the national interest, emphasising the benefits to professional practice, the Australian economy, and society as a whole. The success of the engineers’ committee method in facilitating this transition is proved by its inconspicuousness, with the official history of Standards Australia concluding that “the original determination to ‘bite the bullet’ paid off in a rapid transition that minimised whatever trauma conversion entailed and left little trace in the collective memory” [31].

Understanding the historical context of standard-setting in Australia can help us better frame contemporary efforts to transition Australian engineering practice in line with key public policy objectives. Past successes suggest that we should avoid the temptation of departing from the core values of democratic engineering governance. For example, by seeking decisive, overriding, top-down political intervention to enforce acceptance of change among engineers. Staunch objections from affected parties are inherent to consequential change, and the Engineers’ Committee Method has proven highly effective in managing them. The historical record suggests that contemporary challenges are best met by a return to, rather than short-cutting around, the key principles of the Engineers’ Committee Method, referred to by Ian Stewart, a former Director of the SAA who dedicated his entire 44-year career to this institution, as “the philosophy of standardisation” [31]. Here, Stewart was referring to an appreciation for the role of standardisation in democratic governance, the means by which legitimacy is earned and maintained, and the value of deliberative debate and representative decision-making to this end.

The last section concluded that a particular approach to enacting technical and environmental policy agendas over the last fifty years has reshaped engineering governance by staking out a greater role for non-engineers. This has involved an assertion of legislative authority and public political processes, such as electoral politics. However, we also found in the last section that its external, compliance-driven approach has the effect of constraining the engineering profession’s freedom of action to respond to these externally imposed expectations. This section extends the analysis further by indicating that today’s democratic *public* governance, in the form of public policy and legislative instruments, has encroached on an earlier, reliable mechanism for democratic *engineering* governance in the form of the Engineers’ Committee Method. Revisiting and restoring the values of democratic engineering governance – as an indispensable pillar of governance in a modern, industrial society – can offer a proven, alternative pathway for achieving today’s public policy objectives.

Historical Context: Key Takeaways

The history of standard-setting in Australia and beyond suggests that:

1. The Engineers' Committee Method has proven to be highly effective in enabling past transitions across Australian industry (e.g. conversion from imperial to metric system).
2. This method of democratic engineering governance offers a proven, best practice approach to resolving the tensions and trepidations inherent to transitions.
3. Challenges in forming consensus during transitions require more, rather than less, democratic engineering governance, returning to the first principles of voluntary, consensus-based standard-setting, and cultivating the values and culture this entails.

Recommendation 2: Reaffirming core values of democratic engineering governance

It is recommended that the core values underpinning democratic engineering governance be renewed and reaffirmed in standard-setting contexts for emerging engineering products and practices such as low-carbon concrete structures. These values include broad and legitimate representation, open and transparent dialogue, and constructive deliberation in the public interest.

To give practical effect to these values, it is recommended that:

1. Standard-setting forums include balanced representation of relevant stakeholder interests, including both traditionally 'technical' and 'non-technical' interests. For example, this may include engineers with expertise in sustainability assessment and climate policy and thus capable of representing these emerging public policy objectives in engineering standard-setting.
2. Principal decision-makers and committee members to be selected through a transparent process that establishes them as legitimate representatives with the standing and experience to effectively articulate, negotiate, and compromise on behalf of their stakeholder group.
3. Clear delegations of authority between principal decision-makers and committee members are to be established at the outset, enabling timely escalation where consensus cannot be reached at the committee level.
4. Forums are chaired by competent and respected individuals who facilitate deliberations in the public interest and in accordance with democratic, transparent, and consensus-based engineering governance.

2.4 Political Context: Engineering Leadership for Engineering Governance

Reaffirming the core values of democratic engineering governance is, in itself, manifestly insufficient to deliver transitions. There remains a need for engineers who can embody such values and demonstrate a far greater responsiveness to emerging public policy priorities. Engineers who can grasp the public dimensions of their technical work and are both self-motivated and equipped to act on public policy priorities are an essential missing piece to bringing the core principles of the Engineers' Committee Method to life. It calls for engineering leadership for engineering governance with a focus on “the philosophy of standardisation and its significance for society at large” [31]. The lack thereof represents a gap in both the implementation of the Engineers' Committee Method, embodied in Standards Australia's formal processes, and public policy implementation over the last five decades via a top-down, compliance-based approach.

The significance of engineering leadership becomes clearer when understood in the context of the modern political order. ‘Technocracy’, or rule by experts, is commonly considered a defining characteristic of the modern political order by political theorists. This characteristic describes how authority is often wielded not by the state (or government) – as is often presumed – but rather by experts, particularly in areas such as standard-setting and other technically specialised domains [32]. These domains are increasingly understood as sites of “extrastatecraft” [33], where legitimacy derives primarily from expert authority – grounded in the power to define and enforce what counts as expert knowledge – rather than from traditional state authority, which rests on the formal power to legislate, implement, and enforce the law.

For these reasons, the authority to define standards for engineering practice – and, by extension, for the industries that rely upon it – ultimately resides with the engineering profession itself. That authority is exercised through expertise, which differentiates professional engineers from non-experts and grants them public standing via their employment of specialised knowledge to collective needs [34]. As a consequence, engineers have been responsible for what have been described as some of the most consequential decisions of the past half-century [35]. Moreover, and somewhat paradoxically, state intervention may, in some cases, obstruct efforts toward standardisation, even where private demand is strong and the anticipated public benefits are clear [36].

The nuances of governance arrangements in a modern industrial society suggest a greater role for engineering leadership than is perhaps recognised by most engineers and non-engineers alike. The political context of standard-setting in Australia outlined here offers a useful prism through which to comprehend what is perceived by some as a conservative and lacklustre response by engineering policymakers to a broadening set of public policy aims. Namely, such responses can

be understood as the result of what has been termed a collective “amnesia” [37] among engineers and their professional associations regarding their key role in standard-setting, both in theory and in practice.

Standards Australia’s history makes clear its origins and development as a political project of Australian engineers. In its origins, it is a part of the broader political movement of internationalism post-WWI:

“ACESA [the Australian Commonwealth Engineering Standards Association] was born the creature of the engineering profession, which, in the intoxicating spirit of the early twenties, was a cosmopolitan fraternity with an almost messianic conception of itself and the world it was in the process of building. It flew on the wings of internationalism (symbolised by the League of Nations) that the world embraced in reaction to the horrors of the First World War, and on those of what economic historians call the second industrial revolution.” [31].

In its development, Standards Australia was led by engineers with a big picture understanding of the role of the Australian engineering profession in the broader Australian project. Initially, this was framed in terms of the post-Federation focus on developing basic national infrastructure such as railways. In fact, it was the group of public railway developers, the Interstate Conference of Railway Commissioners, who initiated the formal development of a standard national specification for Portland cement². Later, ACESA/SAA assumed a leading, proactive role in both formulating and implementing the profession’s contribution to the war effort. Notably, this involved proactively conceiving, strategising, deciding, and organising the development of an industrial base characterised by precision engineering and mass-production methods. Thus, in the Australia story, engineers and their standard-setting body were typically ahead of, rather than behind, the curve:

“The peculiarities of Australia’s own development into the front-rank western society it is today cast its peak standards body into the role of socio-economic outrider.” [31]

Post-WWII, SAA adopted an additional leadership role: quality control through statistical methods. This effort went far beyond the formalities of the committee process. SAA recognised a role for itself as having “a definite responsibility to initiate the campaign in Australia for the adoption of the technique of statistical quality control as set out in the Australian Standards” [31]. Its leadership team anticipated that this campaign would last until

² “ACESA’s substantive work began with a number of requests from public authorities to develop specifications. For instance, the Interstate Conference of Railway Commissioners wanted a specification for Portland cement, including sampling, testing on a number of criteria, packing, marking, delivery and inspection.” [31]

it “took root”, with such indicators as “training in its use” becoming “a normal part of the curriculum of technical colleges and university engineering faculties” [31].

Thus, in both theory and practice, nation-building standard-setting calls for engineering leadership. As outlined in political theory, the leadership of the engineering profession is inescapably called upon to govern engineering expertise in a modern industrial society. And, as illustrated in the history of standard-setting in Australia, this modern industrial society owes its creation in part to the leadership role of our national standards body – as a vehicle for individuals and groups with a clear vision for change in the engineering profession and industry more broadly. Recalling and restoring this legacy of leadership by the engineering profession is essential for a meaningful engineering response to emerging public policy objectives.

Key Takeaways: Political Context
1. Owing to their expert authority, the engineering profession’s leadership is an inescapable and essential feature of the particular governance-by-expert arrangements for modern, industrial societies. 2. Engineering leadership is essential to bridging tensions between technical considerations and public policy imperatives in the course of transitions of practice. 3. Engineering leadership requires the ability to craft a vision for the future of Australian engineering that delivers national economic and social advancement. This entails the capability to make decisions and take risks with significant economic and social implications.

2.5 Practice Context: What Makes a Standard a Standard

Because engineering leadership is ultimately realised in the context of engineering practice, we now turn to examine what the notion of ‘standards as a barrier’ means in a practice context. We find that, in practice, the term ‘standard’ is often used to refer not only to formal standards documents, but to the broader set of normative rules that bring order and consistency to the coordinated activities of multiple actors. Accordingly, what is commonly understood by the term ‘standards’ extends well beyond Standards Australia publications to include the full range of explicit and tacit rules that are understood, accepted, and enacted as standards of practice. These may include, among other things, state- and territory-based specifications, internal organisational cultures and traditions, and the routines and habits acquired through professional training and experience.

In the broader sense of the term, ‘standards’ perform important work simply by pinning down certain aspects of practice, thereby establishing the shared understanding that underpins trust and confidence in conducting activities with others. Furthermore, the normative power of ‘standards’ is fundamentally derived not solely from their legislative or contractual backing but more importantly from their usefulness, consistency, and legitimacy in the estimation of those who accept and make use of this common system of rules. These context-specific insights into what makes a standard a standard have two immediate implications for our consideration of ‘standards as a barrier’.

Firstly, prescriptive requirements (‘recipes’) perform an essential function in complex, modern industries. In this context, they are handy, practical, trusted, and agreed-upon shortcuts that help enrol users in predictable, coordinated, and universal systems of rules that drive investment confidence and economic productivity. It is acknowledged that, in an innovation context, they can be seen as arbitrary, sub-optimal, and contingent rules that constitute a systematically entrenched set of hurdles, discouraging both experimentation and widespread adoption of new approaches for all but the most motivated and well-resourced. The temptation here is to address this situation, framed as prescriptive standards being a barrier to innovation, by pursuing performance-based standards. However, establishing a standard (i.e., in the broad sense of a system of rules widely adopted in practice) ultimately requires developing useful prescriptive standards (‘recipes’ or ‘short cuts’) grounded in the realities of everyday engineering. In other words, the prescriptive nature of standards is essential to their function and the fundamental reason for their de facto mandatory (and thus widespread) adoption.

Secondly, the prescriptive nature of standards also renders them as a black box whose amendment involves contestation, insight, experience, and risk. Changing long-held prescriptive standards – whose contents are written into agreements, baked into investment decisions, and embodied in habits, language, and beliefs – as circumstances change is a challenge intrinsic to standard-setting. Changing standards of practice – in real terms, in addition to ‘on paper’ – requires no less than dialogue and consensus. It is one reason why Stewart [31] cautions against “*displacing committee work in favour of standards written by isolated boffins or bureaucrats*”.

However, at the subnational (state and territory) level, where most engineering work is effectively governed in Australia and useful prescriptive standards grounded in everyday engineering are most likely to arise, standard-setting processes can lack the transparency and robustness envisaged by Stewart and reflected in Standards Australia’s formal national arrangements. Instead, subnational standard-setting may reflect an engineering project culture dominated by adversarial, rather than collaborative, contracting that allocates risk in ways that discourage deviations from business-as-usual for each party involved. This can render

subnational standard-setting opaque and unaccountable – at the sole discretion of the appointed engineer-policymaker – preventing the dialogue and consensus-building required for smooth transitions of practice.

While collaborative contracting may not be practical in all instances, the Engineers' Committee Method can offer a ready-made format for collaboration. Partial steps toward the latter have been attempted, such as when engineer-policymakers (e.g. contract and specification owners) lead the development or alteration of specifications outside of a project context. This is sometimes conducted in collaboration with technical consultants and/or academics, and involves consultation with key industry stakeholders. Nevertheless, they can fall short of the principles of voluntary, consensus-based standard-setting and the robustness of the Standards Australia national approach.

Recommendation 3: Introduce the engineers' committee method to standard-setting at the sub-national level

It is recommended that greater emphasis be placed on transparent, nationally coordinated, voluntary, committee-based standard-setting processes to better share emerging evidence and practices. This could include extending or adapting Standards Australia's model of standards development, grounded in the engineers' committee method, to subnational contexts for the purposes of enabling transitions of practice. Subnational standard-setting would continue to be guided by nationally consistent, high-level objectives and work toward national harmonisation via the existing Standards Australia mechanisms. Such an approach would combine the benefits of practice-led standard-setting, conducted from sites of engineering practice, with the strengths of Standards Australia's consensus-based, voluntary standards process.

2.6 Proposed Problem Definition: A Transition of Practice

The preceding analysis has illustrated how Australia's industry and economy expanded during the twentieth century, driven largely by the Engineers' Committee Method and its Australian leaders and advocates. United by a vision of a modern industrial system enabled by a shared framework of rules and definitions, codified through published standard specifications, this standardisation movement established the foundational compact that underpins today's mature engineering practice in concrete structures. We have also outlined a compliance-based regulatory approach that gained traction in the last five decades, which sought to expand the expectations and aims of engineering work and underpins today's complex regulatory structure for buildings, infrastructure, and industry.

We have argued that the public policy objective of decarbonisation points to the need for a new compact: one that involves agreeing on a revised set of rules for an evolving practice, potentially developed and negotiated in Australia and capable of being applied internationally. Such a compact would be expected to provide an acceptable, desirable, and practicable format for delivering on both traditional and emerging aims of engineering work.

By situating decarbonisation and standard-setting in their relevant, non-technical contexts, we have arrived at a more substantive and productive problem definition. Namely, we have reframed the problem as *enabling a transition of practice*, thereby addressing the systemic barriers to the aim of *accelerating the adoption of new products*. Rather than focusing solely on gaps in mechanisms to support the adoption of new products and technologies – such as standards, validation methods, or education – we have sought to direct attention to a more fundamental issue: the absence of mechanisms that enable reaching broad, meaningful consensus on the form and practical operation of engineering practice for concrete structures in a post-transition context. The absence of such mechanisms limits the ability to translate intent into practice both rapidly and legitimately.

This shift in framing or problem definition is both substantive and productive. To date, reductions in greenhouse gas emissions associated with concrete structures have largely come from design and construction efficiency improvements and the use of SCMs. With a practice-based problem definition, we can more substantively understand these actions as incremental improvements within the framework of an existing set of mature rules for the practice of concrete structures in Australia. The current favoured strategy of researching, designing, and marketing low-carbon concrete as a drop-in replacement for OPC concrete has been modest in its effectiveness, as it does not require significant changes to the existing, mature system of rules. On the other hand, outside-the-box thinking on alternative binder systems struggles under the drop-in substitution strategy. Instead, it requires a *practice transition strategy* for the simultaneous, coordinated, and participatory reconfiguration of construction, design, and materials production, amounting to a new paradigm or system of rules.

The proposed practice framing is timely, given that the current drop-in strategy *has reached its practical limits* and will deliver emissions reductions that fall well short of a net-zero outcome in Australia and globally. Further progress towards net zero for concrete structures, therefore, depends either on external abatement measures or on a more fundamental transition of this mature practice to a new paradigm. In this context, the proposed problem definition represents an option for the next stage of decarbonisation: a coordinated transition of an established system of technical knowledge, infrastructure, contracts, and professional practice from one set of fundamentals to another. It offers a way to think through how new and existing materials,

technologies, skills, and ways of working might be combined into a new configuration capable of operating at scale.

The direction of such a paradigmatic transition is understandably contested, with competing visions and narratives that will eventually require collective decision-making to reach closure and consensus, allowing us to move beyond talk and into action. An example of these competing paradigms in the public domain is the set of futures outlined in the VDZ pathway [10] and the BZE pathway [38]. The former envisions continuing the OPC paradigm, whereas the latter envisions transitioning to an alternative binder paradigm. Reaching a broad consensus on post-transition practices for concrete structures requires resolving these ultimately incommensurable visions within the community of practice about what it considers a plausible and desirable future. It is not the intention of this report to advise on the appropriate outcome. Rather, the key takeaways and recommendations of this chapter are about *enabling processes* for a rapid *and* legitimate transition. They are intended to highlight and address shortcomings in our current engineering governance mechanisms. Addressing these gaps is key to enabling a meaningful, legitimate consensus on what a desirable and plausible future entails for this community of practice and the Australian public more broadly.

Recommendation 4: Facilitate a practice-wide consensus and coalition for the next stage of decarbonisation

Build a practice-wide consensus and coalition for the next stage of decarbonisation of concrete structures in Australia, through collective, representative deliberation on what a plausible and desirable future would look like and how a post-transition practice would operate. This should involve renewing engineering governance arrangements, reaffirming the core values of democratic engineering governance, strengthening engineering leadership, and extending the Engineers' Committee Method to subnational settings.

Standards Australia is well placed to facilitate this consensus-building effort, given its institutional role and history in engineering standardisation. As with the establishment of the national standards system, success will depend on the active support of key professional bodies (e.g., Engineers Australia, the Concrete Institute of Australia, Austroads) and strong leadership within the engineering profession.

3. TECHNOLOGY DIVERSITY, COMPETITION AND SUPPLY-CHAIN EQUITY

3.1 Industry Context and Current Market Practice

The following observations are drawn from discussions by the lead author with professionals from key industries, including large and medium-sized producers, as well as a representative cross-section of asset owners.

All tier-one cement and concrete suppliers in Australia, along with many mid-scale producers, currently offer low-carbon concrete products that span established and emerging technologies. High levels of cement replacement have been demonstrated, including clinker replacement levels of 65 per cent or greater in blended cement binders and up to 100 per cent replacement in geopolymer binders. However, these levels are not representative of typical market practice. In mainstream applications, cement replacement levels typically range from 30–50 per cent, with some smaller suppliers constrained to around 20 per cent due to material availability, technical capability, and market conditions. The predominant technologies supporting these outcomes include conventional supplementary cementitious materials such as fly ash (FA) and ground granulated blast furnace slag (GGBFS), alkali-activated binder systems, and, to a more limited extent, geopolymer concrete.

One of the earliest Australian examples of high-volume cement replacement using supplementary cementitious materials is the Pixel Building in Melbourne, illustrated in Figure 2. Completed in 2010, the project utilised a proprietary concrete mix known as Pixelcrete. The 40 MPa concrete achieved a cement replacement level of 60 per cent and incorporated 100 per cent reclaimed and recycled aggregates [39].

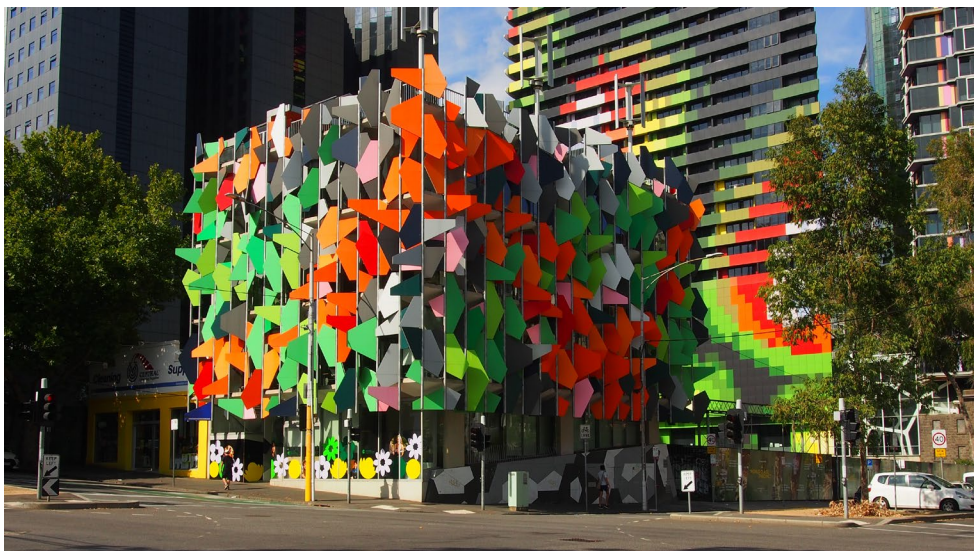


Fig. 2. Pixel Building, Melbourne – completed in 2010, incorporating 60 per cent cement replacement.

Since then, Cement Australia, Rocla, Zeobond, Wagners, and others have explored or developed geopolymers concrete solutions, although not all are currently commercially available. Other suppliers, such as Boral, have focused on alkali-activated binder systems (e.g., Envisia), while Adelaide Brighton has developed GL (limestone) cements blended with high levels of supplementary cementitious materials to reduce carbon intensity. This list is not exhaustive, nor does it imply any preference for one supplier or product over another; a wide range of low-carbon binder products is available from numerous suppliers across the market.

3.2 Supply-Chain and Technology Considerations

The commercial viability of low-carbon concrete products is strongly influenced by supply-chain conditions. Critical factors include transport costs, with material feasibility differing significantly between domestic and international supply, and access to suitable resources and sites. Brownfield sites generally enable faster deployment, whereas greenfield developments involve longer lead times and higher capital risk, and therefore require a higher level of long-term market certainty.

There is no clear evidence that a single technology or product pathway will provide a rapid, sector-wide solution to decarbonisation of cement-concrete products. Where individual companies hold a competitive advantage in specific technologies – such as calcined clays or geopolymers cements – producers without access to the necessary resources are likely to resist adoption. This is further compounded by supply-chain variability, which constrains competition and hinders broader market adoption.

A range of technological options is either commercially available or under active development. Mature and well-understood approaches include calcined clays, metakaolin, and higher substitution rates of conventional supplementary cementitious materials such as GGBFS and fly ash, potentially combined with a higher-volume replacement of ground limestone powder. Pulverised glass powder and manufactured pozzolans also show potential as cement replacement materials, subject to appropriate chemistry and effective mitigation of risks such as alkali-silica reaction. In certain regions of Australia, there is an emerging interest in using slag derived from lithium mining by-products, such as delithiated beta-spodumene, as a cement replacement; however, this technology remains in early research and development.

Overall, some low-carbon concrete technologies are well developed and approaching commercial maturity, whereas others remain in early development. Achieving meaningful, industry-wide decarbonisation will depend not only on technological readiness but also on the structure and accessibility of supply chains. A critical issue for medium and small suppliers is the concentration or lockup of key material supply chains by larger market participants, which can lead to market inequity and reduced competitiveness. Accordingly, any effective solution

must support a portfolio of technologies that enables fair competition and the scalable adoption of low-carbon concrete solutions across the sector.

3.3 Implications for Standards and Specifications

With respect to the development of standards and technical specifications, requirements should reflect both typical and higher-end cement replacement levels demonstrated in Australian practice. While recognising that very high or full cement replacement is achievable in specific systems, compliance pathways should be aligned with replacement levels that can be delivered reliably across a broad range of suppliers and regions. This approach reduces the risk of inadvertently excluding medium and small producers from compliance.

Government business enterprise infrastructure asset owners and policymakers are conscious of supply-chain constraints and the need for sufficient flexibility to accommodate regional variation and future changes in material properties, availability and supply.

Specification writers are also wary of mechanisms that may facilitate market concentration or the locking-up of critical materials by dominant suppliers. Compliance pathways should be structured to ensure that tier-one, mid-scale and smaller suppliers can participate in the low-carbon concrete market on a competitive, transparent and non-discriminatory basis.

A key challenge for asset owners is managing variability in supplier capability, particularly among smaller producers, in both the availability and consistency of low-carbon concrete products. Developing specifications that meaningfully drive emissions reduction, while setting thresholds that do not unintentionally exclude segments of the industry, remains a critical balancing consideration.

Recommendation 5: Promoting technology neutrality, performance-based, standards and specifications

Standards and regulations need to be developed that promote technology neutrality - performance-based rather than prescriptive, allowing multiple binder technologies and material pathways to comply, provided they meet defined durability, strength, serviceability and safety requirements. This approach avoids favouring specific products or suppliers. It accommodates both mature technologies, such as GGBFS and FA systems, and emerging alternatives, including calcined clays, alkali-activated binders and geopolymer concretes.

Material availability differs significantly by region and over time. Standards should explicitly recognise supply-chain constraints, including access to supplementary cementitious materials, transport distances and site availability. Flexibility should be built into accommodate regional differences and future changes in material supply, including the decline of coal-derived fly ash and the emergence of new by-product streams.

4. AUSTRALIAN STANDARDS AND TECHNICAL SPECIFICATIONS

4.1 Addressing Structural Limitations in the Standards Revision Process

Achieving net-zero greenhouse gas emissions across the global construction sector by 2050 – including cement and concrete – will not happen without a step change in how quickly we align practice with innovation. Codes and standards must respond more rapidly to new knowledge, standardisation of emerging material technologies needs to accelerate, and governments, industry and researchers must work together to define and implement clear pathways for transition. The key elements of this challenge and the required actions are summarised schematically in Figure 3.

The pace of standardisation is slow, with delays of 15+ years common between innovation and inclusion in codes

If the aspiration of net-zero greenhouse emissions across the construction sector globally by 2050, including that of the cement and concrete industry, is to be realised:

- codes and standards need to be more responsive to change;
- standardisation efforts for emerging generations of material technologies must be accelerated; and
- Governments, industry and researchers need to define the pathway for this to happen.

This requires significant commitment and investment in:

- research and low-carbon industries and products;
- clear policy direction by governments; and
- speedy roll-outs of new codes and standards



Fig. 3. Closing the time gap between innovation and adoption.

A significant challenge to the timely adoption of low-carbon concrete is the structural and procedural constraints governing standards revision in Australia. AS 3600 operates on an approximately 8-9-year update cycle, whereas AS 5100.5 may take up to 13 years to complete a full revision³. By comparison, international benchmarks for comparable standards, such as the Canadian CSA A23.1 and CSA S6, and the US ACI 318, operate on a six-year cycle, with ACI releasing interim updates every three years. These predictable intervals support industry

³ It is noted that while the last full revision to AS 5100 Part 5 was 2017 and prior to that 2004, correctional and minor technical amendments may be undertaken at more frequent intervals.

planning, facilitate the timely incorporation of research findings, and reduce uncertainty about when improvements will be implemented.

In the Australian context, the standards development process is complicated by interactions with the National Construction Code (NCC), approval processes overseen by the Australian Building Codes Board (ABCB), and, particularly for AS 5100.5, the broader consultation required with state road and rail authorities and national organisations such as Austroads. These additional layers lengthen the pathway to publication and reduce the standards system's capacity to respond to rapidly evolving material technologies.

Improving responsiveness may be achieved by enabling continual, evolutionary updates to specific provisions – especially those most directly influenced by materials science – rather than relying solely on full codal revisions. Durability provisions, for example, can be refined to reflect advances in material testing methods, provided the changes are supported by validated evidence and do not disrupt broader design principles.

The need for timely updates extends to state and territory-based specifications and their amendment following updates to national standards. This dynamic is illustrated by durability provisions in the specifications of different state road authorities for bridges, which continue to prescribe differing minimum cementitious material contents across state and territory boundaries, despite national consensus achieved in AS 5100.5 (as shown in Table 2). Anecdotally, suppliers and designers view such inconsistencies as among the more frustrating features of the current system. Similar issues are evident in the Building Code of Australia, which combines a common set of provisions with nine jurisdictional schedules reflecting unresolved regulatory differences across the seven states, two territories, and the Commonwealth. Beyond the direct costs associated with such inconsistency, fragmentation slows the pace at which new products are developed, assessed, and adopted across national jurisdictions.

Table 2. Minimum cementitious materials content for C1 for the mainland states.

State Authority	Minimum cementitious content for exposure classification C1 (kg/m ³)	Minimum cementitious content for exposure classification C2 (kg/m ³)
AS5100 Part 5 2017 (Amdt. 3) TfNSW TS 146 (NSW) DIT (ST-SC-S7) South Australia Main Roads Western Australia (Specification 820)	420	420
TMR MRTS70 (Queensland)	450	470
VicRoads SECTION 610 (Victoria)	450-470*	450-470*

Note: * Dependent on the type of structural element

4.2 Prescriptive Clauses within a Performance-Based Design Framework

The manner in which prescriptive clauses are included and written in Australian Standards needs to be treated with care. If we are to move with appropriate haste in bringing new and more sustainable binding materials and aggregates to fruition – including those derived from waste products – prescriptive clauses cannot be, or be perceived as, roadblocks to the introduction of new, low-carbon material solutions. A prominent example of such a perceived limitation is the use of minimum cement contents in many State Road Authority specifications and in AS 5100.5:2017, and the way these clauses are drafted, which may readily be interpreted as mandatory, binder-specific requirements.

Throughout the 1970s and 1980s, durability thinking in Australian concrete practice was dominated by a simple yet powerful idea: if you specified a sufficiently high minimum cement content, you would achieve a dense, strong, durable cover zone and thereby avoid “*concrete cancer*”. This rule-of-thumb approach equated durability with kilograms of cement per cubic metre, rather than with more fundamental parameters such as water–binder ratio, transport properties and exposure class. As a result, early efforts to replace a significant proportion of Portland cement with fly ash were often viewed with suspicion, particularly in structural and marine applications.

The dominant concern at the time was that “too much” fly ash would produce concrete that was slow, weak and vulnerable in its early life. Specifications and codes were written around 28-day strength, with little appreciation of continued strength and microstructural development beyond that age. When this traditional minimum-cement mindset met the reality of slower early-age performance in high-fly-ash mixes, the response in practice was largely conservative: caps on replacement levels and a reluctance to deviate from familiar cement contents believed to “*guarantee*” durability.

At the same time, the industry’s informal language around deterioration further reinforced this conservatism. In Australian usage, “*concrete cancer*” became a catch-all term for cracking, rust staining and spalling associated with reinforcement corrosion and, less commonly, alkali–silica reaction. As high-fly-ash concretes began to appear in real projects, any subsequent distress was easily attributed to “all that fly ash” rather than to cover deficiencies, poor curing, aggressive exposure or detailing issues. There was a perception – sometimes explicit, sometimes implied – that replacing cement with fly ash was linked to concrete cancer, either by diluting the cement or by producing a softer, more porous cover zone.

Material science has since clarified that this perception was, at best, incomplete. For chloride-induced corrosion and ASR, well-designed fly ash concretes are typically more resistant than plain OPC mixes, because the pozzolanic reaction refines the pore structure, lowers

permeability and moderates alkali levels. However, at a given water–binder ratio and strength class, high fly ash contents can increase carbonation rates by consuming portlandite and reducing the pH buffer against CO₂ ingress. In the context of 1980s practice – relatively modest cover, often high w/c, limited curing and a focus on minimum cement content rather than performance – it is easy to see how some high-SCM concretes would have been more prone to carbonation-induced corrosion if other aspects of the specification had not been adjusted.

The underlying mismatch is that the limit state being considered is the durability of concrete, which is fundamentally governed by its microstructure – the connectivity, size, and distribution of pores, microcracks, and reaction products within the cementitious matrix and at the aggregate–paste interface – not by cement content per se. A dense, well-hydrated microstructure with a refined pore network limits the ingress of aggressive agents such as chlorides, carbon dioxide and sulphates, and reduces permeability to water and oxygen, thereby slowing the onset and progression of reinforcement corrosion and other degradation mechanisms. Supplementary cementitious materials, such as fly ash, slag, and silica fume, further improve durability by refining the pore structure and reducing calcium hydroxide content, provided that curing and mix design are appropriate. Conversely, high water–binder ratios, poor curing, or deleterious reactions can lead to a coarser, cracked microstructure that facilitates the transport of harmful species, thereby accelerating deterioration. In this way, durability requirements are most effectively controlled by targeting microstructural quality – through water–binder ratio, binder type, curing and compaction – rather than by minimum cement content alone.

Against this backdrop, it is instructive to consider how current clauses are written. For example, AS 5100.5:2017 Amdt 3, Clause 4.4.1 states:

“Members subject to exposure classifications A, B1, B2, C1 and C2 shall –

(a) have minimum specified f'_c , minimum cement material content and maximum water/cement material (W/C) ratio in accordance with Table 4.4.1(A); and

(b) satisfy curing requirements in accordance with Table 4.4.1(B),

unless otherwise approved by the relevant authority.”

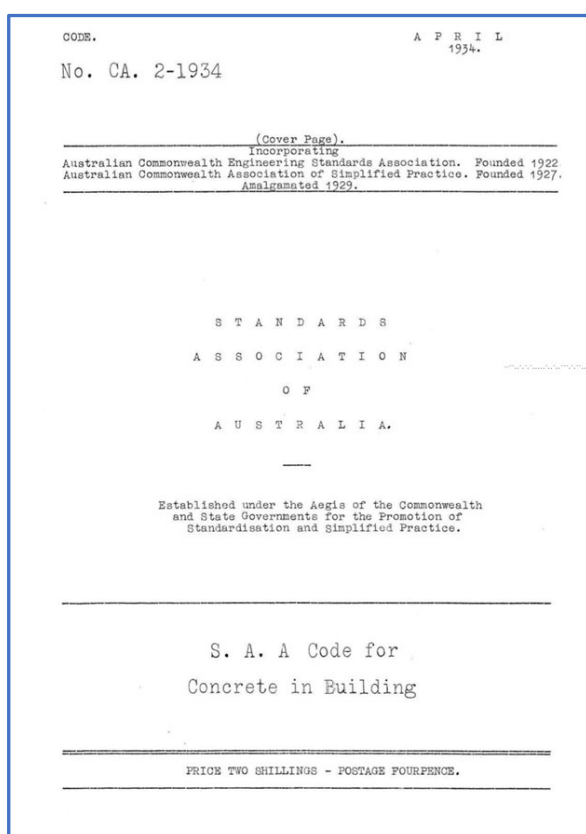
How might a reader interpret this? Is the intent of the clause apparent from its structure? The limit state(s) being assessed – carbonation and ingress of chlorides – are not explicitly identified. Instead, maximum W/C and minimum cement content are presented as deemed proxies for satisfying the durability limit state. The clause is also readily read as a mandatory prescription, rather than as one possible deemed-to-satisfy path within a broader performance-based framework.

An alternative way of writing such a clause, emphasising performance, is illustrated in SA TS 199:2023, where performance requirements are set out first, followed by any deemed-to-satisfy criteria. Such an approach identifies the performance criteria for acceptance – without being binder dependent – and then lists binder-dependent provisions that can be confidently expected to meet those criteria.

4.3 Supporting NCC Performance Pathway through Development of Performance-Based Technical Specifications

The first standard for concrete in buildings, issued in 1934 by the Standards Association of Australia (CA 2–1934), comprised only 59 pages organised into four sections:

- **Materials** (aggregates, storage, water, reinforcement) – three pages;
- **Proportioning, mixing, and construction** (mixing methods, formwork, excavation, transport, placing, curing) – eight pages;
- **Design** (beams, slabs, columns, walls, footings) – 26 pages; and
- **Appendices** (reinforcement sketches, aggregate testing methods, concrete hardness testing) – eight pages.



Since then, the depth and scope of regulatory requirements have expanded considerably in response to advances in technical knowledge and the need for more detailed compliance frameworks. Today, the suite of standards governing the construction of concrete structures exceeds 1900 pages, rising to more than 3000 pages when Volumes 1 and 2 of the BCA are included. The integrated nature and complexity of this system, and its relationship to concrete construction practice, are illustrated in Figure 4.

Given this 90-year evolution, it is neither practical nor efficient to replicate such a comprehensive development pathway for every new binder system or material innovation. A different, more flexible

approach is required. One direction is the development of focused technical specifications that sit alongside the BCA's performance solution pathway; another is the broader use of CodeMark as an alternative means of demonstrating the compliance of specific products.

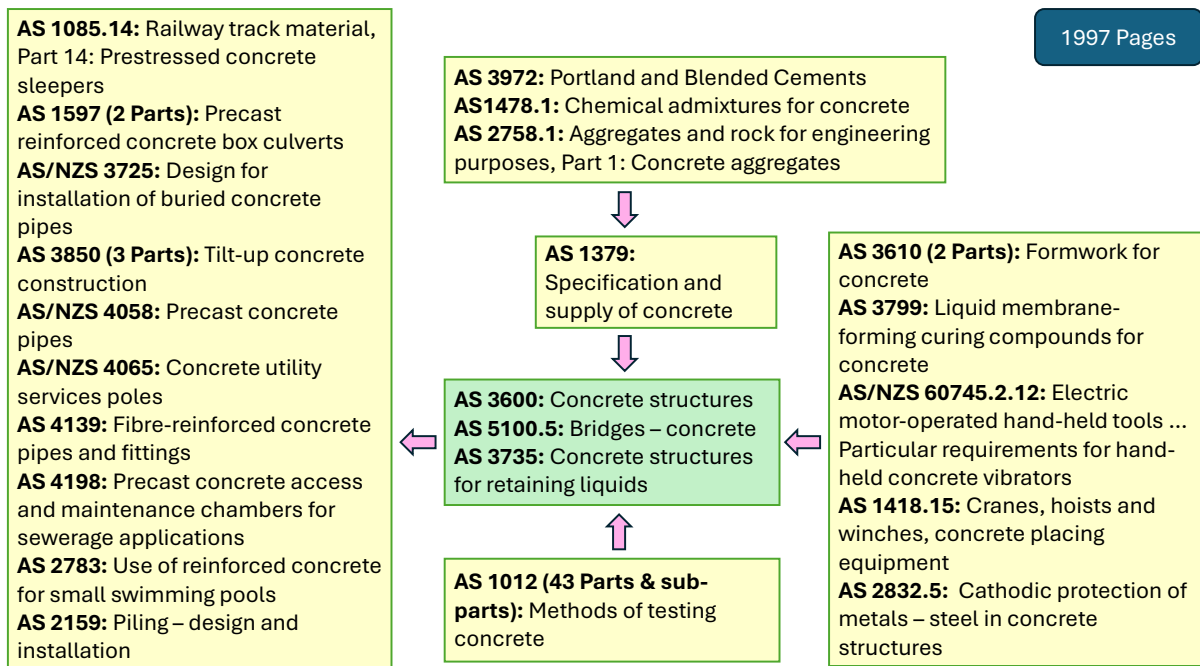


Fig. 4. Map of Australian Standards for design and construction of concrete structures.

SA TS 199 provides a clear example of this type of Standards Australia Technical Specification. As outlined in Aldred and Foster [40], the methodology sets out a structured approach to verifying the performance of geopolymer and alkali-activated binder concretes. Although tailored to those material classes, the framework is inherently general. It can be adapted for any new binder or mix design, including materials derived from industrial by-products or waste streams.

For concrete incorporating alternative binders, these technical specifications provide a systematic approach to establishing the required mechanical and durability performance properties and benchmarking them against established Portland cement-based concrete. This enables designers and practitioners to demonstrate compliance with the NCC/BCA Performance Requirements and creates a recognised pathway for integrating innovative materials into mainstream construction practice.

Recommendation 6: development of technical specifications to support NCC performance solution pathways

Develop and adopt targeted technical specifications – and, where appropriate, assist concrete producers and suppliers in development of CodeMark certification pathways – to provide structured, performance-based mechanisms for demonstrating the compliance of alternative binder concretes and other innovative materials with the NCC.

This approach will enable timely validation of new material systems, support consistent benchmarking against established Portland cement-based concretes, and provide a recognised route for their safe and efficient integration into mainstream construction practice.

Figure 5 illustrates how performance-based technical specifications can be mapped to support the NCC Performance Solution pathway.

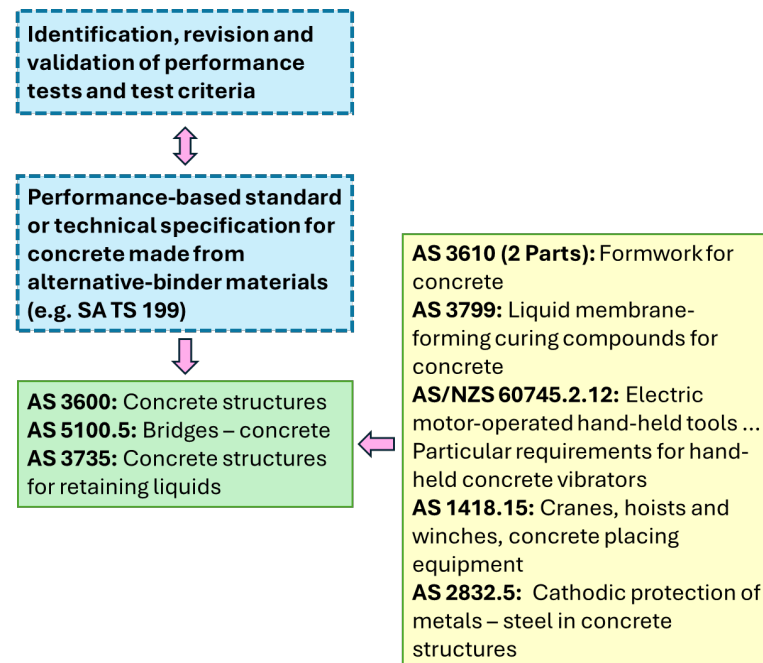


Fig. 5. Map for development of performance-based technical specifications for supporting the NCC Performance Solution pathway.

4.4 Developing a Structured Framework for Test Method Validation

A key barrier to the adoption of low-carbon and alternative binder concretes is the lack of a clear, systematic framework for validating the test methods used to demonstrate compliance with a particular limit state. Industry's caution is well-founded: new materials must be supported by research that is repeatable, technically sound, and verified through appropriate laboratory or field-scale testing. Without a recognised framework for assessing whether a test method is suitable for a particular limit state, standards bodies and practitioners face uncertainty about how to incorporate research findings into practice. The slow pace of standards development, discussed previously, exacerbates this issue.

Durability provides a clear example. Many limit states related to durability and long-term performance depend on accurate assessment of properties such as chloride ingress, sulphate resistance, and permeability. A responsive update pathway is needed that allows newly validated test methods to be incorporated as soon as their reliability is demonstrated, and that provides alternative pathways when reliable accelerated tests are not yet available.

As an illustrative case, consider the adaptation of the ASTM C1202 Rapid Chloride Permeability Test (RCPT) for geopolymer and alkali-activated binder concretes. Chloride

diffusion can be determined using ASTM C1556, “*Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion*”, but this method requires a minimum test duration of 35 days. The RCPT offers a six-hour alternative; however, the standard 60 V protocol was developed for ordinary Portland cement (OPC) concrete and is strongly influenced by the chemistry of alternative binders. As a result, it produces permeability results that are not representative of the relevant limit state associated with chloride ingress.

This challenge exemplifies the type of refinement that a structured validation framework must support. Once it was recognised that the 60 V RCPT yielded misleading indicators for geopolymer and alkali-activated concrete binders, validation studies [41]–[43] demonstrated that a modified 10 V RCPT provides results more consistent with long-duration durability tests, including ponding and chloride diffusion profiling (ASTM C1556). This adapted test method, therefore, potentially offers a reliable accelerated pathway for assessing chloride-related durability performance in non-OPC concretes.

A second example concerns mechanical test methods, including compression, tension, and bond-to-reinforcement testing. Many structural design models – such as those for shear and anchorage – implicitly assume that the tension-to-compression strength ratio remains within a defined range. Suppose an alternative binder concrete exhibits a tension-to-compression relationship that falls within the bounds of established OPC experience. In that case, it can be reasonably inferred that design models grounded in physical–mechanical principles will remain valid, and the associated testing burden will be comparatively modest.

The key question, therefore, is which mechanical tests are necessary to demonstrate the reliability of strength-limit-state models calibrated with OPC concrete data. Further, what additional validation is required when an alternative binder concrete exhibits tension–compression or bond–tension relationships that fall outside the norms observed for conventional OPC concretes?

A test-method validation standard would codify this type of evidence, providing clarity on when:

- an existing test method may be adopted without modification;
- a test method requires adjustment to suit alternative binder chemistries, and/or matrix structures; or
- an alternative (long form) test method that can be used to demonstrate compliance where an accelerated test is not yet available for a particular mix design or limit state.

Such a framework would significantly reduce ambiguity for designers, materials producers, and asset owners, while supporting innovation in material development.

Recommendation 7: Establish a standard for a “*Structured Framework for Test Method Validation for Alternative Binder Concretes*”:

Develop and implement a structured test-method validation framework that defines the suitability of test methods for demonstrating compliance with specific limit states. The framework should:

- identify when existing test methods can be adopted without modification;
- specify how methods may be adjusted for alternative binder chemistries and matrix structures;
- provide approved long-form or alternative test pathways where accelerated methods are not yet validated; and
- enable timely incorporation of newly validated test methods to support durability and other performance limit states.

This framework will reduce ambiguity for practitioners, ensure reliable performance assessment of new materials, and support the safe and efficient adoption of low-carbon and alternative binder concretes.

4.5 What is Cement and the Importance of its Definition

The development of Standards in Australia operates on a consensus-based model, which in most cases provides an effective and timely means of achieving industry-wide agreement. However, there are instances where this process has struggled to deliver outcomes within a reasonable timeframe. One example is the prolonged debate – spanning more than a decade – over the definition of cement in AS 1379. Such discussions have implications far beyond a single standard; they affect AS 5100 Part 5, AS 3600, and all other concrete-related standards, as consistency of definitions across the industry is essential. Decisions of this nature also have practical consequences. For example, in regional areas where batching facilities may have only one silo dedicated to cementitious materials, the adopted definition will influence which products can be stored and used. This, in turn, can affect regional and rural communities' ability to access lower-carbon binder options. These broader impacts merit careful consideration when debating requirements such as minimum limestone content or the classification of blended products.

Public debate about the allowable proportion of limestone in cement and concrete within Australian Standards dates back to the late 1980s and early 1990s, following the introduction of up to 5% mineral additions in AS 3972–1991. The discussion expanded significantly from around 2007, ultimately informing the AS 3972–2010 revision, which increased the permitted limestone content to 7.5%, and prompted further research to support potential increases to approximately 10–12%. Despite this body of work, progress on updating AS 3972 to reflect

emerging scientific evidence appears to have stalled, primarily due to entrenched differences of opinion. At its core, the unresolved question remains: *what does the science indicate is technically justified?*

While economic factors are often raised in these discussions, the primary consideration should remain the technical evidence. Industry will ultimately determine the most efficient and commercially viable pathways; standards must remain grounded in the best available science. The purpose of highlighting these examples is not to assign fault but to illustrate the need for strengthened governance mechanisms to support the timely resolution of issues where debate persists despite substantial technical agreement. In several cases, including the extended discussions on Ductility Class L reinforcement in AS 3600–2009 and AS 5100.5–2017, extensive delays occurred despite the final published requirements differing little from the original committee ballot drafts.

To reduce the likelihood of such delays and to support more efficient committee processes, it is valuable to revisit and reinforce existing dispute-management procedures. In situations where a clear consensus has been reached – albeit without an absolute majority – structured mechanisms such as facilitated mediation could help committees reach decisions more quickly while maintaining transparency and fairness.

5. RELATIONSHIP BETWEEN LOWER CARBON PRODUCTS AND LOW CARBON STRUCTURES AND PROJECTS

5.1 Introduction

In Australia, the treatment of embodied carbon in the building, construction, and infrastructure sectors has shifted over the past two decades from a focus on operational energy to a more explicit, though still partial, representation of whole-of-life GHG impacts. This trajectory followed the development of various sustainability rating tools, which, to date, have been relied upon as the primary instrument for emissions reduction in the building, construction, and infrastructure sectors in Australia. For buildings, Green Star (administered by the Green Building Council of Australia, GBCA) and NABERS (the National Australian Built Environment Rating System) now both include embodied-carbon requirements. For infrastructure, the IS (Infrastructure Sustainability) Rating Scheme, administered by the Infrastructure Sustainability Council (ISC), incorporates material-related embodied impacts, is complemented by state-based schemes developed for lower-capex projects (e.g., TfNSW’s Sustainable Design Guidelines and VIDA’s Transport Infrastructure Decarbonisation Strategy 2024), and is reinforced by State and Commonwealth guidance on embodied-carbon measurement. Together, these schemes provide a de facto national framework for embodied carbon, although each remains a streamlined proxy for whole-of-life assessment and lifecycle thinking.

This section first reviews the development and current status of rating schemes and assessment systems used to quantify embodied carbon and 100-year global warming potential (GWP) for concrete structures in Australia. It then presents several examples comparing different approaches to assessing greenhouse gas (GHG) emissions from new and emerging cementitious materials used in infrastructure.

5.2 Evolution of Building and Infrastructure Rating Tools Addressing Embodied Carbon

5.2.1 Green Star

Green Star was launched in the early 2000s as Australia’s first voluntary sustainability rating scheme for buildings and, more recently, for communities. Early Green Star tools focused primarily on operational performance – including energy, water, and indoor environmental quality – with embodied impacts addressed largely indirectly through prescriptive materials-selection requirements, such as recycled-content and minimum SCM requirements for binders. Explicit consideration of embodied carbon through whole-of-life (cradle-to-grave) assessment emerged in Green Star around 2013–2014, initially via Innovation Challenge pathways, before being formalised as the “*Life Cycle Impacts*” credit in Green Star Design and As Built v1. As

international LCA practice matured and Australian datasets improved, this more explicit LCA-based credit was adopted by some practitioners to quantify and reduce combined embodied and operational (i.e., whole-of-life) impacts relative to a reference case. By 2020, the latest version of the tool, *Green Star Buildings v1.1*, no longer contains a prescriptive pathway and instead adopts a mandatory, performance-based requirement for a 10% reduction in embodied carbon compared to a reference case. Looking ahead, the GBCA has published plans to ratchet up embodied-carbon-related requirements in its rating tools through its *Climate Positive Roadmap for the built environment* [44].

Despite these positive developments, Green Star is fundamentally a credit-based framework that measures relative improvement of a building versus a reference building, rather than absolute alignment with a national carbon budget and target. While it is acknowledged that Green Star Buildings (v1.1) has tightened the definition of a reference building, its ability to send a clear market signal for a step-change in industry settings for investment toward decarbonisation remains constrained by its methodology that favours incremental improvements.

5.2.2 Infrastructure sustainability (IS) rating

For infrastructure, the primary rating tool is the Infrastructure Sustainability (IS) Rating Tool, administered by the Infrastructure Sustainability Council and launched in 2012. The IS Rating provides a framework for assessing and accrediting the sustainability performance of infrastructure projects across planning, design, construction, and operation phases [45]. It addresses embodied carbon through a dedicated materials credit (Mat-1 or Rso-6) and the IS Materials Calculator, which draws on production (A1-A3), construction (A4-A5), and use-stage (B2-B5) impact data from the AusLCI database and EN15804-compliant Environmental Product Declarations (EPDs) [46]. The IS Rating Mat-1 credit rewards projects that reduce their materials-related embodied environmental impacts relative to a hypothetical base case representing business-as-usual approaches. A range of environmental impacts is considered, with climate change impacts (measured by 100-year GWP) weighted at 47.5% of the total, aggregated impact score (IS EnviroPoints). In this context, IS explicitly addresses embodied impacts in infrastructure applications.

On the one hand, the IS Rating's capacity to drive embodied carbon reductions in the infrastructure sector is limited by several structural and methodological factors. Firstly, the inclusion of a range of non-carbon-related environmental impact categories, which together account for greater than 50% of the impact score, means that embodied carbon is only one factor considered when assessing embodied impacts. It differs in this respect from Green Star, which has had a dedicated embodied carbon requirement since 2020. Secondly, the optional status and low weighting of the IS Rating Mat-1/Rso-6 credit (a default of 4.7 points out of 110 available points) mean that embodied carbon reduction is not guaranteed for IS-rated projects.

Again, this differs from Green Star, which, since 2020, has established an embodied carbon requirement as the minimum for any project with a Green Star Buildings rating, regardless of the number of stars achieved.

On the other hand, the IS Rating is similar to Green Star in its fundamental methodology, which relies on measurements of relative improvement (actual versus a base case). This fundamental feature of both rating tools is anchored in their institutional origins as voluntary, opt-in, industry-led schemes. Today, this institutional legacy, without modification, may limit its potential to provide an explicit framework for emissions reductions aligned with state and national targets. Furthermore, a combined limitation of the Green Star and IS Rating tools is their focus on the higher end of the market for building and infrastructure delivery. To address this, several tools have been developed to bring the best practice in sustainable construction, cultivated by Green Star and IS Ratings, to general practice across the Australian construction industry. These include the NABERS rating, BASIX materials index, and TfNSW's Sustainable Design Guidelines.

5.2.3 NABERS and the emergence of embodied carbon for buildings

NABERS historically focused on operational performance (e.g. star ratings for energy and water) rather than embodied carbon. This began to shift in the early 2020s with a 2022 technical report outlining a framework for embodied emissions as a precursor to a rating tool [47].

In late 2024, NABERS launched its Embodied Carbon rating tool for eligible new buildings and partial rebuilds, incorporating measured embodied carbon across materials, transport and construction emissions [48]. Ratings are awarded at practical completion, with projects benchmarked against similar structures, and star ratings applied once sufficient data is available.

While the NABERS tool represents a significant advance over earlier prescriptive materials-replacement requirements, it does not employ LCA methodologies; rather, it uses LCA data. The scope of its LCA data remains narrower than that of a cradle-to-grave LCA. It focuses on upfront emissions (modules A1–A5) for major materials and construction activities, with use-phase and end-of-life stages generally excluded from the scope of the data employed in the rating. Nevertheless, its simplicity is its strength in extending embodied-carbon measurement across the entire Australian construction sector through its integration into the National Construction Code and the Building Energy Efficiency Disclosure Act.

5.2.4 CCAA/GCCA and MECLA low carbon ratings for concrete

In December 2025, Cement Concrete & Aggregates Australia (CCAA) released the Australian Low Carbon Concrete Rating System, derived from the GCCA Global Low Carbon Concrete Rating System [23]. Developed in collaboration with the Global Cement and Concrete

Association (GCCA), the guide adapts international carbon-performance bands for use in Australian concrete mix design, specification, and documentation frameworks and is largely based on established, historically deployed solutions that rely on proven technologies. Building on the GCCA system released internationally in April 2025, and informed through consultation with the Materials and Embodied Carbon Leaders' Alliance (MECLA), which had previously developed and proposed a similar Australian rating framework for concrete [24], and which was updated in December 2025 to align with the CCAA-GCCA ratings [23]. The system defines a method for assigning carbon ratings to Australian concrete mixes supported by verified Environmental Product Declarations (EPDs). The approach aligns with the VDZ decarbonisation pathway identified in [10] and the Australian Government Built Environment Sector Plan [49] and is intended to establish an evidence-based definition of 'low carbon concrete' by introducing performance bands. This helps establish a common language for considering embodied carbon claims during procurement and for setting expectations during specification. It does not, however, establish, in itself, pathways for acceptance of new or emerging low-carbon concrete products or materials.

While the intent of MECLA initiative is to define variations of low carbon concrete through the establishment of performance bands (e.g. low, lower, lowest) and the use of EPD data to demonstrate achievable outcomes – thereby challenging conventional assumptions such as treating 30% fly ash blends as inherently low carbon concrete, there are several important considerations when interpreting the MECLA benchmark evaluations in terms of a current state-of-practice. First, the reported values are national means, and the associated standard deviations are derived from a survey of EPDs sourced from the Low Carbon Materials Hub [50]. The dataset consists of published EPDs largely from larger suppliers and is likely biased towards lower-carbon binder mixes. While many materials suppliers have adopted EPDs in response to incentives from IS and GS Ratings and the procurement policies of specific corporations and agencies, EPD adoption has not yet reached the point of full market coverage, with little commercial incentive to publish higher-emission mixes used on smaller projects where use of rating tools is not common. As a result, the dataset may not be representative of the full spectrum of products placed in the Australian marketplace.

Second, the published mixes predominantly come from larger market participants. While these companies account for a substantial share of supply, a significant proportion of concrete is produced by smaller suppliers whose products are not captured in the evaluation. This further limits the benchmark's representativeness.

Third, the analysis assumes that all mixes are supplied in equal quantities – that is, they are equally weighted. In practice, this assumption is unlikely to hold true. Lower-carbon products in the Australian market are likely supplied in considerably smaller volumes than higher-carbon ones, meaning the benchmark may understate the mean embodied carbon intensity of the concrete actually delivered to the site.

For comparison, the 2025 update, based on 2024 data, for Embodied Carbon of Concrete – Market Benchmark, published by the Lower Carbon Concrete Group (LCCG) in October 2025 in the UK [51], adopts a different approach. The UK LCCG benchmark is determined from data covering the Mineral Products Association (MPA) membership, which represents approximately 56% of the UK market. Notably, 44% of market supply falls outside this dataset and is likely sourced from smaller suppliers with more limited access to supply chains and the technical capabilities required to produce lower-carbon concrete mix designs. It should be noted that the LCCG Market Benchmark is intended to provide a regularly updated snapshot of embodied carbon in concrete available in the UK market, and is designed to operate alongside complementary frameworks such as the Arup Embodied Classification Scheme for Concrete [52]. The former provides a reliable indicator of what is available in the market, while the latter can be used to set targets aligned with decarbonisation pathways. The two are complementary in bringing together market capability with industry-wide goals and objectives.

The UK data – discussed further in the following section – report a 50% fractile nominal embodied carbon of 268 kg CO₂-e/m³. This compares with a national value of 237 kgCO₂-e/m³ for Australia under the MECLA methodology, and lower values of approximately 212–213 kgCO₂-e/m³ for the ACT and South Australia.

In reviewing current practices, it is evident that progress towards lower-carbon concrete and associated infrastructure would benefit significantly from improved data transparency and a recognised single source of truth – ideally led by industry associations. An industry-led approach to market-based, volume-weighted data collection could establish a credible and dynamic reference point for procurement and specification, enabling consistent comparison and measurable decarbonisation progress across the Australian market.

Recommendation 8: Volume-adjusted market benchmark for Australian concrete

Following the UK LCCG Market Benchmark as best practice, it is recommended that the Australian concrete sector establish an industry-led, volume-adjusted market benchmark for the A1–A3 embodied carbon intensity of ready-mixed concrete. The benchmark should target greater representativeness by using volume-weighted supply data covering at least 60–70% of national market volume and be statistically adjusted, for example, through sampling, to account for supply volumes not captured in direct reporting.

It is further recommended that the volume-adjusted market benchmark be used consistently to set progressive project and portfolio-level embodied carbon targets (e.g., in rating schemes and other forms of specification, such as direct specification in contracts) aligned with the Australian government’s sectoral pathways to net zero.

5.2.5 Other data sources for assessing cement and concrete emissions intensity

Other relevant datasets for evaluating carbon intensity in cement and concrete include the EPiC database developed at the University of Melbourne [52], and the Inventory of Carbon & Energy (ICE) Database V4.1, originally developed at the University of Bath in the United Kingdom. The ICE database was first established in 2005 (Version 1.0), although earlier versions, including those prior to Version 1.6 (released in 2008), are no longer readily accessible. The development of the database in its early stages is documented in [54], with the most recent edition published by Circular Ecology in 2025 [55].

The EPiC database, funded by the Australian Research Council, is specifically aligned to Australian conditions and adopts a comprehensive modelling approach. It applies a Path Exchange hybrid life-cycle inventory method, integrating process-based data with environmentally extended input–output analysis to improve completeness of upstream supply chains. This enables the capture of both direct and indirect impacts – including supporting services and capital equipment – and provides cradle-to-gate (A1–A3) embodied energy (MJ) and greenhouse gas emissions (kg CO₂-e) coefficients. This is discussed further below.

ICE provides cradle-to-gate embodied carbon factors for a wide range of cement types and in-situ concrete mixes in the UK and European contexts. It includes CEM I (GP cement) and multiple blended cements with varying clinker substitution rates, as well as strength-class-based concrete estimates modelled on assumed cementitious content per cubic metre. In an Australian context, ICE is best understood as a comparative or benchmarking dataset: while production emissions may be broadly similar, differences in electricity grid intensity, kiln fuel mix, transport distances, and the availability of supplementary cementitious materials can lead to divergence from Australian conditions. Nevertheless, ICE remains a useful reference point where project-specific data are incomplete or unavailable.

5.3 Evolving Australian Approaches to Embodied Carbon Measurement

5.3.1 Introduction

Australian guidance has increasingly positioned IS and GBCA tools as reference methodologies for decarbonising infrastructure and precinct-scale projects. The 2024 federal technical guide on embodied-carbon measurement for infrastructure identifies the IS Materials Calculator and GBCA's Upfront Carbon Calculator as the primary existing tools for quantifying material-related emissions. It seeks to standardise scopes and definitions to reduce inconsistencies between project estimates [22].

A clear trend is emerging toward greater alignment between infrastructure and building methodologies, and ultimately toward whole-of-life GHG assessment – although this

convergence remains incomplete. Since 2014, Australian rating systems have shifted away from operational energy as a proxy for GHG impacts toward a more explicit representation of embodied carbon. The adoption of tools that properly account for embodied carbon and/or 100-year GWP as more accurate measures of emissions from the product and construction stages [A1–A5] represents a substantial improvement over earlier approaches. It is also increasingly recognised that, as operational emissions continue to fall, embodied carbon will become the dominant emissions source, particularly in infrastructure projects such as roads and bridges, where operational carbon emissions are comparatively minor.

5.3.2 Cradle-to-gate (A1–A3) embodied carbon and embodied energy for typical Australian normal-class ready-mix concretes

This section presents cradle-to-gate (A1–A3) embodied carbon and embodied energy (EE) results for typical Australian normal-class ready-mix concrete, expressed per 1 m³ of material. Embodied carbon is reported as GWP–100 in kg CO₂-e/m³, and embodied energy is reported as total primary energy demand – defined as the sum of renewable primary energy (PERT) and non-renewable primary energy (PENRT) – in GJ/m³. Two mix designs are assessed: a conventional GP blend and an environmental blend comprising 70% GP cement and 30% fly ash (GP/FA 70/30).

For benchmarking, the results are compared with Environmental Product Declarations (EPDs) published by Boral – selected for their comprehensive scope and national coverage – and with values reported in the Environmental Performance in Construction (EPiC) database [52]. Although Boral is used as the primary comparator, EPDs from other major and mid-tier Australian producers, including Holcim, Hanson and Gunlake, were also reviewed and show broadly comparable embodied carbon and energy intensities (see [50]).

The Boral Australia-wide values are derived from the published regional datasets [56] and summarised as simple, unweighted arithmetic means, with minimum–maximum ranges reported across regions. Data coverage comprises 22 regional datasets for GP concrete across NSW/ACT, QLD, SA, VIC and WA, and 21 regional datasets for GP/FA 70/30 concrete across NSW/ACT, QLD, SA and VIC [56].

The results for the 100-year GWP and EE are presented in Table 3 and Table 4, respectively. Consistent with national dataset trends, the GP/FA 70/30 blend exhibits a lower Australia-wide average embodied carbon than GP across all strength grades, with an average reduction of approximately 13–16% – equivalent to around 43–65 kg CO₂-e/m³. For embodied energy, the Australia-wide averages indicate a reduction of approximately 7–11% for the GP/FA mix relative to the GP mix, depending on strength grade.

Table 3. Reference GWP-100 data (A1–A3) for the following examples – average (min–max), kg CO₂-e/m³.

Strength grade (MPa)	Boral (Australia Wide) EPDs		EPiC Database	
	GWP-100: GP Ave (Min-Max)	GWP-100: GP/FA Ave (Min-Max)	GWP-100: GP	GWP-100: GP/FA
20	267 (190–330)	224 (155–307)	328	251
25	294 (218–363)	249 (178–337)	368	279
32	329 (250–421)	278 (203–390)	416	314
40	386 (300–463)	333 (244–424)	497	373
50	483 (375–572)	418 (305–527)	626	467

Table 4. Reference embodied energy (A1–A3, PERT + PENRT) for use in the following examples – in GJ/m³.

Strength grade (MPa)	Boral EPDs [56]		EPiC Database [52]	
	EE: GP Ave (Min-Max)	EE: GP/FA Ave (Min-Max)	EE: GP	EE: GP/FA
20	2.0 (1.3–2.7)	1.7 (1.2–2.6)	2.4	2.0
25	2.1 (1.3–2.9)	1.9 (1.3–2.8)	2.7	2.3
32	2.3 (1.4–3.3)	2.1 (1.5–3.1)	3.0	2.5
40	2.7 (1.4–3.9)	2.4 (1.9–3.4)	3.5	2.9
50	3.3 (1.7–4.7)	3.0 (2.0–4.1)	4.2	3.6

Tables 3 and 4 indicate that EPiC values are systematically higher than the Boral EPD averages. For 100-year GWP, EPiC results are approximately 25% higher for GP mixes and around 12% higher for GP/FA (70/30) blends. For embodied energy, the uplift is approximately 25–30% for GP mixes and around 20% for GP/FA (70/30) blends.

These differences are attributable to the underlying methodological approaches and the use of different datasets. The EPiC database uses a Path Exchange hybrid life-cycle inventory method, integrating process-based datasets with environmentally extended input–output analysis to improve completeness of upstream supply chains. This framework captures both direct and indirect impacts, including supporting services and capital equipment, and reports cradle-to-gate (A1–A3) embodied environmental flow coefficients for energy (MJ) and greenhouse gas emissions (kg CO₂e).

By contrast, manufacturer EPDs developed under EN 15804 follow a process-based LCA methodology with defined cut-off rules, typically excluding capital goods and personnel.

Accordingly, EPiC's hybrid approach, with its broader system boundary, will generally produce higher values than process-based LCA results for otherwise equivalent products.

In terms of datasets, the EPiC database employs process data from AusCLI and ecoinvent, and, for the input-output analysis, from publicly available reports compiled by the Australian government (i.e., the Australian Bureau of Statistics, the Australian Department of Industry, and the Department of the Environment and Energy) for the 2014-2015 financial year. By contrast, EPDs developed under EN 15804 employ detailed, up-to-date EPD owner-specific data (i.e., supplier data) and data from LCA databases that are assessed for geographic, temporal, and technological relevance. These differences in data sources can also lead to lower EPD values than those reported in the EPiC database.

5.3.3 Embodied carbon and embodied energy of Australian GP cement

This section presents cradle-to-gate (A1–A3) embodied carbon and embodied energy (EE) results for Australian general-purpose (GP) cement, expressed on a per-tonne basis. Embodied carbon is reported as GWP-100 in kg CO₂-e per tonne, while embodied energy is reported as total primary energy demand – defined as the sum of renewable primary energy (PERT) and non-renewable primary energy (PENRT) – in GJ per tonne.

The dataset comprises published Environmental Product Declarations (EPDs) from the three major Australian cement producers: Adbri, Cement Australia and Boral. Reported values are taken directly from the A1–A3 modules of those declarations and summarised using simple, unweighted arithmetic statistics.

Across the Australian GP cement EPDs considered, cradle-to-gate embodied carbon results are summarised in Table 5. The lowest reported value corresponds to Adbri Birkenhead GP cement, while the upper bound reflects higher-intensity production sites within the national dataset. The overall range of approximately 331 kg CO₂-e per tonne indicates substantial inter-site variability. This variation reflects differences in kiln efficiency, fuel mix, clinker factor within GP specification limits, electricity grid intensity and overall plant configuration.

Embodied energy is reported in EPDs as total primary energy demand (PERT + PENRT) for modules A1–A3. Although not all GP cement EPDs present energy indicators in an identical tabulated format, the reported totals are consistently on the order of several gigajoules per tonne, reflecting the inherently high thermal energy demand of clinker production. These results are summarised in Table 5 and Figure 6.

As with embodied carbon, embodied energy varies across production sites due to differences in kiln technology, alternative-fuel substitution rates, electricity sourcing, and process efficiency.

For project-specific assessments, site-specific EPD energy indicators should be adopted directly from the relevant product declaration to ensure methodological consistency and accuracy.

In summary, it is important to adopt a sustainability assessment method that aligns with the purpose of the benchmarking activity. For example, the hybrid LCA method is valuable for whole-of-economy decision-making because of its comprehensiveness, while the EPD method is valuable for project-based decision-making, creating competition between suppliers to drive down emissions through procurement and design.

Table 5. Summary statistics of A1–A3 embodied carbon and embodied energy for Australian GP cement production.

Property	100-yr GWP (kg CO ₂ -e/tonne)	Embodied Energy (EE) MJ/tonne
Mean (unweighted)	868	4960
Median	861	4700
Sample Std. Dev.	107	1480
25 %ile value	796	3960
Min–Max	677 – 1009	3220 – 8280

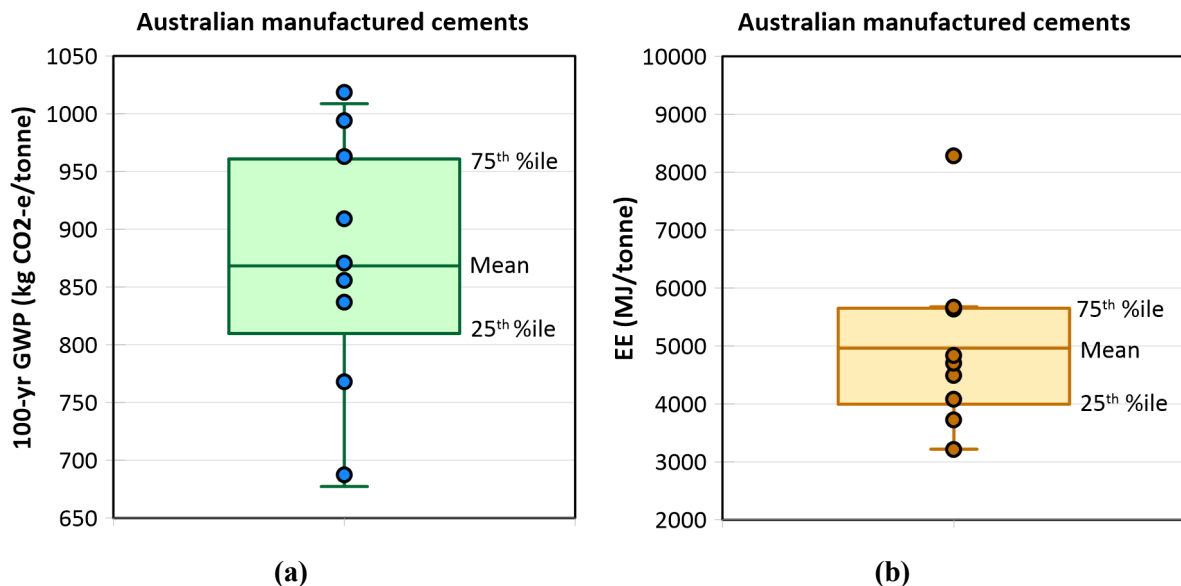


Fig. 6. Statistical distributions of (a) 100-year global warming potential (GWP100) and (b) embodied energy for Australian cements.

5.4 Example 1: Cyclonic Drain Retaining Wall – Comparison of Conventional, Geopolymer and UHPC Structural Forms

5.4.1 Introduction

This example, updated from [57] using current inventory data presented in the previous sections, evaluates the use of high-performance cementitious materials and cement-replacement binders in the sustainable design of a reinforced-concrete retaining wall. The assessment is undertaken within a sustainability-oriented design framework that integrates limit-state design principles with an explicit evaluation of environmental impacts and long-term durability performance.

Two complementary low-carbon strategies are assessed. The first strategy examines material-level substitutions for conventional Portland cement concrete. This includes a moderate-SCM blended cement concrete (BCC) mix comprising 70 per cent general-purpose (GP) cement and 30 per cent fly ash (FA), as well as a high-volume SCM alternative in the form of an alkali-activated binder concrete (AABC) incorporating 70 per cent activated ground granulated blast furnace slag (GGBFS). The second strategy considers ultra-high-performance concrete as a structurally efficient alternative, leveraging its enhanced mechanical properties to reduce material demand.

5.4.2 Project description

The case study examines a retaining wall that forms part of a cyclonic drainage system for a residential development. The wall is approximately 180 m long and 1.35 m high from the top of the drain to the top of the wall, and it retains backfilled soil subjected to a service surcharge of 10 kPa and an ultimate surcharge of 15 kPa. The site is characterised by acid sulphate soil and is assigned an exposure classification of B1 in accordance with AS 3600:2018. The minimum concrete cover is 60 mm at the cast-on-ground base, and 40 mm elsewhere, with a minimum concrete strength of 32 MPa.

Three design scenarios are assessed:

- a cast-in-situ conventional reinforced concrete L-shaped retaining wall using Portland cement concrete;
- an equivalent retaining wall constructed using (i) a moderate SCM replacement for GP cement (30% FA) concrete; and (ii) a high activated-SCM replacement (70% GGBFS); and
- a precast thin-walled retaining system constructed using UHPC.

The configurations are shown in Figure 7.

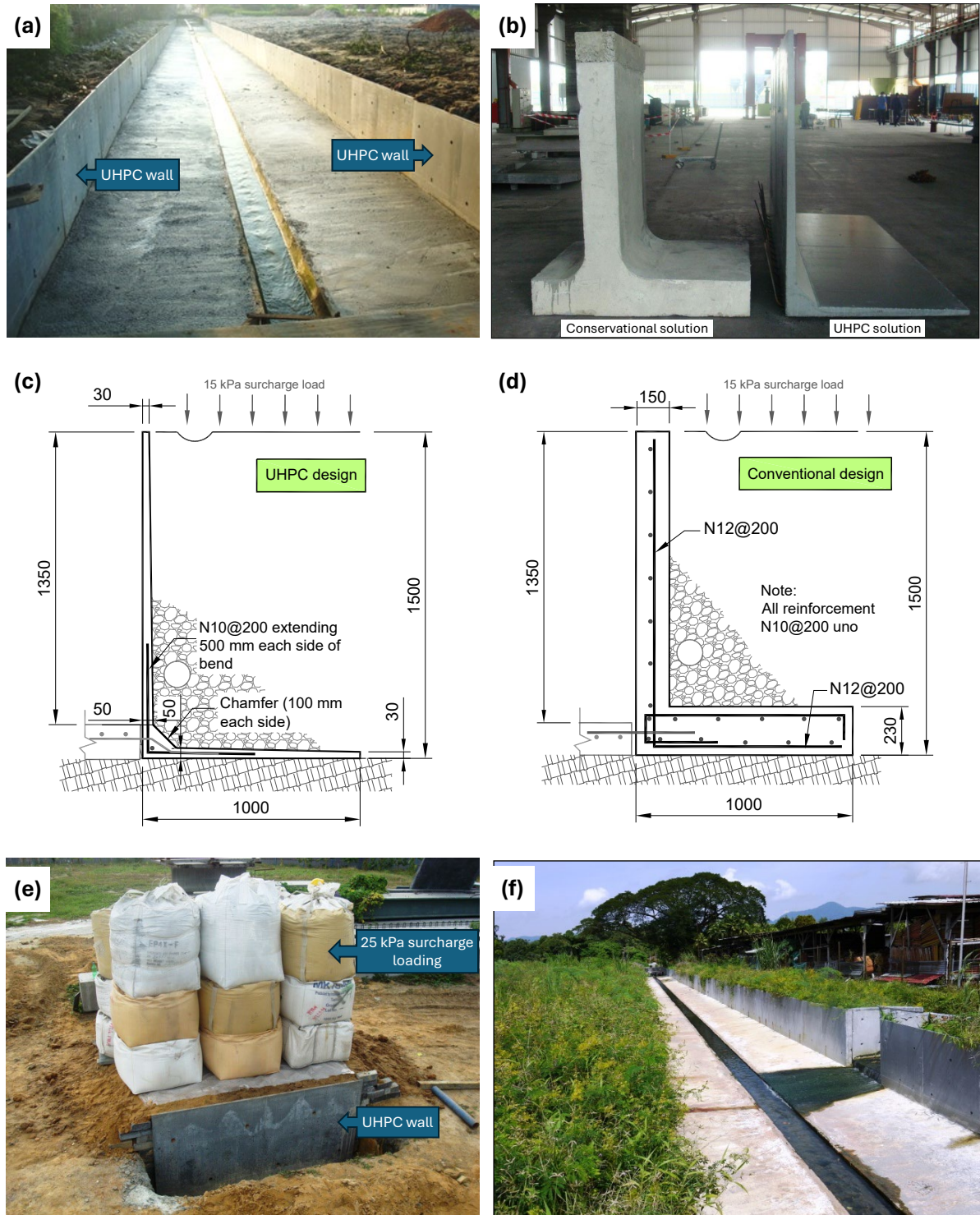


Fig. 7. (a) 90 m long monsoon drain using UHPC retaining wall constructed in Malaysia, (b) comparison of conventional section for cast-in-situ L-shape wall compared to a UHPC precast solution, (c) cross sectional details for conventional precast L-shape retaining wall used in this study, (d) cross sectional details for UHPC retaining wall, (d) load proof test of the UHPC wall back filled and with a 25 kPa surcharge loading; and (f) wall in service, 2-years on (photos courtesy of Dura Technology, Malaysia).

5.4.3 Material characteristics

The performance of retaining walls is governed not only by strength but also by stiffness, crack control, durability and resistance to aggressive environments. UHPC and AABC exhibit material characteristics that differ fundamentally from conventional normal-strength and high-strength concretes [61], [62].

UHPC is a dense, homogenous cementitious composite produced using optimised particle packing, very low water-to-binder ratios, silica fume and high-strength fibres to provide post-cracking ductility [58], [64]. Coarse aggregates are typically omitted or replaced with very fine aggregates to maximise matrix continuity. Heat curing may be employed to accelerate strength development and reduce long-term shrinkage, depending on the mix design and production method. Owing to its high compressive and tensile capacities, UHPC enables substantially thinner structural elements than conventional reinforced concrete. Steel fibres provide crack bridging and post-cracking toughness, allowing partial or complete elimination of conventional reinforcing bars in thin-wall sections [63]. After appropriate curing, UHPC exhibits negligible long-term shrinkage and creep, making it well-suited to slender retaining wall panels where deformation control is critical [61]. Its dense microstructure also provides excellent resistance to carbonation and chloride ingress, directly enhancing durability and reducing maintenance requirements.

From a sustainability perspective, although UHPC may have higher embodied carbon per cubic metre than conventional concrete, its superior mechanical performance enables significant reductions in structural thickness, reinforcement and total material volume. When assessed functionally, this structural efficiency can reduce the retaining wall's overall embodied carbon. The mix design for the UHPC is given in Section 5.4.5 and [57].

Alkali-activated binder concrete is manufactured by alkali activation of aluminosilicate supplementary cementitious materials that are contained within a cementitious matrix – most commonly fly ash and ground granulated blast-furnace slag – using alkaline activator solutions such as sodium hydroxide or sodium silicate. [62], [65]. This process forms a three-dimensional aluminosilicate network and enables high utilisation of industrial by-products. A principal advantage of AABC is its substantially lower carbon footprint relative to Portland cement concrete, owing to the avoidance of clinker production [59] [60]. In addition, AABC exhibits good resistance to sulphates and acids, thereby improving durability in aggressive soil environments [66], [67].

In contrast to UHPC, geopolymers primarily function as a lower-carbon material substitution. Carbon reduction is achieved by lowering embodied emissions per cubic metre of

concrete, while maintaining structural forms and construction methods broadly consistent with conventional practice

5.4.4 Sustainability-focused design framework

Sustainable structural design extends beyond compliance with strength and serviceability requirements. In this example, sustainability is addressed through an integrated framework comprising:

1. Environmental impact assessment (EIC) – embodied energy, CO₂ emissions and 100-year global warming potential (GWP);
2. Design for durability and longevity – to minimise maintenance and life-cycle material consumption;
3. Limit states structural design – serviceability, strength and stability.

This framework enables optimisation of both material selection and structural form for retaining walls while minimising life-cycle environmental impacts.

The UHPC solution employs thin-wall panels with thicknesses of 30–50 mm. The material's high strength and ductility, combined with steel fibre reinforcement, significantly reduce or eliminate the need for conventional reinforcing bars. The resulting wall weighs approximately 260 kg per metre, representing a 75 per cent reduction in self-weight compared with the conventional solution [63]. Thin-panel details and in-service photographs are shown in Figures 7(a) and (c).

The conventional reinforced concrete cast-in-situ wall comprises a footing 230 mm thick and a wall stem 150 mm thick, reinforced with conventional steel bars – representative of standard practice for walls of this height (Figure 7d). The dimensions are selected to ensure robustness under typical construction tolerances. The BCC and AABC walls adopt a geometry similar to the conventional solution but achieve lower embodied carbon through binder substitution.

To confirm the adequacy of the UHPC wall design, a full-scale mock-up was proof-loaded by backfilling to full height and applying an additional surcharge of 25 kPa, representing 67 per cent above the design ultimate load. No structural failure or observable distress was recorded during testing (Figure 7e). The finished wall, two years on, is shown in Figure 7f.

5.4.5 Environmental impact calculation (EIC)

Environmental performance is evaluated using embodied energy (EE, MJ) and 100-year global warming potential (GWP100, kg CO₂e) as primary indicators, enabling consistent inter-material comparison. For conventional reinforced concrete, clinker production associated with

Portland cement is the dominant source of both embodied energy and greenhouse gas emissions, thereby governing the system's overall environmental intensity [68].

The reference case is an N32 concrete incorporating Boral GP cement, with mix parameters given in Table 3. The blended cement concrete (BCC) is also specified at 32 MPa and comprises 70% GP cement and 30% fly ash (FA) by mass of binder. Environmental coefficients are derived from the Boral datasets rather than EPiC values, as the former represent best-practice or near-best-practice manufacturing conditions and therefore provide an upper-bound industry benchmark for performance.

The alkali-activated binder concrete (AABC) reduces environmental intensity primarily by substituting high-clinker cement with lower-carbon precursors, thereby decreasing binder-specific GWP and EE on a per-unit-volume basis. By contrast, ultra-high-performance concrete (UHPC) exhibits substantially higher embodied impacts per cubic metre due to elevated cementitious contents and admixture dosages. However, its superior compressive strength, tensile capacity and durability enable reductions in structural volume, potentially lowering system-level impacts despite higher material-level intensities.

The UHPC mix design comprises:

- 720 kg/m³ GP cement
- 180 kg/m³ silica fume
- 1150 kg/m³ sand
- 137 kg/m³ steel fibres
- 144 L/m³ water
- 40 L/m³ superplasticiser

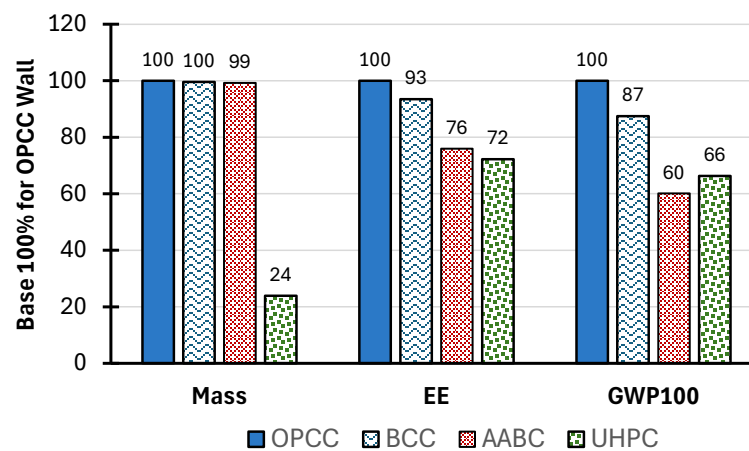
Steam curing is assumed to require 30 litres of diesel per cubic metre, which is incorporated into the embodied impact calculation (EIC). Embodied carbon and energy values for cement are based on the average Australian production intensity (Table 5). Steel fibres contribute 316 kg CO_{2e}/m³ and 2.4 GJ/m³, respectively. The diesel emission and energy factors are set to 2.7 kg CO_{2e}/L and 35.8 MJ/L, respectively, with 30 litres required per cubic metre cast (giving 80.4 kg CO_{2e}/m³ and 1.07 GJ/m³).

The environmental coefficients adopted for the EIC are summarised in Table 6. Scenario-based results for the retaining wall configurations – defined in Figures 7(c) and 7(d) – are compared in Figure 8, allowing assessment of both material-level and system-level environmental performance.

Table 6. Data for an EIC for the retaining wall example.

Property	Units	UHPC (1.75% Steel Fibres)	Grade N32 GPC-C	Grade N32 BCC (30% FA)	Grade N32 AABC (70% GGBFS)	Steel bar Reinf.
Density	kg/m ³	2380	2400	2390	2380	7850
EE	GJ/m ³	8.64	2.3	2.1	1.6	94.8
100-yr GWP	kg CO ₂ -e/m ³	1060	329	278	167	9,580

Note: # Environmental values include the contribution of steel fibres

**Fig. 8.** Comparison of environmental impact calculations per metre length of a 1.53 m-high wall for tropical rainfall drainage.

5.4.6 Performance and environmental impact

The environmental assessment identifies two principal decarbonisation strategies – reducing binder carbon intensity and reducing total material demand through structural efficiency.

Partial substitution of Portland cement with 30% fly ash (FA) yields a modest but consistent improvement over the GPC-C baseline, reducing embodied energy by 7% and GWP100 by 13%. The reduction in GWP reflects the lower clinker factor and associated decrease in process emissions. More substantial gains are observed for the AABC retaining wall, which achieves 24% lower embodied energy and 40% lower GWP relative to the conventional solution. This represents the lowest carbon intensity among the alternatives considered and is primarily attributable to extensive replacement of Portland cement with GGBFS, which significantly reduces binder-related emissions.

In contrast, the UHPC solution delivers impact reductions through structural optimisation rather than binder substitution. Although its embodied carbon per cubic metre is substantially

higher due to the increased cementitious content, its superior mechanical performance enables significant reductions in total concrete volume. At the system level, this results in 28% reductions in embodied energy and 34% in 100-year GWP relative to the baseline design, as shown in Figure 8. It is to be noted that the comparison between the UHPC and conventional designs is sensitive to the assumed embodied energy and GWP values for steel reinforcement relative to those adopted for fibres, as well as to the origin and production route of the steel.

Overall, the results demonstrate that comparable system-level environmental benefits can be achieved through fundamentally different mechanisms – either by lowering binder carbon intensity or by exploiting material efficiency to reduce total volume.

5.4.7 Conclusions from example 1

This example demonstrates two complementary low-carbon strategies for the design of reinforced concrete retaining walls. AABC concrete can be a lower-carbon material alternative, reducing embodied carbon emissions by replacing clinker-based cement with alkali-activated industrial by-products. UHPC, despite a higher carbon footprint per unit volume, is a lower-carbon structural solution, achieving emissions reductions through enhanced structural efficiency and substantial reductions in material volume.

5.5 Example 2: Infrastructure of Different Structural Forms for a 40 metre Long Prestressed Concrete Girder Bridge

5.5.1 Introduction

This second example extends the comparative assessment of low-carbon concrete technologies to a 40 m-long (39.5 m-span) road bridge. As in the previous retaining wall study, two principal decarbonisation pathways are examined:

- Reduction in binder-related emissions through clinker substitution or alkali-activation.
- Reduction in total material demand through structural efficiency enabled by higher-performance materials.

Five superstructure solutions are evaluated against an Ordinary Portland Cement Concrete (OPCC) benchmark: a blended cement concrete (BCC), an alkali-activated binder concrete (AABC) with 60-70% GGBFS and 30% cement, a standard UHPC using average Australian environmental data, and an eco-UHPC incorporating lower-percentile cement impacts, reduced fibre impacts and bio-diesel curing.

The assessment boundary is limited to the superstructure, and all results are presented relative to the OPCC solution, which is normalised to 100%.

5.5.2 Project description

As detailed above, the case study consists of a 39.5 metre-span simply supported bridge. The deck width is 15 metres. The bridge elevation and cross-sections are shown in Figures 9 and 10, respectively.

The super-T superstructure comprises precast girders acting compositely with a 200 mm in-situ reinforced concrete deck slab. The concrete strength in the super-T girders is 50 MPa for the OPCC and BCC designs, and 65 MPa for the AABC design to satisfy durability requirements, recognising the higher carbonation rates associated with concretes containing high volumes of GGBFS at equivalent strength. The concrete strength for the deck slab and ancillary elements is 40 MPa.

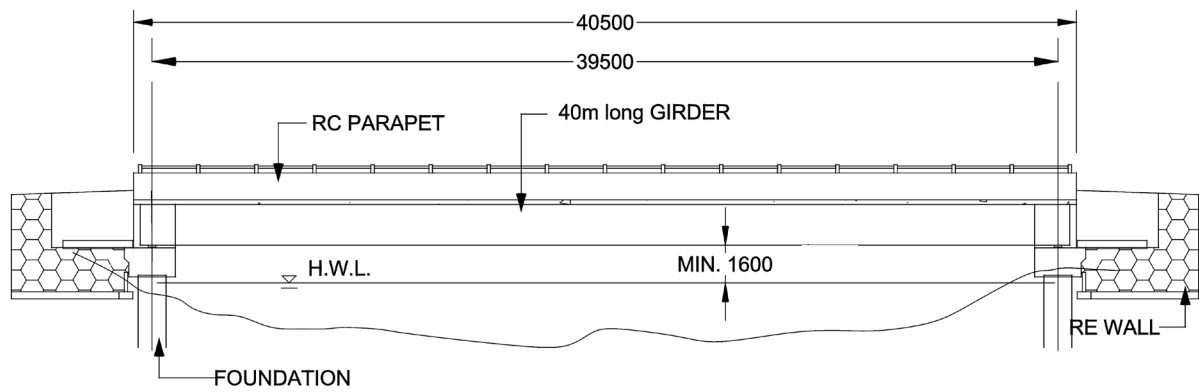


Fig. 9. Elevation (top) of a 40 m prestressed concrete road bridge (clear span 39.5 m); comparable design to the Sungai Liawan Bridge, Malaysia (bottom). Photo courtesy of Dr Yen Lei Voo, Dura Technology.

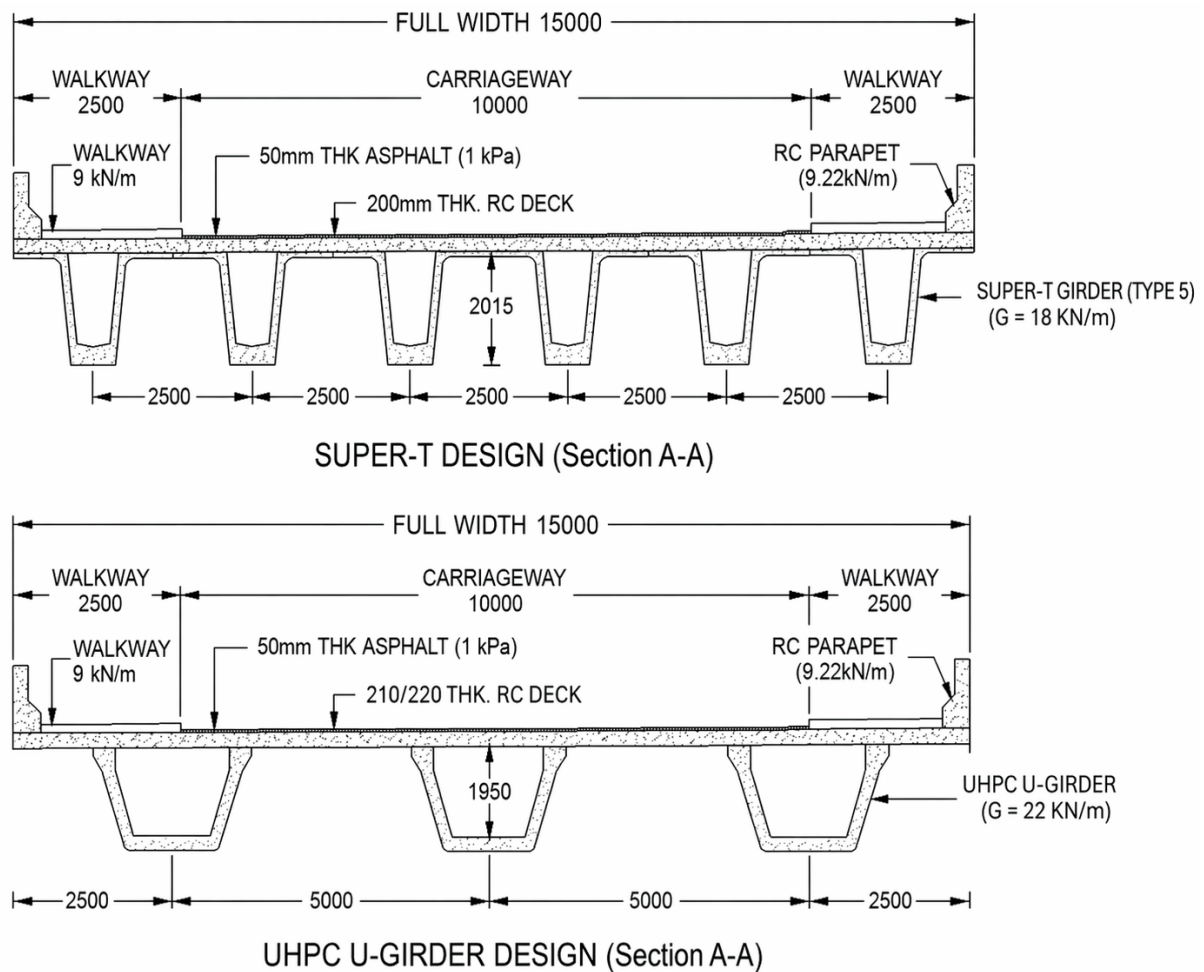


Fig. 10. Cross sections for prestressed concrete Super-T girder design (top) and UHPC U-girder design (bottom).

The slab contains four layers of reinforcement – two top layers (longitudinal and transverse) and two bottom layers – with a total reinforcement ratio of 1.5%. The deck is surfaced with a 50 mm asphalt wearing course. The bridge is located in a coastal environment and is designed for a 100-year service life (exposure classification B2).

A similar configuration is adopted for the UHPC girder solution; however, the deck slab strength is increased from 40 MPa to 50 MPa, and the slab thickness is increased to meet durability requirements associated with exposure of the slab soffit. Specifically, the slab depth is increased by 10 mm for the BCC design (to 210 mm) and by 20 mm for the AABC design (to 220 mm), providing additional cover to accommodate the higher rate of concrete carbonation and to protect the underside reinforcement. In the baseline super-T arrangement, the girder flanges protect the deck soffit, whereas in the UHPC U-girder configuration, the underside of the slab is directly exposed to the atmosphere.

The Australian bridge design standard, AS 5100.5–2018, specifies that structural elements exposed to tidal or splash environments or subject to sea spray must have a minimum

cementitious material content of 420 kg/m³. A compliant baseline mix requires at least 96% GP cement and 4% amorphous silica. In this study, the OPCC solution is a 95% GP cement-5% silica fume blend. The BCC mix comprises 70% GP cement and 30% silica fume, exceeding the Standard's minimum 25% fly ash requirement for blended systems. The alkali-activated binder concrete (AABC) incorporates a 70% GGBFS substitution, which represents the upper limit currently permitted under AS 5100.5–2018.

For the OPCC, BCC and AABC alternatives, six precast pre-tensioned super-tee girders are required, with a dead load (G) of 18 kN/m each (total 108 kN/m). These girders utilise conventional prestressing strands and reinforcing bars to provide flexural and shear resistance.

By contrast, the UHPC alternatives use three precast U-girders with a dead load of 22 kN/m each (total 66 kN/m), reflecting the material's superior strength and durability. The girders are post-tensioned and incorporate steel fibres to resist tensile shear stresses, eliminating the need for conventional web reinforcement. The enhanced mechanical performance of UHPC enables a substantial reduction in total material demand, resulting in a superstructure mass of approximately 83% of the OPCC benchmark.

5.5.3 Materials assumptions

This section summarises the data used to evaluate the embodied impacts of the concrete and reinforcement materials adopted in this example. The data are obtained from EPDs, national emission factor databases, and values derived from representative mix designs when final product data are unavailable.

Table 7 and 8 present the data used for the EICs of the OPC, BC, and AAB concretes, and the UHPC, prestressing strand, and bar reinforcement, respectively. The mix design data for the 40 MPa OPCC and BCC concretes are provided in Table 3. For the 65 MPa mixes, EPD data from Boral [56] are adopted. For the 40 MPa 70/30 GGBFS/GP AABC blend, Boral data are again used for the 100-year GWP values. At present, EPD data for a 65 MPa AABC mix are not available; the value of 565 kg CO₂-e/m³ (Table 7) is established by extrapolation from mix designs containing 30–60% GGBFS.

Table 7. Data for an EIC for a 40-metre bridge example – concrete.

Property	Units	OPCC-40 (40 MPa)	OPCC-65 (40 MPa)	BCC-40 (30% FA)	BCC-65 (30% FA)	AABC-40 (70% GGBFS)	AABC-50 (70% GGBFS)	AABC-65 (60% GGBFS)
Density	kg/m ³	2400	2400	2390	2390	2380	2380	2380
EE	MJ/m ³	2700	3270	2400	2900	1750	1900	2025
100-yr GWP	kg CO ₂ eq./m ³	359	449	285	485	151	163	267
EE	MJ/kg	386	483	305	418	162	175	287
100-yr GWP	kg CO ₂ eq./kg	1125	1363	1004	1213	735	798	851

Table 8. Data for an EIC for a 40-metre bridge example – UHPC and steel.

Property	Units	UHPC (1.5% fibres)	eco-UHPC (1.5% fibres)	Strand	Bar Reinf.
Density	kg/m ³	2360	2360	7850	7850
EE	MJ/m ³	8305	7592	319500	94800
100-yr GWP	kg CO ₂ eq./m ³	1015	890	26200	9580
EE	MJ/kg	3519	3217	40701	12076
100-yr GWP	kg CO ₂ eq./kg	0.430	0.380	3.34	1.22

According to the NABERS National Material Emission Factors Database [72], the 100-year GWP for reinforcing bar ranges from 0.31 to 3.48 kg CO₂-e/kg, with an average of 1.60 kg CO₂-e/kg. This wide range reflects differences in steel production routes, including electric arc furnace (EAF) and blast furnace–basic oxygen furnace (BF–BOF) processes. In this example, the 100-year GWP value for reinforcing bar is taken from InfraBuild’s EPD for 500N reinforcing bar. InfraBuild being the largest supplier of reinforcing bar products to the Australian market.

Prestressing strands require a significantly higher level of carbon purity than conventional reinforcing bars to achieve their very high tensile strength and are therefore typically produced from blast furnace steel. Environmental product data for strand products are limited; a value of 3.34 kg CO₂-e/kg is adopted in this evaluation. This value corresponds to the 100-year GWP reported for 7-wire prestressing strand in the Humes Pipes EPD [73] and is consistent with the upper range suggested by NABERS.

The 100-year GWP value for the UHPC was calculated based on the mix design presented in Section 5.4.5, using mean emission factors for the constituent materials. The resulting 100-year GWP and EE values are presented in Table 9. The eco-UHPC mix differs from the conventional mix in two respects: the 25th percentile cement emission factor is adopted (see Table 5 and Fig. 6), and the 100-year GWP of the fibres is reduced from 2.3 kg CO₂-e/kg to 2.1 kg CO₂-e/kg. The 100-year GWP and EE values for the eco-UHPC mix are presented in Table 10.

Table 11 presents the material volumes required for the OPCC, BCC and AABC designs and Table 12 for the UHPC and eco-UHPC designs. The environmental impact calculations presented in the following section are obtained by summing the products of the material volumes and their corresponding per-cubic-metre 100-year GWP or EE values.

5.5.4 Performance and environmental impact

In this section, a comparative evaluation of the structural efficiency and environmental performance of the five bridge superstructure alternatives is presented. Results are provided both in normalised form relative to the OPCC benchmark and as absolute 100-year GWP

values. Environmental impacts are disaggregated into contributions from concrete, steel (including reinforcement, prestressing strands, and fibres), and diesel used for curing. In addition to whole-of-superstructure totals, the girder system, deck slab and ancillary components – including the end crosshead, wingwalls, approach slabs and diaphragms – are assessed separately to clarify how material selection and structural configuration influence overall carbon performance.

With the OPCC benchmark set to 100%, the relative performance of the five superstructure solutions is shown in Figures 11 and 12. The BCC solution provides modest but consistent improvements relative to OPCC, with embodied energy reduced by approximately 5% and 100-year GWP reduced by 10%. As observed in the previous example, this improvement reflects partial cement substitution and the associated reduction in clinker-related process emissions.

Table 9. Calculation of 100-yr GWP and EE for one cubic metre of UHPC.

Conventional UHPC 1.5% mix 100-yr GWP						
Component	Quantity	Quantity Unit	GWP Factor	Factor Unit	GWP Contribution (kg CO ₂ -e)	%age contribution to GWP
Cement	720	kg	0.868	kg CO ₂ -e/kg	625.0	61.6%
Steel fibres (1.5%)	117.8	kg	2.30	kg CO ₂ -e/kg	270.8	26.7%
Silica fume	180	kg	0.030	kg CO ₂ -e/kg	5.4	0.5%
Sand	1150	kg	0.009	kg CO ₂ -e/kg	10.4	1.0%
Water	144	kg	0.00	kg CO ₂ -e/kg	0.0	0.0%
Superplasticiser	44	kg	0.53	kg CO ₂ -e/kg	23.3	2.3%
Diesel (curing)	30	L	2.68	kg CO ₂ -e/kg	80.4	7.9%
TOTAL					1015	100%

Conventional UHPC 1.5% mix Embodied Energy						
Component	Quantity	Quantity Unit	EE Factor	Factor Unit	EE Contribution (MJ)	%age contribution to GWP
Cement	720	kg	4.95	MJ/kg	3564	43%
Steel fibres (1.5%)	117.8	kg	17.0	MJ/kg	2002	24%
Silica fume	180	kg	1.00	MJ/kg	180	2%
Sand	1150	kg	0.02	MJ/kg	23	0%
Water	144	kg	0.01	MJ/kg	1.4	0%
Superplasticiser	44	kg	33.2	MJ/kg	1461	18%
Diesel (curing)	30	L	35.8	MJ/L	1074	13%
TOTAL					8305	100%

Table 10. Calculation of 100-yr GWP and EE for one cubic metre of eco-UHPC.

eco-UHPC 1.5% mix 100-yr GWP						
Component	Quantity	Quantity Unit	GWP Factor	Factor Unit	GWP Contribution (kg CO ₂ -e)	%age contribution to GWP
Cement	720	kg	0.796	kg CO ₂ -e/kg	573.1	64.4%
Steel fibres (1.5%)	117.8	kg	2.10	kg CO ₂ -e/kg	247.3	27.8%
Silica fume	180	kg	0.030	kg CO ₂ -e/kg	5.4	0.6%
Sand	1150	kg	0.009	kg CO ₂ -e/kg	10.4	1.2%
Water	144	kg	0.00	kg CO ₂ -e/kg	0.0	0.0%
Superplasticiser	44	kg	0.53	kg CO ₂ -e/kg	23.3	2.6%
Diesel (curing)	30	L	1.00	kg CO ₂ -e/kg	30.0	3.4%
TOTAL					890	100%

eco-UHPC 1.5% mix Embodied Energy						
Component	Quantity	Quantity Unit	EE Factor	Factor Unit	EE Contribution (MJ)	%age contribution to GWP
Cement	720	kg	3.96	MJ/kg	2851	38%
Steel fibres (1.5%)	117.8	kg	17.0	MJ/kg	2002	26%
Silica fume	180	kg	1.00	MJ/kg	180	2%
Sand	1150	kg	0.02	MJ/kg	23	0%
Water	144	kg	0.01	MJ/kg	1	0%
Superplasticiser	44	kg	33.2	MJ/kg	1461	19%
Diesel (curing)	30	L	35.8	MJ/L	1074	14%
TOTAL					7592	100%

Table 11. Material volumes for OPCC, BCC and AABC designs (m³).

No	Description	Grade-40	Grade-65	Strand	Bar
1	Precast 40m super-tee girders (m ³)	0.0	176.7	2.29	4.49
2	Crossheads, wingwalls, approach slabs and diaphragms (m ³)	124.9	0	0	2.12
3	R.C. deck (total) - 1.5% Reo. (m ³)	120	0	0	1.80
4	R.C. Parapet - 1.0% Reo. (m ³)	31.3	0	0	0.31
Total		276.2	176.7	2.29	8.71

Table 12. Material volumes for UHPC and eco-UHPC designs (m³).

No	Description	Grade-50	UHPC	Strand	Bar
1	Precast 40m super-tee girders (m ³)	0.0	108	1.72	0.46
2	Crossheads, wingwalls, approach slabs and diaphragms (m ³)	124.9	0	0	2.12
3	R.C. deck (total) - 1.5% Reo. (m ³)	120	0	0	1.80
4	R.C. Parapet - 1.0% Reo. (m ³)	31.3	0	0	0.31
Total		276.2	108.0	1.72	4.68

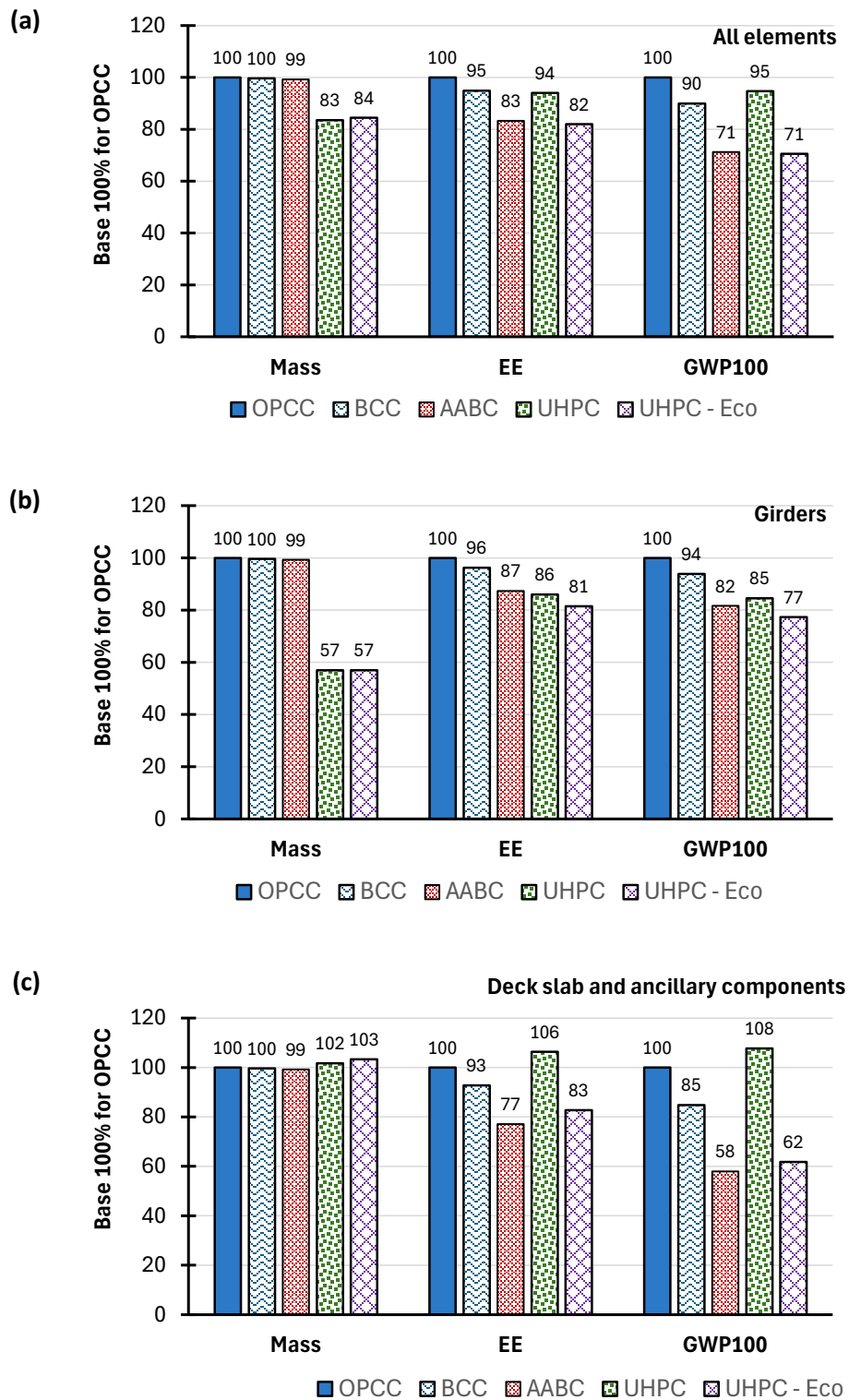


Fig. 11. Comparison of environmental impact calculations for the 40 metre span bridge example: a) all components; (b) girders only; and (c) deck slab and ancillary components.

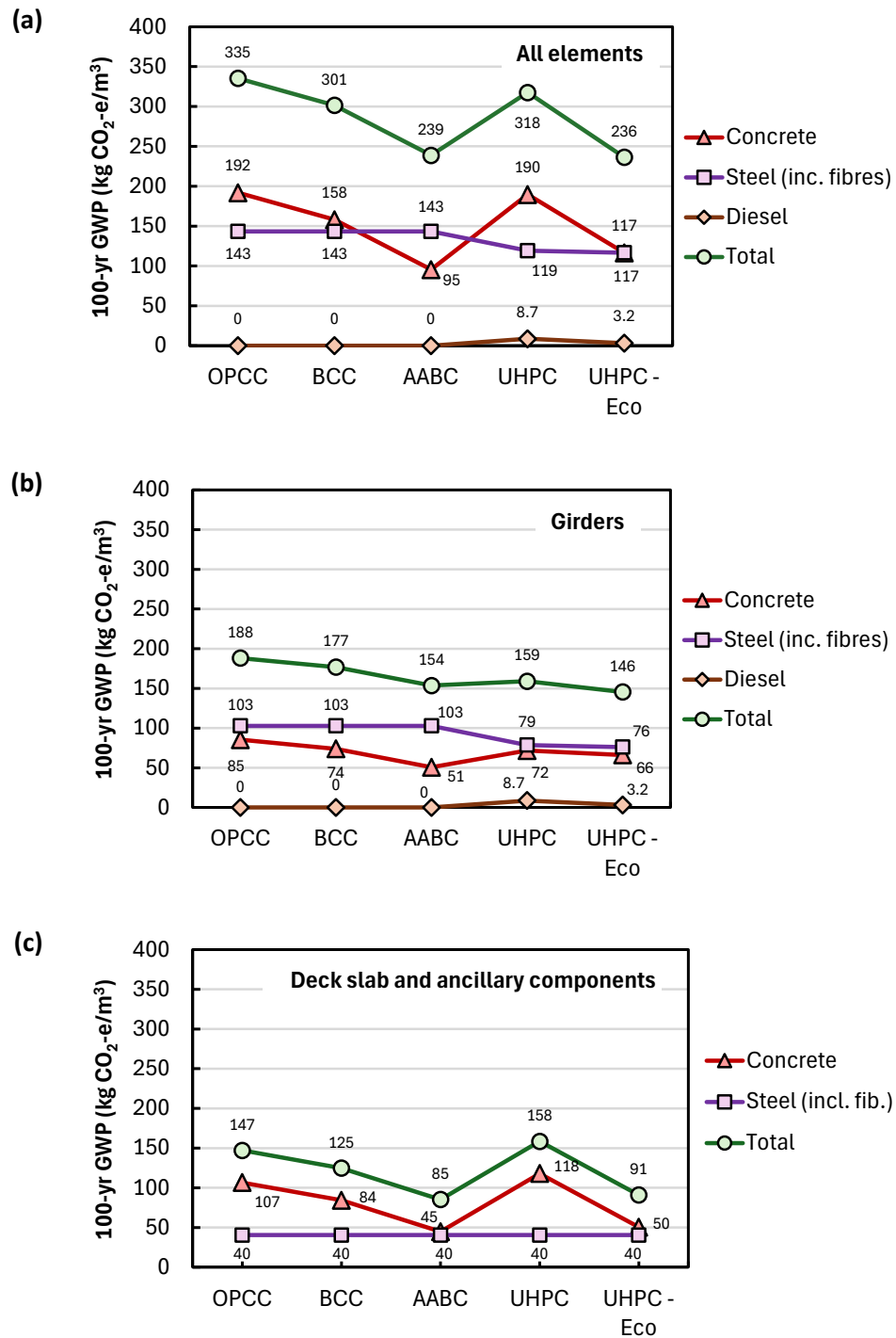


Fig. 12. Greenhouse gas contributions of concrete materials (excluding fibres), steel (including fibres), and steam-curing diesel to the total emissions of the 40 m span bridge: (a) all components; (b) girders only; and (c) deck slab and ancillary components.

The AABC design delivers substantially greater reductions, lowering embodied energy to 83% and GWP100 to 71% of the benchmark. Because the structural configuration remains unchanged from the OPCC design, these reductions are attributable to the high level of GGBFS replacement and the consequent decrease in binder-related emissions. The decarbonisation mechanism in this case is therefore material-driven rather than design-driven.

The UHPC solutions achieve the GWP reductions through enhanced structural efficiency of the girders. While the embodied carbon per cubic metre of UHPC is substantially higher than that of conventional concrete, its superior mechanical performance enables significant reductions in overall material demand. The total superstructure mass is reduced by approximately 16% relative to the OPCC benchmark, with girder mass reductions of approximately 43%. This corresponds to a GWP100 of approximately 95% of the benchmark for the standard UHPC mix and 70% for the eco-UHPC variant.

These efficiency gains at the girder level are partially offset by increased deck slab thickness and higher strength requirements (50 MPa versus 40 MPa), introduced to address durability demands associated with the slab underside being exposed to the atmosphere. The implications of these design adjustments are examined in more detail in the following sections.

Notably, the eco-UHPC and AABC solutions achieve closely aligned overall GWP performance – approximately 70–71% of the OPCC baseline – despite relying on fundamentally different decarbonisation pathways. The AABC solution is driven primarily by binder substitution to reduce process emissions, whereas the eco-UHPC approach achieves comparable system-level outcomes through a combination of structural optimisation and lower-impact constituent materials.

5.5.5 Absolute 100-year GWP – superstructure total

The total 100-year GWP values for the superstructure are presented in Figure 12(a). The OPCC superstructure results in a total GWP₁₀₀ of 335 t CO₂-e. For the BCC solution, reductions are confined to the concrete component, lowering total emissions to 301 t CO₂-e.

The AABC solution achieves a substantial reduction in the concrete contribution, from 192 t to 95 t CO₂-e – approximately a 50% decrease in binder-related emissions – resulting in a total GWP of 239 t CO₂-e. However, the steel contribution remains unchanged at 143 t CO₂-e, thereby increasing its proportional share of total emissions.

The standard UHPC solution reduces both concrete and steel quantities but introduces an additional 8.7 t CO₂-e from diesel consumption for steam curing. This benefit is partially offset by the increased material demand associated with a 10 mm thicker slab, resulting in a total

GWP of 318 t CO₂-e. The eco-UHPC variant further reduces the contributions of concrete and steel and lowers curing emissions to 3.2 t CO₂-e, yielding a total of 236 t CO₂-e. However, these gains are slightly diminished by the requirement for an additional 20 mm slab thickness to mitigate durability risks, specifically the risk of carbonation-induced corrosion of the bottom reinforcement in the deck slab relative to the super-T girder design.

5.5.6 Component-level breakdown – girders

The GWP contributions for the girder components alone are shown in Figure 12(b). For the conventional girder systems, steel dominates the girder-level GWP. In the OPCC girder, steel accounts for approximately 55% of total girder emissions (103 of 188 t CO₂-e), with much of this being due to the higher emission intensity of the tendons. In the AABC girder, due to the substantial reduction in concrete emissions, steel accounts for roughly two-thirds of the total GWP (103 t CO₂-e of 154 t CO₂-e).

The BCC girder achieves a modest reduction relative to OPCC through decreased concrete impacts, lowering total emissions to 177 t CO₂-e, while the steel contribution remains unchanged.

The UHPC girder results in total emissions of 159 t CO₂-e, comparable to the AABC girder, but with a different distribution: both concrete and steel quantities are reduced due to improved structural efficiency, partially offset by 8.7 t CO₂-e associated with diesel for steam curing. The eco-UHPC girder further reduces both material and curing impacts, yielding the lowest girder-level GWP at 146 t CO₂-e.

5.5.7 Component-level breakdown – deck slab and ancillary elements

The GWP contributions for the deck slab and ancillary components are shown in Figure 12(c). As the bar reinforcement configuration of these elements is consistent across all design options, the steel contribution remains constant at 40 t CO₂-e. Variations in total impact are therefore driven by differences in concrete-related emissions.

Relative to the OPCC baseline (147 t CO₂-e), the BCC alternative reduces total emissions to 125 t CO₂-e through lower concrete impacts, while the AABC solution achieves a more substantial reduction to 85 t CO₂-e due to the use of a lower-carbon binder.

For the UHPC-based solutions, the deck slab design is modified to meet increased durability requirements for the slab's underside, which is exposed to the atmosphere, compared with the baseline super-T configuration. This necessitates increasing concrete strength from 40 MPa to 50 MPa in the decks, along with a 10 mm increase in slab thickness for the UHPC solution and

a 20 mm increase for the eco-UHPC solution. These changes lead to higher concrete-related emissions, with the UHPC option resulting in the highest total impact of 158 t CO₂-e.

The eco-UHPC solution reduces the concrete contribution relative to standard UHPC, yielding a total of 91 t CO₂-e. However, despite the lower-carbon binder, the increased slab thickness and strength requirements mean that its impact remains slightly higher than that of the AABC solution.

5.5.8 Structural carbon floor and system implications

Across all configurations, a consistent trend is observed: as concrete-related emissions decrease, the proportional contribution of steel increases. In the OPCC superstructure, steel accounts for approximately 43% of GWP₁₀₀ (143 of 335 t CO₂-e), increasing to around 60% in the AABC configuration (143 of 239 t CO₂-e). At the girder level, steel is the dominant contributor in all cases, exceeding 50% of total emissions and reaching approximately two-thirds in the AABC girder.

This behaviour highlights the emergence of a structural carbon floor. As cement-related emissions are reduced through the adoption of lower-carbon binders, the relative and absolute contributions of steel – including reinforcing bars, prestressing strands and fibres – become the primary constraints on further reductions. Consequently, achieving deeper decarbonisation at the system level will require not only continued optimisation of concrete materials and structural efficiency, but also substantial reductions in the carbon intensity of steel production.

At the component level, reductions achieved in deck and ancillary elements are likewise governed by binder selection; however, for the UHPC-based solutions, these gains are partially offset by increased durability requirements. Specifically, the need to protect the underside of the deck slab exposed to atmospheric conditions necessitates an increase in concrete strength (from 40 MPa to 50 MPa) and slab thickness (by 10 mm for UHPC and 20 mm for eco-UHPC), which elevates concrete-related emissions relative to what would otherwise be achieved with thinner sections.

Finally, it should be emphasised that the assessment boundary is limited to the superstructure. The reduced mass of the UHPC solutions would likely enable lighter substructures and foundations and reduce transport-related emissions. These additional benefits are not included in the present analysis and would further enhance the system-level performance of the UHPC alternatives.

5.5.9 Conclusions from example 2

This bridge example reinforces and extends the findings of the preceding retaining wall study. Two distinct but complementary decarbonisation strategies are confirmed:

- Lowering binder carbon intensity through clinker substitution or alkali activation.
- Reducing total material demand through structural efficiency enabled by high-performance materials.

The AABC and eco-UHPC solutions deliver comparable overall reductions in GWP100, approximately 30% relative to the OPCC baseline, but achieve these outcomes through different mechanisms. The AABC solution is primarily material-driven, targeting reductions in binder-related emissions within otherwise conventional structural configurations. In contrast, the eco-UHPC solution is system-driven, combining structural efficiency with reductions in constituent material impacts; however, these gains are partially offset by increased deck slab thickness and higher concrete strength requirements (50 MPa versus 40 MPa) introduced to satisfy durability demands associated with exposure conditions.

5.6 Example 3: Three Bay-by-Three Bay Flat Slab Floor

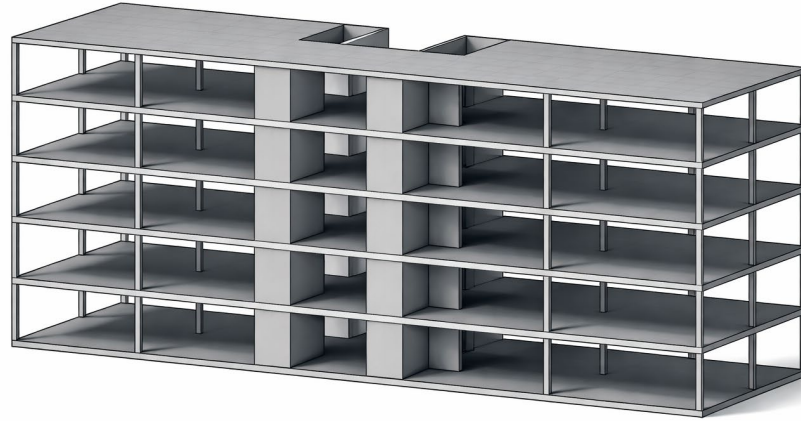
5.6.1 Introduction and project description

In this third and final example, the flat-slab floor system shown in Figure 13 is analysed for a mixed-use building comprising retail and commercial office spaces. The slab design follows the example presented in Muttoni et al. [74], which details the slab reinforcement layout. The thickness of the slab is 250 mm. The building is symmetric about its central line.

Each side of the building is supported by six 350 mm square columns, dimensioned to achieve a two-hour fire rating, each 2.8 m high between storeys, reinforced with eight N16 longitudinal bars and N10 transverse ties at 175 mm spacing in a diamond-tie configuration. The specified concrete compressive strength for all elements is 32 MPa. The system boundary encompasses the half-floor slab and the supporting columns and walls (stairs are not included).

This example evaluates a single structural system across five mix design scenarios. As in the previous examples, these comprise an Ordinary Portland Cement concrete (OPCC) benchmark, a blended cement concrete (BCC), and an alkali-activated binder concrete (AABC) with 70% GGBFS and 30% cement. In addition, two scenarios based on LC3 binder concrete are considered: LC3-70 (30% clinker replacement in the binder) and LC3-50 (50% clinker replacement in the binder); details are provided below.

(a)



(b)

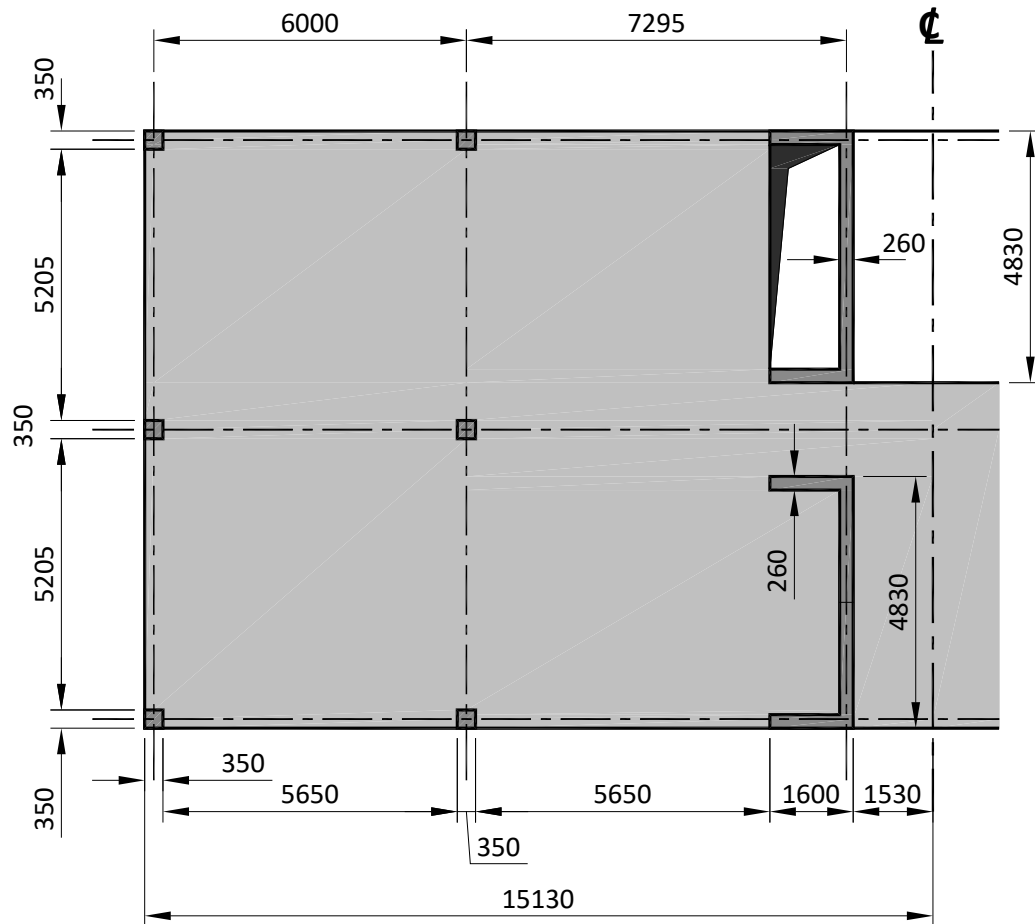


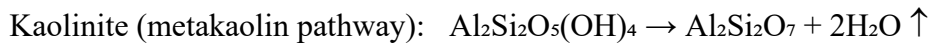
Fig. 13. Reinforced concrete flat slab floor system for Example 3: (a) 3D Perspective of the Building; (b) plan view showing key dimensions (in m).

5.6.2 Materials assumptions

In this example, the carbon and embodied-energy footprints for the 32 MPa OPCC and BCC concretes are taken as those of the relevant Boral product listed in Table 3. For the AABC comprising 70% activated GGBFS, the adopted 100-year GWP and EE are 155 kg CO₂-eq./m³ and 1.5 GJ/m³, respectively. The total reinforcement volume in the slabs and edge beams is 1.63 m³, including a 15% allowance for laps, anchorages and headed shear reinforcement.

For the LC3 concretes, the notation of Scrivener et al. (2018) is adopted, in which LC3–X denotes the clinker content of the blend. The standard blend used as the principal reference is LC3–50, comprising 50% clinker, 30% calcined clay, 15% limestone and 5% gypsum. The higher-clinker blend considered in this study is LC3–70. For this study, LC3–70 was modelled by preserving the 2:1 calcined clay:limestone ratio and the same 5% gypsum content as in LC3–50, resulting in an assumed binder composition of 70% clinker, 16.7% calcined clay, 8.3% limestone, and 5% gypsum.

Calcined clay is produced by thermally activating natural clays, typically kaolinitic or aluminosilicate-rich clays containing reactive phyllosilicates, through controlled calcination. After extraction, the clay is dried, crushed, and milled to achieve the desired fineness and homogeneity. The key step is heating the clay to approximately 750–900 °C, where kaolinite undergoes dehydroxylation to form amorphous metakaolin, while other clay minerals, such as pyrophyllite, follow a similar dehydroxylation pathway to form corresponding amorphous aluminosilicates [75]:



In both cases, the reaction releases water vapour rather than CO₂, producing highly reactive amorphous phases suitable for use as supplementary cementitious materials. However, CO₂ may be emitted if carbonate impurities (e.g. calcite) are present and decompose during calcination [75], [76]. Calcination conditions must be carefully controlled: insufficient temperatures limit reactivity, while excessive temperatures (typically above 900 °C) lead to sintering and recrystallisation, reducing performance [75]. Industrial production is typically undertaken in rotary kilns or flash calciners, followed by cooling and, where required, grinding to enhance reactivity. The resulting material is a highly reactive amorphous aluminosilicate suitable for use as a supplementary cementitious material [75].

Concrete-level 100-year GWP and embodied-energy data for LC3 remain limited, particularly for 32 MPa concretes and for higher-clinker variants such as LC3–70. However, manufacturer EPDs for calcined-clay and LC3-type cements are now beginning to emerge internationally. Recent examples include a 2025 Type IT (LC3) cement EPD for NCC of California [77], a 2025 calcined clay cement EPD for Holcim Emirates Cement (EPD library owner listed as Lafarge Emirates Cement LLC) [78], and a 2025 FUTURECEM® CEM II/B-M(Q-LL) EPD published by CCB [79].

Across these three EPDs, declared clinker contents span approximately 59%–65%, with an unweighted mean GWP of 555 kg CO₂-e/tonne and an EE proxy of 3710 MJ/tonne (see Table 13), based on total primary energy in A1–A3. This compares with an unweighted mean of 868 kg CO₂-e/tonne and 4960 MJ/tonne for Australian cement manufacture (see Table 5),

representing reductions of approximately 36% in 100-year GWP and 25% in embodied energy. A more representative comparison is the 25th percentile of Australian cement manufacture; on this basis, the LC3 binders correspond to reductions of approximately 30% in 100-year GWP and 6% in embodied energy. These values should be interpreted as indicative, as they are derived from a small number of EPDs with differing product compositions and PCR frameworks, and are sensitive to the electricity mix, particularly the share of low-carbon electricity, including renewable and nuclear generation.

Table 13. 100-year GWP and EE for LC3 binders.

Product	GWP100 kg CO ₂ -e/t	EE (MJ/t)	Clinker (%)	Calcined clay (%)	Limest. (%)	Gypsum (%)	Other/grouped non-clinker (%)
NCC of California	582	4550	64	–	–	–	36% grouped as limestone, gypsum, calcined clay and others
Holcim Emirates	559	3476	59–61	19–21	14–16	4–6	–
FUTURECEM®	525	3097	65	–	–	–	30% limestone-calcined clay + 5% other minor components

Scrivener et al. [80] report that LC3–50 achieves approximately 30% CO₂ savings at the cement level relative to OPC. Analyses conducted at IIT Madras [81] further indicate that LC3–50 concretes exhibit the lowest CO₂ emissions among the 30 MPa and 50 MPa concrete families considered.

For this project, the adopted LC3 values were derived from the project OPC baseline of 329 kg CO₂-eq./m³ and 2300 MJ/m³. The principal LCA anchor was the matched concrete pair reported by Gettu et al. [81] as M3 (OPC concrete) and M28 (LC3 concrete). For LC3–50, project values were obtained by directly scaling the M28:M3 ratios to the OPC baseline. For LC3–70, no direct 32 MPa concrete LCA data were identified in the sources reviewed; accordingly, LC3–70 was estimated by interpolating between the cement-level impacts reported by Gettu et al. for OPC and standard LC3 cement, and applying the resulting binder-level adjustment to the matched M3 concrete.

The results of these assessments are presented in Table 14 and are adopted for subsequent calculations. Table 15 and Table 16 summarise the data used to determine the EICs for the OPC, BCC, AABC, and LC3 concretes, and the reinforcing bar, respectively.

Table 14. 100-year GWP and EE for LC3 concrete used in Example 3.

Mix	Binder composition	100-year GWP (kg CO ₂ -eq./m ³)	EE (MJ/m ³)	Basis
OPCC	Reference OPC concrete	329	2300	Project baseline
LC3-70	70% clinker, 16.7% calcined clay, 8.3% limestone, 5% gypsum	281 (15% redn)	2170	Literature-anchored estimate
LC3-50	50% clinker, 30% calcined clay, 15% limestone, 5% gypsum	239 (27% redn).	2020	Scaled from matched M28:M3 concrete pair [81]

Table 15. Data for an EIC for the reinforced concrete slab and supporting elements.

Property	Units	OPCC (32 MPa)	BCC (30% FA)	AABC (70% GGBFS)	LC3-70 (70% Clinker)	LC3-50 (50% Clinker)	Bar Reinf.
Density	kg/m ³	2400	2390	2380	2400	2400	7850
EE	GJ/m ³	2.30	2.10	1.50	2.17	2.02	94.8
100-yr GWP	kg CO ₂ eq./m ³	329	278	155	281	239	9580
EE	GJ/kg	0.96	0.88	0.63	0.90	0.84	12.1
100-yr GWP	kg CO ₂ -e/kg	0.137	0.116	0.065	0.117	0.100	1.22

Table 16. Material volumes for concrete and bar reinforcement (m³).

No	Item	Concrete (m ³)	Reinforcement (m ³)
1	Flat plate slab (30.26 m x 11.46 m - excluding cut-outs)	79.1	0.990
3	Four supporting shear walls	22.2	0.311
4	Twelve 0.35 m square x 2.8 m long columns (m ³)	16.4	0.329
Total		58.9	1.63

5.6.3 Performance and environmental impact

The comparative assessment shown in Figure 14 highlights the influence of binder composition on both material efficiency and whole-of-system environmental performance for the flat slab and its supporting elements. The results consistently show that reductions in clinker content translate directly into lower embodied impacts, while the contribution of reinforcement remains effectively constant across all scenarios.

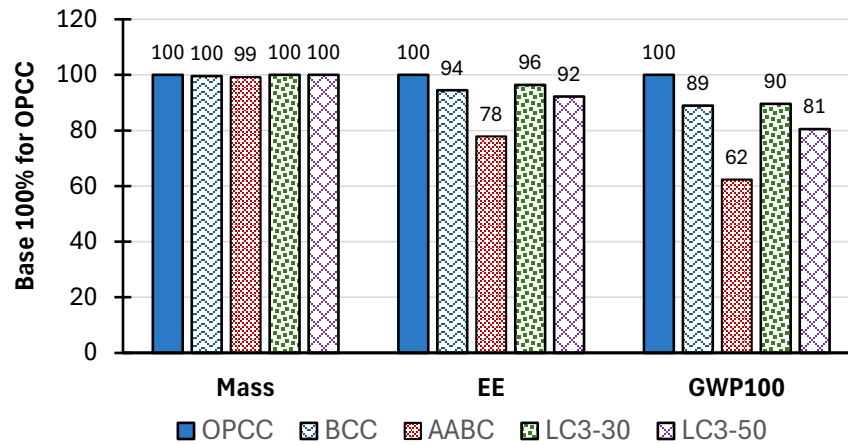


Fig. 14. Comparative environmental impact assessment of the flat slab and its supporting elements.

Figure 15 compares the total and relative GHG emissions of concrete and reinforcement. It is immediately evident that, at the material level, the 100-year GWP of concrete varies significantly with binder type. The conventional OPCC mix records a GWP of 39 kg CO₂/m³, which reduces to 33 kg CO₂/m³ with 30% fly ash substitution (BCC). A substantially lower value of 18 kg CO₂/m³ is achieved for the AABC mix, reflecting the high replacement of Portland cement with GGBFS. The LC3 systems demonstrate performance comparable to fly ash substitution, with values of 33 kg CO₂/m³ for LC3-30 and 28 kg CO₂/m³ for LC3-50. Steel reinforcement contributes a constant 16 kg CO₂/m³ across all cases, resulting in total impacts ranging from 54 kg CO₂/m³ (OPCC) to 34 kg CO₂/m³ (AABC).

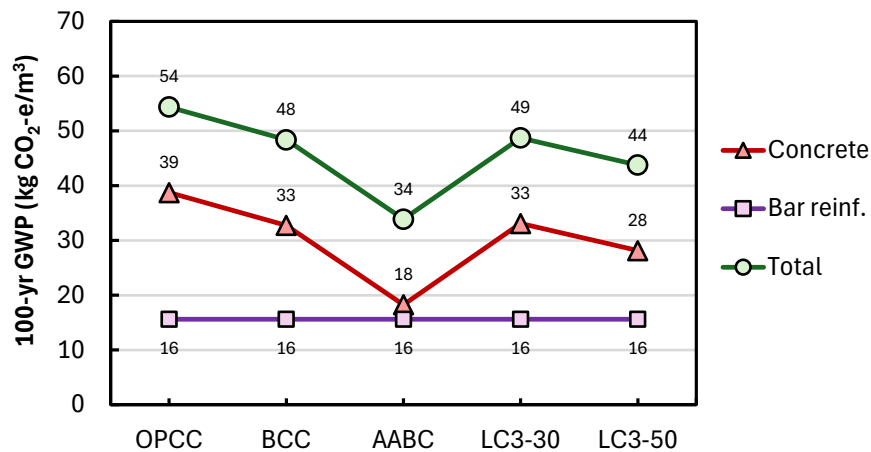


Fig. 15. Greenhouse gas emissions breakdown of concrete and reinforcing bar contributions to the total emissions of the flat slab and supporting elements.

At the structural level, these material differences are reflected in the total embodied impacts. The OPCC solution exhibits the highest GWP at 51.0 t CO₂-e, followed by BCC and LC3-70 with comparable values of 45.4 and 45.8 t CO₂-e, respectively. The LC3-50 alternative achieves a further reduction to 41.2 t CO₂-e, while the AABC system delivers the lowest impact at 32.0 t

CO₂-e. This corresponds to an approximate 37% reduction relative to the OPCC baseline. Trends in embodied energy are consistent with the GWP results, decreasing from 425 GJ (OPCC) to 331 GJ (AABC), indicating that lower-carbon binders also reduce overall energy demand.

The relative contributions of concrete and reinforcement to total GWP further clarify this relationship. Concrete accounts for between 54% and 71% of total emissions, with the highest share observed in the OPCC system (71%) and the lowest in the AABC system (54%). As the carbon intensity of concrete decreases, the proportional contribution of reinforcement correspondingly increases, reaching 46% in the AABC case. This highlights an important transition point: as demonstrated in Example 2, the adoption of low-carbon binders increases the relative significance of reinforcement, warranting targeted optimisation.

5.6.4 Conclusions from example 3

The results from Example 3 further demonstrate that, while binder substitution is an effective strategy for reducing embodied carbon, it is insufficient on its own to achieve deep decarbonisation of reinforced concrete structures. Meaningful reductions require a holistic approach that considers not only binder chemistry but also structural efficiency and total material demand.

Across the alternatives assessed, AABC consistently delivers the lowest environmental impact, followed by LC3-50, indicating the strong potential of high clinker-replacement systems. BCC and LC3-70 provide more moderate improvements, confirming that partial clinker reduction yields incremental but limited benefits relative to more transformative binder technologies.

Importantly, as observed in Example 2, the relative contribution of reinforcement becomes increasingly significant as the carbon intensity of concrete decreases. This shift highlights the need to address reinforcement alongside concrete in future optimisation efforts, particularly through efficient design, material selection, and sourcing strategies.

Overall, the findings reinforce that clinker-reduction strategies are critical for near-term emissions reductions but must be integrated with broader design and material-efficiency measures to achieve substantial structural-level decarbonisation.

5.7 Conclusions

Across the retaining wall, bridge and flat-slab example studies, consistent patterns emerge. First, partial cement/clinker substitution yields modest improvements, whereas high levels of cement replacement or alkali activation yield substantial binder-related reductions. Second, UHPC offers an alternative pathway, reducing emissions at the structural level by significantly reducing structural volume despite its higher per-unit carbon intensity.

Most importantly, comparable environmental outcomes can be achieved through fundamentally different strategies – either by reducing the carbon intensity of materials or by reducing the quantity of material required. In practice, the optimal solution will depend on structural form, performance requirements, material availability, and supply chain carbon intensity, and is likely to involve a coordinated combination of approaches – spanning materials innovation, structural and architectural design optimisation, construction methods and technologies and standard-setting – that together form a systems approach capable of delivering greater reductions than any single measure can in isolation.

Finally, the calculations highlight an emerging constraint: as concrete-related emissions decrease, steel increasingly governs total embodied carbon. Achieving further structural-level reductions will therefore require integrated innovation across both cementitious materials and steel production. Together, these case studies demonstrate that meaningful decarbonisation of civil infrastructure is achievable, but it requires coordinated advances in materials science, structural design, and industrial processes.

6. CASE STUDY: VIDA RAIL LOW-CARBON CONCRETE PROJECT

6.1 Introduction

The Victorian Infrastructure Delivery Authority (VIDA) Rail is a transport infrastructure delivery organisation for public rail projects in Victoria, Australia [82]. It is responsible for delivering the Level Crossing Removal Project (LXRP), a multi-decadal urban rail safety upgrade program. The program is underpinned by the objective of eliminating the inherent conflict between road and rail networks at level crossings. Official evaluations identify these interfaces as critical points of conflict that pose safety risks, traffic delays, and network inefficiencies, particularly as train frequencies increase in a growing metropolitan area. Accordingly, the program focuses on removing level crossings through grade-separation interventions – including elevated rail corridors, such as the Preston Station precinct shown in Figure 16, and road overpasses or underpasses. These measures facilitate a safer and more reliable transport system, increase network capacity, and reduce congestion for road users, thereby improving overall transport network efficiency [83].



Fig. 16. Preston Station precinct (Victoria) – example: elevated railway line.

This program of works is being delivered via an alliance contracting model, which is intended to establish a contractual framework for collaborative working relationships between the client (i.e. the Victorian state government) and the contractors engaged to design and construct the works.

Project context
• Victorian state government • Rail transport infrastructure delivery organisation • Multi-decadal urban rail safety upgrade program • Alliance contracting model

Several findings and recommendations from this report are already embodied in the VIDA Rail Low Carbon Concrete Project (“the Project”). Established by the organisation, the Project supports program alliances in delivering the Transport Infrastructure Decarbonisation Strategy [84]. It has been structured to confront the systemic barriers to widespread adoption of low-carbon concrete – barriers that extend beyond the remit of any single project or agency and challenge conventional engineering objectives and practices.

To address these complexities in a coordinated manner, the Project is organised into three integrated workstreams spanning materials and technology, standards and specification, and market readiness, ensuring that technical innovation, regulatory frameworks, and commercial viability are advanced in parallel [85].

This section outlines how the Project has identified and responded to a number of core themes in this report, including:

- Setting targets for embodied carbon;
- Collaborating between sustainability and engineering functions;
- Contributing to a reset of engineering governance; and
- Addressing structure-level decarbonisation.

6.2 Theme 1: Setting Targets for Embodied Carbon

VIDA Rail sits within a vertically integrated policy framework that sets explicit greenhouse gas reduction targets at global, state and portfolio levels. At the portfolio scale, these targets extend to upfront carbon emissions, including embodied carbon and construction-related energy use.

Aligned with science-based global and state targets, the VIDA Transport Infrastructure Decarbonisation Strategy [84] establishes upfront embodied-carbon targets over a multi-decadal timeline to 2045 (Figure 17), benchmarked against a 2005 project equivalent and corresponding emission intensities. Notably, design standards have evolved substantially since this baseline. Since 2005, higher-strength concrete grades have become available, with AS 3600 extending the maximum compressive strength of concrete from 65 MPa to 100 MPa in 2009, and further to 120 MPa in 2018. Reinforcing steel grades have similarly advanced – increasing from 500 MPa to 600 MPa in 2018, with provisions for up to 800 MPa in limited

applications, and further extensions anticipated in the 2026 revision of the standard. Concurrently, in 2018, design models were recalibrated to optimise efficiency, resulting in improved strength reduction factors (ϕ -factors).

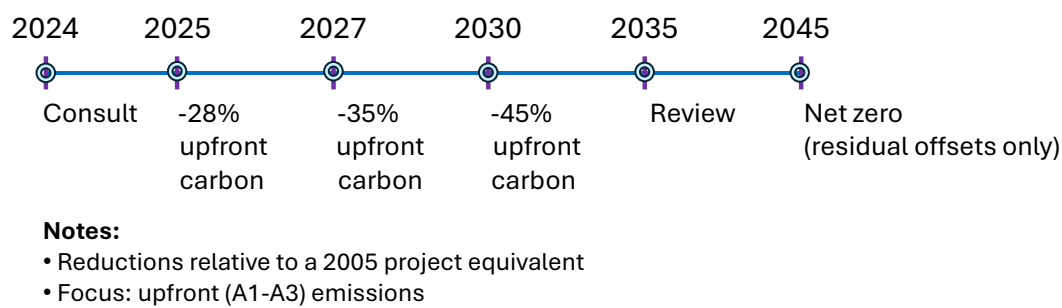


Fig. 17. Summary of VIDA Transport Infrastructure Decarbonisation Strategy – Upfront Carbon Reduction Pathway 2024–2045 [84].

Within the VIDA framework, these developments in materials technology present an opportunity at the structural level to reduce emission intensities relative to the 2005 baseline, particularly in compression-dominated structural elements such as foundations, columns and heavily loaded bridge piers.

In parallel, the LXP Sustainability Strategic Plan 2024–2028 [86] sets targets to reduce construction-related greenhouse gas emissions – encompassing both material production and construction energy use – over a comparable timeframe (Figure 18).

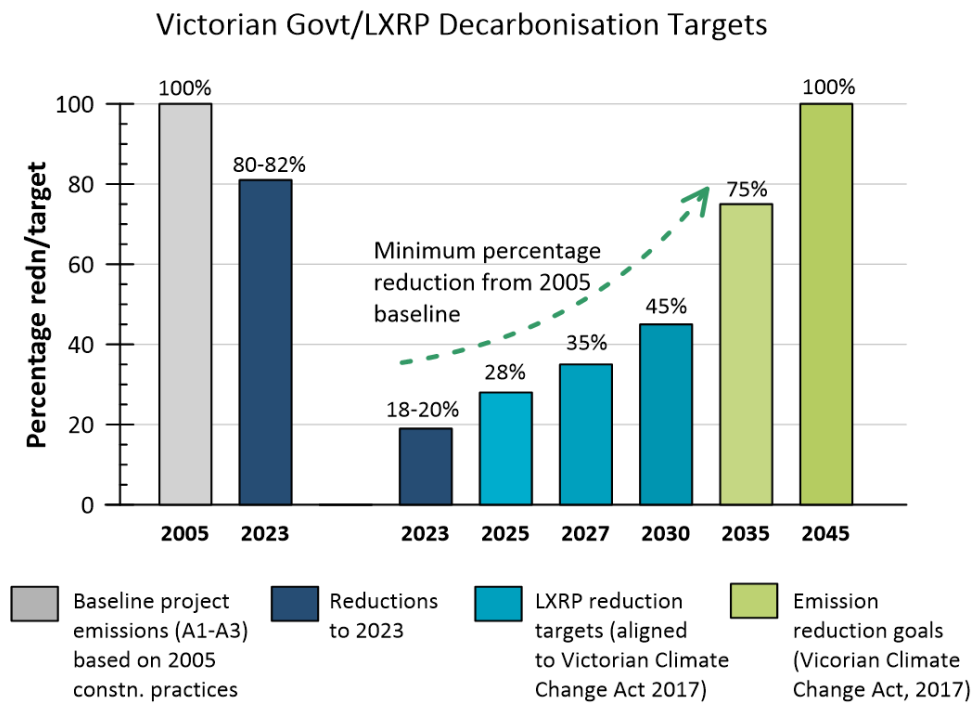


Fig. 18. Summary of LXP Sustainability Strategic Plan 2024–2028 targets and alignment with Victorian Climate Change Act 2017 [86].

Key features: VIDA Rail's targets for embodied carbon

- *Numerical targets for upfront carbon:* targets for reducing 'upfront carbon' have been quantitatively derived and communicated based on a clear and comprehensive standard (PAS 2080). 'Upfront carbon' encompasses the greenhouse gas emissions associated with raw material extraction, manufacturing, and transport of products used during construction.
- *Multi-decadal time horizon:* targets have been set over a long-term time horizon to clearly signal a long-term commitment.
- *Science-based targets:* targets are aligned with the climate science, as reported by consensus via the Intergovernmental Panel on Climate Change (IPCC). The climate science calls for halving emissions in the medium term (i.e. 2030-2035) and net zero by 2050 [87].
- *Measured against a common, fixed baseline:* performance against the targets is assessed relative to a consistent baseline based on 2005 business-as-usual practices, rather than a project-specific baseline tied to the year of commencement.

VIDA Rail's approach to setting carbon targets partially addresses **Recommendation 8:**

"Set progressive project and portfolio-level embodied carbon targets (e.g., in rating schemes and other forms of specification, such as direct specification in contracts) aligned with the Australian government's sectoral pathways to net zero."

This may be further supplemented by disaggregating upfront carbon targets to send an explicit signal to the construction materials and plant-and-equipment markets about expected outcomes in project delivery. For example, into embodied carbon and construction energy emissions, or into material and equipment-specific targets. Without disaggregation, suppliers will require clarification and translation of the upfront carbon targets into sector-specific targets, which detracts from the intention of providing an early lead time for investment and R&D by setting long-term, quantitative goals.

6.3 Theme 2: Collaborating Between Sustainability and Engineering Functions

To deliver on its upfront carbon targets, VIDA Rail established the Project as "a collaboration" between its sustainability and (traditional) engineering teams [85]. This collaboration has driven the portfolio-level development of design and construction requirements (i.e., technical policy) that are co-created by sustainability and (traditional) engineering professionals and integrate climate change mitigation as an aim of engineering work. This represents a significant

step change in the overall approach to enacting technical and environmental policy agendas. Whereas the approach to date has seen the *parallel development* of policy and regulatory instruments – i.e. with technical agendas pursued largely independently of environmental agendas and vice versa – this Project seeks to bring the two agendas into conversation in a more integrated fashion.

Key features: VIDA Rail’s collaboration between sustainability engineering and traditional engineering functions

- *Engineering function takes on a sustainability project:* the Project is the responsibility of the engineering team, with the sustainability team providing an advisory role through regular catch-ups. This means sustainability aims are recognised as an integral part of engineering work, and sustainability professionals are equipped to succeed in collaborating with (traditional) engineering professionals as teammates within a shared project.
- *Upstream integration of climate policy and established technical aims:* client-level or specification-level integration of climate policy and established technical aims means clear, consistent, and coherent directions to contracting partners and their suppliers. This means contracting partners and their suppliers can focus on delivering outcomes rather than managing compliance.
- *Climate action delivered as engineering, or expanding engineering aims to encompass climate action:* climate policy agendas (e.g. climate and energy transitions) are operationalised as engineering challenges, and are delivered using established engineering problem-solving methods, together with the promotion of internal cultural change within the engineering profession.

The VIDA Rail Low Carbon Concrete Project provides a case study in greater collaboration between ‘sustainability engineering’ and ‘traditional engineering’ functions. In this manner, it can be used as a model for **Recommendation 2**: “Standard-setting forums include balanced representation of relevant stakeholder interests, including both technical and non-technical interests”. The integration and collaboration between sustainability engineering and traditional engineering in the VIDA Rail model can be extended further upstream in the engineering aim-setting and decision-making hierarchy, i.e., at the national level in standard-setting forums.

To extend this collaborative model, the following additional feature could be explored:

- *Mutual recognition of expertise:* recognising that a publicly accountable engineering profession integrates emerging public policy objectives into engineering practice. In the context of climate policy, this includes sustainability engineering expertise to ensure

outcomes align with intended climate objectives. Equally, achieving these objectives depends on working with – not around – traditional engineers, supporting the evolution of their expertise to integrate policy goals while maintaining established engineering goals.

The above features can help address **Recommendation 1**:

“That enduring values such as safety and durability are maintained while new values are systematically integrated in a way that is responsive to public expectations and responsibly evolves engineering expertise.”

6.4 Theme 3: Contributing to a Reset of Engineering Governance

The Project also recognises the role of government transport infrastructure delivery authorities in engineering policymaking and seeks to contribute to a reset of engineering governance by stepping up in this capacity. Stepping up has involved taking on a leadership role in proactively seeking to ‘pull’ emerging materials and technologies from the lab to trials and, ultimately, to widespread adoption. The Project notes that “VIDA Rail has an opportunity to use its influence and knowledge to support the development of the most fit-for-purpose materials” [88].

Key features: VIDA Rail’s contribution to a reset of engineering governance

- | |
|---|
| <ul style="list-style-type: none"> • Identifying opportunities for <i>trials and pilots</i> on VIDA Rail’s multi-decadal program of works. • Working with specification owners and research organisations to clarify <i>testing requirements for asset owner acceptance</i> and providing this as set guidance to alliance and supply chain partners. |
|---|

The initiation and scope of the VIDA Rail Low Carbon Concrete Project is an example of engineering leadership in engineering governance. Specifically, it recognises the essential role of engineers in the development of technical policy and the need for engineering leadership to reshape it in response to emerging public policy objectives, while continuing to deliver on the established aims of engineering work. In this manner, the Project brings to life **Recommendation 1**: “Recognising that decarbonisation depends upon our capability for governing engineering practice through periods of transition...”.

To further extend VIDA Rail’s contribution to a reset of engineering governance, **Recommendation 3** (“Introduce the Engineer’s Committee Method to Standard-setting at the Sub-National Level”) may be considered.

6.5 Addressing Structure-Level Decarbonisation – Study 1: Transport Interchange Car Park Structure

6.5.1 Background

In this example, we consider a case of a typical multi-storey car parking structure of a form similar to that located adjacent to Berwick Station on the Pakenham rail line in Victoria (Figure 19).

Delivered as part of the Clyde Road level crossing removal project, the Berwick Station car park increases capacity by 661 spaces and supports improved integration with the surrounding transport infrastructure [89]. The need for this structure was justified by its role in connecting bus and private vehicle users to train services, sometimes referred to as ‘last mile transportation infrastructure’. In this manner, it is an example of a case where new structures are considered necessary to meet broader sustainability and climate goals (e.g., reducing traffic and transport emissions by enabling mass public transport). To meet its intended aim, the structure comprises multiple parking decks with an integrated bus interchange at the lower level, enabling combined parking and public transport functions within a single facility [90].



Fig. 19. Berwick Station precinct (Victoria) – example: commuter car park structure and bus interchange.

The primary vertical load-resisting system is constructed from reinforced concrete, comprising one-way slabs supported by band beams, blade-columns and walls. Lateral loads are resisted by shear walls in combination with the columns. In the base design, the walls are taken as cast-in-situ concrete elements, whereas in the as-built configuration, they are precast concrete.

For a structure of this size and nature, the foundation system plays a critical role in overall sustainability, as reflected in A1-A3 embodied carbon and greenhouse gas emissions associated with the structure's delivery. However, the geotechnical characteristics of a site strongly influence the type of foundation required and cannot be assumed based on a typical or standard site condition. Instead, foundation design must be assessed on a case-by-case basis.

For example, a project may initially adopt a deep pile system as part of a base design, but this could later be replaced with a raft foundation, or vice versa. Such changes can significantly alter the required quantities of concrete and reinforcing steel in the below-ground structure. As a result, estimates may either overstate or understate material usage, leading to misleading conclusions about changes in greenhouse gas emissions achieved via design work, whether perceived as savings or increases.

Compared to above-ground structural elements, foundation systems are far more sensitive to early-stage assumptions. Variations arising from preliminary design decisions or the transfer of solutions between sites can introduce substantial inaccuracies. This sensitivity underscores the importance of site-specific analysis and careful validation of assumptions before establishing a base-case design against which design-related emissions reductions are measured.

This study evaluates the sustainability outcomes associated with a reinforced-concrete design. A comparison is made between an issued-for-construction design and an as-built structure.

6.5.2 Baseline definition and structural optimisation approach

As discussed in the previous section, a credible assessment of emissions savings depends on selecting a foundation system that is both suited to site conditions and structurally efficient. Accordingly, the issued-for-construction (IFC) design provides an appropriate baseline against which to measure design improvements, as both the substructure and superstructure have been fully resolved to address site constraints.

From this baseline, subsequent modifications to the structural system – such as replacing cast-in-situ walls with precast panel walls – can deliver measurable material efficiencies. These changes may also enable further reductions in embodied carbon through improved material specifications, including increased clinker replacement via supplementary cementitious materials (SCMs).

6.5.3 Industry benchmark datasets

For this study, industry-average embodied-carbon benchmarks were derived from publicly available EPDs issued by Australian suppliers⁴, with the results summarised in Table 17 and Figure 20.

For the concrete, mix-level A1–A3 GWP100 values were compiled and grouped by compressive strength class (20, 25, 32, 40, 50 and 65 MPa). Each EPD mix was treated as an individual data point, with SCM content capped at 40% cement replacement. The resulting datasets capture the range of typical Australian practice within each strength class, including general-purpose, blended, and moderate-SCM mixes.

Figure 20 indicates that the data are moderately positively skewed, with skewness values ranging from 0.44 to 0.63. The coefficient of variation (CoV) for concretes in the 20–50 MPa range lies between 0.19 and 0.21 (Table 17). The lower CoV observed at 65 MPa is attributed to the smaller number of available EPDs at this strength level.

Given the similar CoVs across the different strength classes, the datasets can reasonably be normalised and combined into a single distribution, as presented in the bottom-right plot of Figure 20. In this plot, each data point is expressed as the ratio of its GWP100 value to the mean GWP100 of its corresponding strength class. For example, for a 32 MPa concrete, the GWP100 value is normalised by dividing by the mean value for that class (252 kg CO₂-e/m³).

Table 17. Summary statistics of embodied carbon for concrete and reinforcement derived from Australia-wide industry EPDs.

Concrete strength grade	n	Average kg CO ₂ -e/m ³	Median kg CO ₂ -e/m ³	CoV	25 th %ile kg CO ₂ -e/m ³	75 th %ile kg CO ₂ -e/m ³
20 MPa	61	208	200	0.195	180	235
25 MPa	63	225	219	0.211	193	257
32 MPa	69	252	248	0.200	218	286
40 MPa	71	299	298	0.198	259	338
50 MPa	62	376	373	0.186	329	423
65 MPa	13	410	380	0.130	374	446
Product	n	Average kg CO ₂ -e/t	Median kg CO ₂ -e/t	CoV	25 th %ile kg CO ₂ -e/t	75 th %ile kg CO ₂ -e/t
Reinforcing steel bar	5	1,312	1,220	0.206	1,110	1,530
Reinforcing steel mesh	2	1,985	1,985	0.032	1,963	2,008
Concrete pipe	14	248	244	0.176	220	276

⁴ Supplier products sampled include: Adbri Concrete; Advanced Readymix; Aurora Construction Materials; Boral; BGC Concrete; Concrite; Elvin Group; Gunlake Concrete; Neilsens Concrete; WA Premix Concrete; InfraBuild; Neumann Steel; Stride Reinforcing; Reozone; Humes; Reinforced Concrete Pipes Australia (RCPA); MJB Industries.

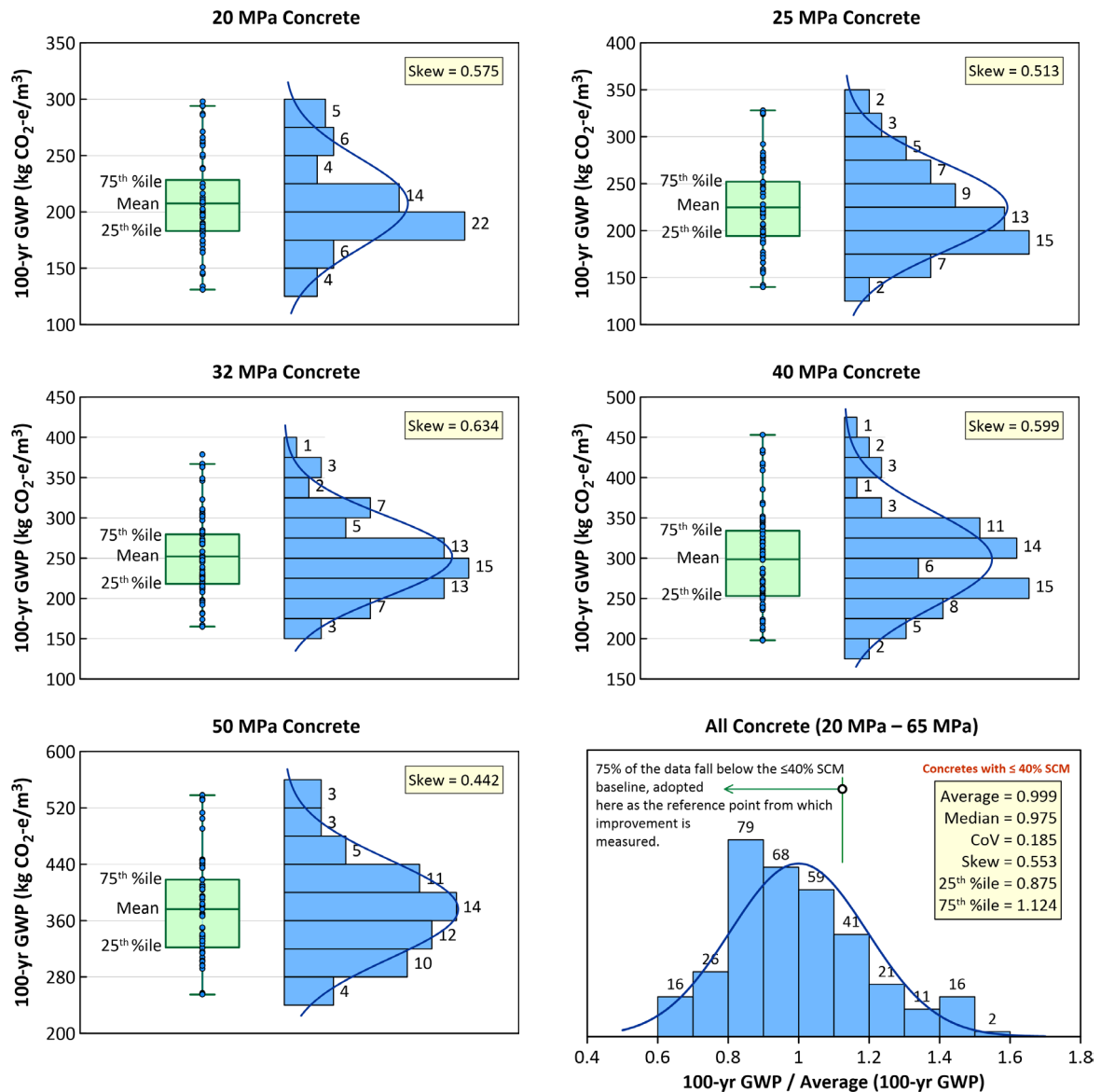


Fig. 20. Statistical distributions of GWP100 for 20–65 MPa concrete based on evaluated EPDs for SCM content ≤ 40%.

While concrete mixes incorporating higher levels of clinker replacement (e.g., 60–70% SCM) are available, they are not common in current Australian practice and typically have much lower production volumes than mixes with lower SCM contents. Including such mixes in unweighted averages will result in artificially low industry-average emission factors. This approach differs from NABERS, which includes a broader range of lower-emission mixes, resulting in materially lower industry-average emission factors against which improvements for benchmarking purposes can be measured.

For reinforcing steel and concrete pipes, each product-level or site-specific EPD was treated as an individual observation. Reinforcing steel datasets include both bar and mesh products from multiple Australian manufacturers. For RC pipes, industry-average embodied carbon values

were derived from Australian EPDs by compiling 100-year GWP data and normalising to one tonne of finished pipe, including all components.

In Table 18, data from several methodologies used to assess emissions are presented, together with CCAA/GCCA rating bands for calculated industry-average values based on industry EPDs for a selected set of mixes with different levels of SCMs.

Table 18. Summary statistics of embodied carbon for concrete and reinforcement derived from Australia-wide industry EPDs.

Concrete mix A1-A3 (kg CO ₂ /m ³)	Base GWP100 - BEF -	Base GWP100 75 th %ile *	NABERS Ind. Ave. EFs	Industry Ave. - by mix -	CCAA/GCCA Ratings Band
Ready Mix Concrete 20MPa 15% SCM	210	230	201	240	Band E
Ready Mix Concrete 20MPa 40% SCM	210	230	201	190	Band D
Ready Mix Conc. 20MPa 40% SCM (lean)	210	230	201	130	Band C
Ready Mix Concrete 25MPa 15% SCM	230	250	222	270	Band E
Ready Mix Concrete 25MPa 20% SCM	230	250	222	260	Band E
Ready Mix Concrete 25MPa 35% SCM	230	250	222	230	Band D
Ready Mix Concrete 25MPa 40% SCM	230	250	222	210	Band D
Ready Mix Concrete 32MPa 15% SCM	250	280	249	300	Band E
Ready Mix Concrete 32MPa 35% SCM	250	280	249	260	Band D
Ready Mix Concrete 32MPa 40% SCM	250	280	249	240	Band D
Ready Mix Concrete 40MPa 15% SCM	300	340	305	350	Band E
Ready Mix Concrete 40MPa 40% SCM	300	340	305	270	Band D
Ready Mix Concrete 65MPa 30% SCM	410	460	402	420	Band E
Ready Mix Concrete 65MPa 40% SCM	410	460	402	370	Band D
No-fines concrete	170	190	181	150	-
Precast concrete 32MPa 0% SCM	260	300	249	310	Band E
Precast concrete 40MPa 0% SCM	320	360	305	370	Band E
Precast concrete 40MPa 15% SCM	320	360	305	350	Band E
Precast concrete 40MPa 40% SCM	320	360	305	270	Band D
Precast concrete 65MPa 40% SCM	420	480	402	370	Band D
Product A1-A3 (kg CO ₂ /tonne)	Base GWP100 - BEF -	Base GWP100 75 th %ile *	NABERS Ind. Ave. EFs	Industry ave - by product -	-
Steel Reinforcing Bar	1310	1480	1600	1220	
Steel Welded Reinforcement Mesh	1990	2240	1600	1940	
Reinforced Concrete Pipes	250	280	233	250	

Note. * Base emissions for the 75th percentile, based on a normal distribution and a CoV of 19%.

Three baseline cases are established for comparison:

1. BEF75 baseline – IFC quantities with 75th-percentile emission factors derived from EPD datasets;
2. NABERS baseline – IFC quantities with NABERS industry-average emission factors; and

3. Industry Average Mix (IAM-EF) baseline – IFC quantities with average EPD-derived emission factors disaggregated by strength grade and SCM content.

The Base GWP100 (BEF) data are those determined as described above and presented in Table 17 (rounded to the nearest 10 units). The BEF75 baseline is derived from BEF by assuming a normal distribution of the data and using the 75th percentile, with a CoV of 18%.

This is taken as the reference point against which improvements in material selection are assessed, representing a distinguishable level at which mixes can be supplied without the deliberate specification of low-GHG alternatives. The adoption of a specific baseline level is discussed further below.

In addition to the EPD-derived datasets, the NABERS Materials Database (Version 2026.1 [48]) was used to provide an independent set of industry-average emission factors. These values are broadly consistent with, but generally lower for concrete (more conservative from a benchmarking perspective), while slightly higher for bar reinforcement and lower for mesh.

In the IAM–EF baseline, concrete mixes are further delineated by level of SCM substitution for a given strength grade. This enables the effects of material specification and structural system optimisation to be separated. It is noted that the “Industry Average by Mix” data represent gross volumes of cement replacement and are not disaggregated by SCM type (e.g., fly ash, GGBFS, limestone, etc.). The corresponding CCAA/GCCA ratings range from E (no or low SCM replacement products) to C (higher SCM replacement).

For the IAM–EF baseline, for consideration of reinforcing steel, the emissions intensity values are taken from InfraBuild's reported data for their N-grade bar and mesh products (as at the time of the study), reflecting its position as the dominant supplier by tonnage in the Australian market. The emissions for RC pipes are taken as the industry average determined in the BEF calculations.

6.5.4 Results and discussion

The results of the analysis are presented in Table 19. The total upfront (A1–A3) embodied carbon for the IFC design is:

- 4,062 t CO₂-e using BEF75 emission factors;
- 3,893 t CO₂-e using NABERS emission factors; and
- 3,735 t CO₂-e using IAM-EF emission factors.

Table 19. Calculation of total A1–A3 emissions for the example car park: material inventory and total GHG emissions based on 100-year GWP.

Total									
Product	units	IFC-BEF75-Base (90 th %ile)	100-yr GWP (tonnes CO ₂ -e)	IFC-NABERS-AVE Base	100-yr GWP (tonnes CO ₂ -e)	IFC-IAM-Base (Ind-Mix Ave.)	100-yr GWP (tonnes CO ₂ -e)	As Built	100-yr GWP (tonnes CO ₂ -e)
Cast-in-situ concrete	Ready Mix Concrete 20MPa 15% SCM	m ³	0.0	0.0	0.0	0.0	0.0	155.0	37.2
	Ready Mix Concrete 20MPa 40% SCM	m ³	2.5	10.7	2.2	10.7	2.0	0.0	0.0
	Ready Mix Concrete 20MPa 40% SCM (lean mix)	m ³	41.3	179.4	36.1	179.4	23.3	0.0	0.0
	Total RMC 20MPa	m³	190	44	38	190	25	155	37
	Ready Mix Concrete 25MPa 15% SCM	m ³	0.0	0.0	0.0	0.0	0.0	134.0	36.2
	Ready Mix Concrete 25MPa 20% SCM	m ³	0.0	0.0	0.0	0.0	0.0	2.0	0.5
	Ready Mix Concrete 25MPa 35% SCM	m ³	0.0	0.0	0.0	0.0	0.0	93.2	21.4
	Ready Mix Concrete 25MPa 40% SCM	m ³	676.9	169.2	150.3	676.9	142.2	222.4	46.7
	Total RMC 25MPa	m³	677	169	150	677	142	452	105
	Ready Mix Concrete 32MPa 15% SCM	m ³	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Ready Mix Concrete 32MPa 35% SCM	m ³	0.0	0.0	0.0	0.0	0.0	29.8	7.7
	Ready Mix Concrete 32MPa 40% SCM	m ³	15.5	4.3	3.9	15.5	3.7	19.4	4.7
	Total RMC 32MPa	m³	16	4	4	16	4	49	12
	Ready Mix Concrete 40MPa 15% SCM	m ³	5919.2	2012.5	1805.3	5919.2	2071.7	1109.4	388.3
	Ready Mix Concrete 40MPa 40% SCM	m ³	0.0	0.0	0.0	0.0	0.0	4253.0	1148.3
	Total RMC 40MPa	m³	5919	2013	1805	5919	2072	5362	1537
Precast Concrete	Ready Mix Concrete 65MPa 30% SCM	m ³	0.0	0.0	0.0	0.0	0.0	155.7	65.4
	Ready Mix Concrete 65MPa 40% SCM	m ³	1.1	0.5	0.4	1.1	0.4	0.0	0.0
	Total RMC 65MPa	m³	1	1	1	1	1	156	65
	No-fines concrete	m ³	178.8	34.0	32.4	178.8	26.8	0.0	0.0
	Total no-fines concrete	m³	178.8	34.0	32.4	178.8	26.8	0.0	0.0
	Precast concrete 32MPa 0% SCM	m ³	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Precast concrete 40MPa 0% SCM	m ³	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Precast concrete 40MPa 15% SCM	m ³	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Precast concrete 40MPa 40% SCM	m ³	666.6	240.0	203.3	666.6	180.0	1553.3	419.4
	Total Precast 40MPa	m³	667	240	203	667	180	1553	419
Reinf.	Precast concrete 65MPa 40% SCM	m ³	109.1	52.4	43.9	109.1	40.4	0.0	0.0
	Total Precast concrete 65MPa	m³	109	52	44	109	40	0	0
	Total concrete (cast-in-situ + precast)	m³	7757	2556	2277	7757	2490	7727	2110
	Steel Reinforcing Bar	tonnes	983.9	1456.2	1574.3	983.9	1200.4	957.9	1168.6
RC pipe	Steel Welded Reinforcement Mesh	tonnes	0.0	0.0	0.0	0.0	0.0	4.9	9.5
	Total Reo steel	tonnes	984	1456	1574	984	1200	963	1178
	Reinforced Concrete Pipes	tonnes	176.4	49.4	41.1	176.4	44.1	171.0	42.8
Total Reinforced Concrete Pipes		tonnes	176	49	41	176	44	171	43
Total 100-year GWP A1-A3 (tonnes CO₂-e)			4062		3893		3735		3331
Comparison with emission factors for the 75th percentile base (BEF75) Comparison with NABERS average emission factors (NABERS-AVE) Comparison with calculated Industry Average Mix emission factors (IAM-EF)									
			4.2%	8.1%	4.1%	10.8%			

In this example, the final as-built structure would achieve a total embodied carbon of 3,331 t CO₂-e, representing reductions across all baseline scenarios.

The results of the analysis, presented in Table 19, show that concrete dominates total emissions, accounting for 2,110 t CO₂-e in the as-built case ($\approx 63\%$ of total). The most significant changes arise from a combination of material substitution and redistribution of volumes across strength classes and construction types, with increased adoption of higher-SCM mixes (e.g., 40% SCM), particularly through substitution to 40 MPa precast elements.

Reinforcing steel contributes 1,178 t CO₂-e in the as-built case, representing the next largest emissions source. Reinforced concrete pipes make only a minor contribution to the overall total.

Relative to the determined BEF75 baseline, the total emissions reduction achieved in this example is 18.0%. When combined with the estimated 18–20% reduction in emissions between 2005 and 2023, as reported in the 2024–2028 LXR Sustainability Strategic Plan [86], this equates to an overall reduction of approximately 36–38% relative to the 2005 benchmark.

A significant portion of this reduction reflects nearly two decades of progress in lower-carbon concrete technologies, particularly the increased adoption of higher-volume SCM mixes. While these mix designs were well established prior to 2005, their uptake at scale has been more gradual in practice, with broader industry adoption emerging only in recent years. As a result, a material share of the observed reduction is attributable to scaling existing technologies rather than to the introduction of fundamentally new ones. Further reductions will be more difficult to achieve and will require measures to accelerate the transition of low-carbon technologies from research to widespread industrial application, faster than in the last two decades.

Compared with the IAM-EF baseline, the total emissions for the as-built structure are 10.8% lower. This reduction reflects structural system optimisation, isolating the impact of design changes (e.g., the transition from cast-in-situ to precast elements and improved material efficiency) while holding emission factors constant at industry-average levels.

6.5.5 Conclusions from the example

Overall, the results demonstrate that reductions in embodied carbon of approximately 36–38% relative to the 2005 benchmark are achieved through a combination of:

- structural system optimisation (e.g. replacement of less sustainably efficient cast-in-situ concrete walls with a more efficient precast solution);
- increased use of higher-SCM concrete mixes; and
- specification of lower-emission materials informed by EPD data.

This list of initiatives represents the currently available solutions, developed over the last twenty years. The results highlight the importance of both identifying new solutions that can further reduce emissions and implementing process changes to accelerate their adoption.

The analysis also highlights the importance of clearly defining the baseline against which emissions savings are measured. In this regard, further work is required to establish an appropriate reference case, particularly the 2005 baseline against which reductions will be assessed.

Finally, a key conclusion from the EPD review is the need to move to volume-weighted benchmarks to support robust modelling and decision-making (in line with **Recommendation 8**). Unweighted statistics that treat all EPDs equally, regardless of production volume or market share, can misrepresent system-wide performance – particularly when mix designs and production scales vary widely. Volume-weighting would provide a more representative basis for assessing embodied carbon and align decisions with real-world impacts rather than dataset artefacts.

6.6 Addressing Structure-Level Decarbonisation – Study 2: Railway Bridge Application

6.6.1 Background

The example considers a railway bridge comprising five simply supported spans, each 33 metres long, for a total span length of 165 metres. Each span contains two precast prestressed concrete U-trough girders, with one girder supporting each rail line direction. The supporting structure comprises two abutments, one at each end of the bridge, and four intermediate piers. The pier heights above foundation level are 2.91 m, 3.45 m, 2.50 m and 1.73 m, respectively. The example is a variation of the arrangement shown in Figure 21, with the dual piers and pier crossheads replaced by a single-pier and crosshead configuration at each pier support.

The assessed structural elements are the abutment pedestals, pile caps, piers, pier crossheads, and U-trough girders. Foundations and below-ground elements, comprising piles and bored piers, are excluded from the assessment. Wing walls and non-load-bearing decorative precast elements are also outside the scope.

The U-trough girders constitute the dominant material quantity in the bridge, with 10 in total, each containing substantial amounts of 65 MPa concrete, reinforcing steel, and prestressing strand. The abutments make the next-largest contribution due to the relatively high quantities of concrete and reinforcement in the pile cap and pedestal components.



Fig. 21. Narre Warren Station precinct (Victoria) – example of a dual-track rail bridge structure and abutment.

6.6.2 Material benchmark basis and assessment cases

The assessment uses 100-year global warming potential values for concrete, bar reinforcement and prestressing strand. The concrete benchmark values are consistent with the EPD-derived material datasets used in the preceding example, in which concrete mixes are grouped by compressive strength class and reported as 25th- and 75th-percentile 100-year GWP values, as presented in Table 17. For the 55 MPa concrete used in the pier crossheads, the GWP values are interpolated from the 50 MPa and 65 MPa data, yielding 340 kg CO₂-e/m³ at the 25th percentile and 430 kg CO₂-e/m³ at the 75th percentile.

For the precast pier crossheads and U-trough girders, the assessment also includes GWP emissions associated with steam curing. The steam-curing allowance is based on 30 litres of diesel per cubic metre of concrete and an emissions factor of 2.7 kg CO₂-e per litre of diesel. For the calculations, this is applied as an additional 80.4 kg CO₂-e per m³ of concrete. This adds 2.5 tonnes CO₂-e for the pier crossheads and 8.9 tonnes CO₂-e for the U-trough girders, giving a total steam-curing addition of 11.4 tonnes CO₂-e in each case. This component can be reduced by using biofuels or renewable energy sources to generate the steam required for the process.

Three cases are considered:

1. **Case 1 – baseline case.** Concrete is assessed using the 75th percentile 100-year GWP values (see Table 17). Bar reinforcement is assessed using 1220 kg CO₂-e/t, and prestressing strand is assessed using 3338 kg CO₂-e/t.

2. **Case 2 – lower-GWP concrete case.** In this case, the baseline concrete in all elements is replaced with lower-carbon concrete products that align with the 25th-percentile emission factors in Table 17. The GWP values for bar reinforcement and prestressing strand remain unchanged from Case 1.
3. **Case 3 – lower-GWP concrete and lower-GWP bar reinforcement case.** In this case, the concrete GWP factors are the same as for Case 2. For the bar reinforcement, selected Grade 500 MPa reinforcing bars are replaced with Grade 600 MPa bars, reducing the bar reinforcement GWP from 1220 kg CO₂-e/tonne to 982 kg CO₂-e/tonne for the replaced bars. The reinforcement area is also reduced proportionally to the increase in yield strength, using a factor of 500/600, corresponding to a 16.7% reduction.

Reinforcement substitution is applied to fitments and reinforcement in non-flexural regions, where bars can be reasonably replaced without affecting member serviceability. This includes all reinforcement in the abutments, the shear and stitch reinforcement in the U-trough girders, the longitudinal bars and ligatures in the piers, and the ligatures in the pier crossheads. The longitudinal bars in the U-trough girders and pier crossheads remain at 500 MPa, and the prestressing strand factor is unchanged.

6.6.3 Basis of the calculations

The calculation was undertaken at the element level by multiplying the material quantities for concrete, bar reinforcement, and prestressing strand by their respective 100-year GWP emission factors. The assessment includes the direct material-level GWP of the bridge elements only (A1-A3). Construction activities, transport, temporary works, maintenance, replacement and end-of-life impacts are not considered in this example. In the following, the volume of concrete is the total volume of the element minus the volume of the reinforcement.

The piers comprise an 1800 mm-wide by 2600 mm-deep obround sections, formed with 50 MPa concrete and reinforced with 64 N40 longitudinal bars for Cases 1 and 2. For Case 3, the reinforcement is replaced with an equivalent-sized 600 MPa-grade bar. For Cases 1 and 2, the transverse reinforcement consists of 12-mm- and 20-mm-diameter ligatures at various spacings. Again, for Case 3, the ligatures are replaced with the equivalent 600 MPa grade bar. For Cases 1 and 2, the total weight of reinforcement is 2.5 tonnes; for Case 3, it is 2.1 tonnes.

The precast pier crossheads are 55 MPa concrete elements. They are 11.8 metres wide and vary in depth, with a maximum depth of 1.8 metres. The width is 1.8 metres. Each crosshead has a concrete volume of 31.3 m³ and a total reinforcement weight of 8.9 tonnes for Cases 1 and 2, and 8.5 tonnes for Case 3. For the baseline case, the four crossheads contribute 63.9 tonnes CO₂-e from concrete (including steam curing) and 43.4 tonnes CO₂-e from reinforcement, for a total of 107.3 tonnes CO₂-e.

The U-trough girders are 65 MPa concrete elements. Each girder has a concrete volume of 109.8 m^3 , along with 36.9 tonnes of reinforcing bar and prestressing strand. For the baseline case, the ten U-trough girders contribute 577.8 tonnes CO₂-e from concrete, including steam curing; 375.1 tonnes CO₂-e from bar reinforcement; and 206.1 tonnes CO₂-e from prestressing strand, giving a total of 1159 tonnes CO₂-e.

Each abutment comprises a pilecap and a pedestal, and is cast with 40 MPa concrete. The pile caps are taken to have dimensions of 13.2 metres long, 6.3 metres wide, and 1.7 metres deep. The pedestals are taken as 13.1 metres long, 1.2 metres wide and 1.7 metres deep. The concrete volume per abutment is 161.7 m^3 , while for Cases 1 and 2, the total weight of reinforcement is 62.7 tonnes. This reduces to 52.9 tonnes of reinforcement for Case 3. For the baseline case, each abutment contributes 54.7 tonnes CO₂-e from concrete and 76.4 tonnes CO₂-e from reinforcement, giving 131 tonnes CO₂-e per abutment and 262 tonnes CO₂-e for the two abutments.

6.6.4 Results and discussion

The results of the analysis of the 100-year GWP values for the three cases are summarised in Tables 20 to 22. Figure 22 compares the 100-year GWP results for the three cases, while Table 23 summarises the total 100-year GWP by material category.

The GWP for the elevated rail line is dominated by the U-trough girders. In Case 1, the baseline bridge total is 1554 tonnes CO₂-e, including the steam-curing allowance for the pier crossheads and U-trough girders. Replacing the baseline concrete with mixes aligned with the 25th-percentile 100-year GWP values reduces the total to 1435 tonnes CO₂-e in Case 2. This is a reduction of 119 tonnes CO₂-e, or 7.7%, without changing the bar reinforcement or prestressing strand emission factors.

Case 3 achieves a further reduction by combining the lower-GWP concrete with selected substitution of Grade 500 MPa reinforcement with Grade 600 MPa reinforcement. This reduces both the reinforcement mass required in the nominated non-flexural regions and the GWP factor applied to the substituted bars. As a result, the total bridge GWP reduces to 1292 tonnes CO₂-e, equivalent to a reduction of 262 tonnes CO₂-e, or 16.9%, relative to the baseline.

At the material-category level, the reduction from Case 1 to Case 2 is entirely attributable to lower-GWP concrete, with concrete emissions decreasing from 765 tonnes CO₂-e to 646 tonnes CO₂-e. From Case 1 to Case 3, concrete emissions reduce by 116 tonnes CO₂-e, while the combined bar reinforcement and prestressing strand emissions reduce by 146 tonnes CO₂-e. The concrete contribution in Case 3 is slightly higher than in Case 2 because the reduced reinforcement mass increases the net concrete volume, as concrete volume is calculated as the total element volume minus the volume of reinforcement.

Table 20. Results of 100-year GWP values for Case 1: Baseline

Element	Concrete (t CO ₂ -e)	Concrete (% of total)	Bars & strand (t CO ₂ -e)	Bars & strand (% of total)	Total (t CO ₂ -e)
Abutments	109.3	7.0%	152.9	9.8%	262.2
Piers	14.2	0.9%	11.0	0.7%	25.1
Pier crossheads	63.9	4.1%	43.4	2.8%	107.3
U-girders	577.8	37.2%	581.2	37.4%	1159.0
Total	765.2	49.3%	788.5	50.7%	1554

Table 21. Results of 100-year GWP values for Case 2: Low-carbon concrete.

Element	Concrete (t CO ₂ -e)	Concrete (% of total)	Bars & strand (t CO ₂ -e)	Bars & strand (% of total)	Total (t CO ₂ -e)
Abutments	83.8	5.8%	152.9	10.7%	236.7
Piers	11.0	0.8%	11.0	0.8%	22.0
Pier crossheads	52.6	3.7%	43.4	3.0%	96.0
U-girders	498.8	34.8%	581.2	40.5%	1080.0
Total	646.2	45.0%	788.5	55.0%	1435

Table 22. Results of 100-year GWP values for Case 3: Low-carbon concrete and low-carbon reinforcement.

Element	Concrete (t CO ₂ -e)	Concrete (% of total)	Bars & strand (t CO ₂ -e)	Bars & strand (% of total)	Total (t CO ₂ -e)
Abutments	84.4	6.5%	104.0	8.1%	188.3
Piers	11.1	0.9%	7.40	0.6%	18.4
Pier crossheads	52.7	4.1%	39.3	3.0%	92.1
U-girders	500.9	38.8%	491.9	38.1%	992.8
Total	649.1	50.2%	642.5	49.8%	1292

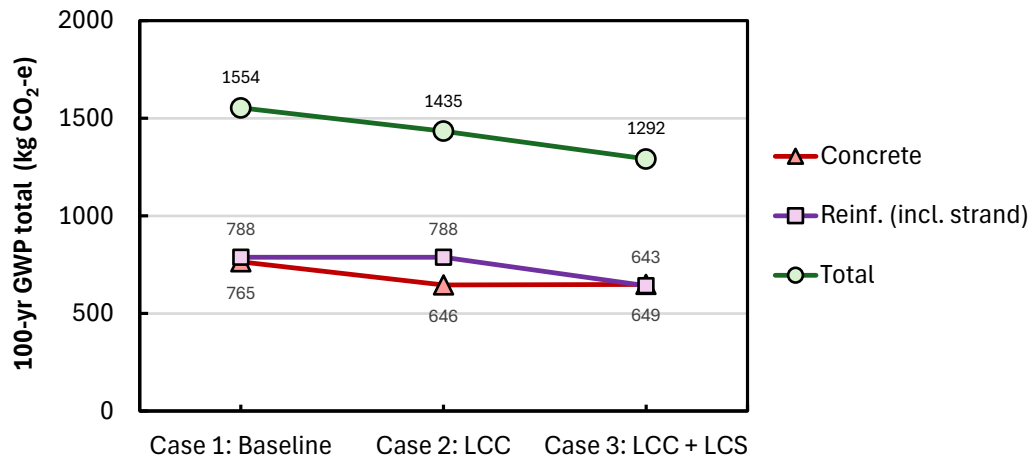


Fig. 22. Comparison of 100-year GWP results for Case 1 (Baseline), Case 2 (Low-carbon concrete), and Case 3 (Low-carbon concrete and low-carbon steel).

Table 23. Summary of the total 100-year GWP by material category.

Case	Concrete (t CO ₂ -e)	Bars & strand (t CO ₂ -e)	Total (t CO ₂ -e)	Redn. from baseline (t CO ₂ -e)	Redn. from baseline (%)
Case 1: Baseline	765	788	1554	–	–
Case 2: Low-carbon concrete (LCC)	646	788	1435	119	7.7%
Case 3: LCC & Low carbon steel	649	643	1292	262	16.9%

The largest reduction opportunity is in the U-trough girders, which contribute 1159 tonnes CO₂-e in Case 1, reducing to 1080 tonnes CO₂-e in Case 2 and 993 tonnes CO₂-e in Case 3. Despite these reductions, they remain the dominant contributor, accounting for approximately 75% – 77% of the total bridge GWP across the three cases.

The abutments provide the second-largest opportunity for reduction, decreasing from 262 tonnes CO₂-e in Case 1 to 237 tonnes CO₂-e in Case 2 and 188 tonnes CO₂-e in Case 3. The Case 3 reduction is primarily driven by the substitution of Grade 500 MPa reinforcement with Grade 600 MPa reinforcement, which is particularly effective in these non-flexural elements due to the high reinforcement quantity in the pile caps and pedestals.

The pier crossheads contribute 107 tonnes CO₂-e in Case 1, reducing to 96 tonnes CO₂-e in Case 2 and 92 tonnes CO₂-e in Case 3. The reduction is more modest than for the abutments and U-trough girders because only selected reinforcement in the crossheads is substituted with Grade 600 MPa bar, while the main longitudinal reinforcement remains Grade 500 MPa.

The piers contribute a comparatively small proportion of the total due to their modest heights and relatively low material quantities. Their contribution reduces from 25 tonnes CO₂-e in Case 1 to 22 tonnes CO₂-e in Case 2 and 18 tonnes CO₂-e in Case 3. Although the absolute reduction is small, the change to Grade 600 MPa reinforcement still provides a measurable reduction in the piers' GWP.

Overall, the results indicate that the most effective reduction strategy is to target the high-volume structural elements, particularly the U-trough girders and abutments. Lower-GWP concrete alone provides a whole-bridge reduction of 7.7%, while combining lower-GWP concrete with selected lower-GWP Grade 600 MPa reinforcement increases the reduction to 16.9%.

6.6.5 Conclusions from the example

The results show that the bridge GWP is strongly controlled by the superstructure, particularly the U-trough girders. The baseline total of 1554 tonnes CO₂-e is reduced to 1435 tonnes CO₂-e by adopting lower-carbon concretes (LCC), in this example, concretes that correspond to the 25th-percentile 100-year GWP values. This represents a 119 tonnes CO₂-e, or 7.7%, whole-bridge reduction without changing the bar reinforcement or prestressing strand emission factors.

A further reduction is achieved when lower-GWP concrete is combined with lower-carbon steel (LCS) reinforcement. In the study, a selected substitution is undertaken: replacing higher-emission Grade 500 MPa reinforcement with lower-emission Grade 600 MPa reinforcement, resulting in lower bar volumes in some regions (corresponding to non-flexural actions). Under Case 3, the total 100-year GWP reduces to 1292 tonnes CO₂-e, corresponding to a reduction of 262 tonnes CO₂-e, or 16.9%, relative to the baseline. At the material-category level, concrete emissions reduce from 765 tonnes CO₂-e in Case 1 to 649 tonnes CO₂-e in Case 3, while combined bar reinforcement and prestressing strand emissions reduce from 788 tonnes CO₂-e to 643 tonnes CO₂-e. The two measures (LCC and LCS) therefore contribute broadly similar magnitudes of whole-bridge reduction.

The analyses indicate that the most effective focus areas for further decarbonisation are the U-trough girders and abutments, which together account for approximately 91%–92% of the total bridge GWP. Opportunities include the use of lower-GWP concrete and the optimisation of shear, stitch and other non-flexural reinforcement. The results also show that reinforcement specification can materially influence total GWP where higher-performance material substitution is feasible. This is particularly relevant to compression-dominated and non-flexural elements, especially where reinforcement quantities are high, such as in pile caps and pedestals, or where non-flexural actions such as shear govern, provided that serviceability requirements, such as crack widths, do not control.

Current prestressing-strand production technologies do not provide a readily available lower-GWP alternative; however, the strand contributes approximately 206 tonnes CO₂-e, 18% of the U-trough girder total and 13% of the whole-bridge baseline GWP. As the industry moves closer to net-zero targets, mechanisms to reduce this component will need to be explored.

7. CONCLUDING REMARKS

This report has examined the decarbonisation of concrete structures and infrastructure in Australia through a multi-layered analysis spanning technical, regulatory, market, and governance dimensions. The work comprised a review of Australian Standards and technical specifications, an assessment of policy and legislative frameworks, and an evaluation of procurement and rating schemes shaping industry practice. These investigations were supported by conversations with professionals across government business enterprises, Standards Australia, asset owners, consultants, and materials suppliers, providing a cross-sector perspective on capabilities, constraints, and emerging pathways.

In addition, the study explored the relationship between lower-carbon concrete products and their application in structural systems and projects. This included an analysis of material technologies, supply chain considerations, and design implications, as well as a detailed case study drawn from the VIDA Rail Low Carbon Concrete Project. Together, these components enabled examination of how embodied-carbon reductions are currently being achieved, the limitations of existing approaches, and the systemic changes required to support the transition toward lower-carbon concrete structures at scale.

It is long recognised that decarbonisation of concrete in Australia cannot be achieved through product substitution alone. While lower-carbon concretes, alternative binders, and higher levels of clinker replacement are all important, the central challenge is broader: a transition in practice. Progress depends on the coordinated evolution of standards, specifications, procurement, testing methods, design approaches, construction methods, and engineering governance, so that emerging materials can be adopted rapidly, credibly, and at scale rather than only through isolated project-level exemplars.

The report highlights a well-recognised conundrum: current barriers are not purely technical, but are embedded in a fragmented regulatory environment, protracted standards revision cycles, multiple sources of specifications with different aims and heads of authority, and approval pathways that are slow, opaque, and poorly aligned with innovation. In this context, standards should be understood not primarily as barriers but as essential instruments that enable legitimate, widespread, and durable transitions in practice. However, for standards to play that enabling role, they must be more responsive and articulate, emphasise performance intent over

prescriptive requirements, and provide better support for pathways to validate new materials, test methods, and design assumptions.

A central conclusion of the study is that engineering governance must be strengthened to reconcile decarbonisation objectives with essential and established requirements for safety, durability, reliability, and public confidence. The historical record indicates that voluntary, consensus-based standard-setting – as exemplified by the Engineers’ Committee Method – has enabled major national transitions and remains a valuable model for the present challenge. The study’s findings underscore the need for renewed engineering leadership, more robust, principled, and transparent deliberative processes, and stronger upstream integration of technical and environmental objectives across both national and subnational standard-setting regimes.

Informed by consultations with supplier representatives, it is evident that no single technology pathway will deliver sector-wide decarbonisation. Future low-carbon concrete mix designs will depend on regional material availability and access to supply chains. In some regions, calcined clay may provide a new source of SCM, while in others, the opportunity may lie in limestone deposits or industrial by-products such as lithium slags and fly ash recovered from ash dams.

Australia’s transition will therefore require a portfolio of solutions, including higher-SCM concretes, alternative binder systems, and improved material efficiency. This portfolio must be supported by standards and specifications that are technically robust yet sufficiently flexible to accommodate regional supply constraints, variations in supplier capabilities, and the need to maintain a level playing field among tier-one, mid-scale, and smaller producers. An effective decarbonisation framework must, in turn, support technological diversity, supply chain equity, and scalable market participation.

The structural case studies undertaken in this project demonstrate that embodied-carbon reduction is not solely a materials-substitution problem. Meaningful reductions are achieved through the interaction of material selection, structural optimisation, constructability, and project-specific design aims and value judgements. Lower-carbon binders can deliver substantial benefits, but these benefits are amplified and translate to tangible structure-level emissions savings when combined with efficient structural systems, reduced material demand, and informed specification using reliable emissions data. The case studies also show that, as emissions from concrete decrease, other materials, particularly reinforcing steel, become more

significant contributors to total embodied carbon. Future decarbonisation efforts must address the structure as a whole rather than solely treat each component in isolation.

As a case study, the VIDA Rail Low Carbon Concrete Project provides a practical demonstration of how some of these challenges are currently being addressed. Its use of explicit long-term embodied-carbon targets, collaboration between sustainability and engineering functions, and coordinated work across materials, standards, and market readiness illustrates how public infrastructure agencies can play a leadership role in reshaping engineering governance for decarbonisation. This case study suggests that state-based delivery authorities can do more than implement policy – they can help create the technical, contractual, institutional, and market conditions required for transition.

A key observation from the case study is the importance of benchmarking against a clearly defined baseline, from which performance can be measured using product EPDs. In this study, the 75th percentile value derived from publicly available EPDs for concretes containing up to 40 per cent SCM was adopted as the reference point. This baseline was selected to reflect a level of performance routinely achievable without the explicit specification of low-GHG alternatives, thereby providing a meaningful starting point for comparison.

Future work should extend beyond the use of a fixed reference year – for example, 2005 as adopted in the LXRPP Sustainability Strategic Plan 2024–2028 [86] – to include explicit emissions benchmarks for the individual material components that constitute the baseline. For a given reference year, methodologies will be needed to accommodate materials and design approaches not widely available at that time. For instance, this includes the treatment of components constructed with higher-strength concrete and reinforcing steel that were not routinely adopted under the design standards of the day but may now be available or become available in the future, and that can lead to more efficient structural solutions with lower GHG emissions than designs constrained by benchmark-era assumptions. That is, while such materials may exhibit higher emissions per unit of product, they can enable lower-emissions outcomes at the structural level.

Overall, the report concludes that the next stage of concrete decarbonisation in Australia will require a shift from incremental improvement within the existing rules toward the deliberate and coordinated evolution of those rules. Faster, more adaptive standards processes; specifications with a clear performance basis; validated test-method frameworks; better carbon

benchmarking; integrated engineering and sustainability functions and requirements; and renewed leadership in engineering governance will all be necessary. Without these enabling conditions, progress will remain fragmented and dependent on exceptional projects and motivated individuals. With them, Australia will be better placed to achieve a rapid, legitimate, and industry-wide transition towards lower-carbon concrete structures and infrastructure.

8. REFERENCES

- [1] World Meteorological Organization, (2025). *State of the Global Climate 2024* (WMO-1368). Geneva: WMO. 37 pp, <https://library.wmo.int/records/item/69455-state-of-the-global-climate-2024> [accessed 9 December 2025].
- [2] Our World in Data, <https://ourworldindata.org/co2-and-greenhouse-gas-emissions> [accessed 6 December 2025].
- [3] World Commission on Environment and Development (WCED). (1987). *Our Common Future*. Oxford: Oxford University Press.
- [4] Engineers Australia. (2022). *Code of Ethics and Guidelines on Professional Conduct*. Barton, ACT, Australia. 4 pp. (<https://www.engineersaustralia.org.au/publications/code-ethics>) [accessed 9 December 2024].
- [5] Engineers Australia. (2021). *Our position on climate change*. Engineers Australia. <https://www.engineersaustralia.org.au/publications/our-position-climate-change> [accessed 9 November 2025].
- [6] Intergovernmental Panel on Climate Change (IPCC), (2022). *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.
- [7] Andrew, R.M., 2019. Global CO₂ emissions from cement production, 1928–2018. *Earth System Science Data* 11, 1675–1710, updated October 7, 2025 (<https://doi.org/10.5281/zenodo.831454>) [accessed 9 December 2025].
- [8] United Nations Environment Programme (UNEP), (2024). *Emissions Gap Report 2024*. Nairobi: UNEP, 96 pp. (<https://www.unep.org/resources/emissions-gap-report-2024>) [accessed 9 December 2025].
- [9] World Economic Forum (2024). *Net-Zero Industry Tracker 2024 Edition: Cement Industry*, Geneva, World Economic Forum, 14 pp (<https://www.weforum.org/publications/net-zero-industry-tracker-2024/cement-industry-net-zero-tracker-2024>) [accessed 25 February 2026].

- [10] VDZ, (2021). Decarbonisation pathways for the Australian cement and concrete sector (report commissioned by *Cement Industry Federation, Cement Concrete & Aggregates Australia, SmartCrete CRC and RACE for 2030 CRC*), 55 pp, [full_report_decarbonisation_pathways_web_single_page-3.pdf](#) (accessed 1 February 2026).
- [11] Austroads, Carbon Reduction and the Use of Low Carbon Concrete, Research Report AP-R757-26, Austroads, Sydney, 2026, 116 pp, <https://austroads.gov.au/publications/bridges/ap-r757-26> (accessed 28 March 2026).
- [12] Markard, J., Raven, R., and Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects, *Res. Policy*, Vol. 41, No. 6, pp. 955–967, doi:10.1016/j.respol.2012.02.013.
- [13] Geels, F.W. (2005). The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930), *Technol. Anal. Strateg. Manag.*, Vol. 17, No. 4, pp. 445–476, doi:10.1080/09537320500357319.
- [14] Patterson, J., et al. (2017). Exploring the governance and politics of transformations towards sustainability, *Environ. Innov. Soc. Transit.*, Vol. 24, pp. 1–16, doi:10.1016/j.eist.2016.09.001.
- [15] Barbhuiya, S., Kanavaris, F., Das, B.B., and Idrees, M. (2024). Decarbonising cement and concrete production: Strategies, challenges and pathways for sustainable development, *J. Build. Eng.*, Vol. 86, p. 108861, doi:10.1016/j.job.2024.108861.
- [16] S. Griffiths et al. (2023). Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options, *Renew. Sustain. Energy Rev.*, Vol. 180, p. 113291, doi:10.1016/j.rser.2023.113291.
- [17] Heinz, E., Sovacool, B. K., Kwan, T., and Petit, V. (2025). Reviewing the 95 sociotechnical barriers to the decarbonization of buildings, *Nat. Commun.*, Vol. 16, p. 9983, doi:10.1038/s41467-025-64923-9.

- [18] Kemp, R., Schot, J., and Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management, *Technol. Anal. Strateg. Manag.*, Vol. 10, No. 2, pp. 175–198, doi:10.1080/09537329808524310.
- [19] Schot, J., and Geels, F.W. (2008). Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy, *Technol. Anal. Strateg. Manag.*, Vol. 20, No. 5, pp. 537–554, doi:10.1080/09537320802292651.
- [20] Stoddard, I., et al. (2021). Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve?, *Annu. Rev. Environ. Resour.*, Vol. 46, pp. 653–689, doi:10.1146/annurev-environ-012220-011104.
- [21] Wang, C., Foster, S., Care, R., Kearnes, M., Fisher, R., and Stuetz, R., Standards in Transition: Aligning Governance, Practice, and Research for Concrete Decarbonisation, *fib Congress 2026*, Lisbon, Portugal, 15–19 June, 2026 (under review).
- [22] Infrastructure Transport Ministers (2024), Embodied carbon measurement for infrastructure: Technical guidance, 112 pp., <https://www.infrastructure.gov.au/sites/default/files/documents/embodied-carbon-measurement-for-infrastructure.pdf> [accessed 9 December 2025].
- [23] CCAA (2025). Australian adoption of the Global Cement and Concrete Association Global Ratings for Low Carbon and Near Zero Concrete (Version 1.0), *Cement Concrete & Aggregates Australia*, 9 pp., [CCAA_Australian Adoption of GCCA Global Ratings for Concrete 08.12.25 - 03.pdf](https://www.ccaa.com.au/wp-content/uploads/2025/08/03.pdf) [accessed 8 February 2026].
- [24] MECLA (2025). Guide to Low Carbon Concrete in Australia, Version 2, *Materials and Embodied Carbon Leaders' Alliance*, 11 pp., <https://mecla.org.au/wp-content/uploads/2026/01/MECLAs-guide-to-low-carbon-concrete-Version-2.0.2.pdf> [accessed 8 February 2026].
- [25] Buch, A. (2016). Ideas of holistic engineering meet engineering work practices, *Eng. Stud.*, Vol. 8, No. 2, pp. 140–161, doi:10.1080/19378629.2016.1197227.
- [26] Aslaksen, E.W. (2023). Freedom and Standards in Engineering, in *Rethinking Technology and Engineering: Dialogues Across Disciplines and Geographies* (A.

- Fritzsche and A. Santa-María, Eds.), *Cham: Springer International Publishing*, pp. 43–53. doi:10.1007/978-3-031-25233-4_4.
- [27] Taylor, E. (1998). Peeling the Onion: A Technosprudence for Engineering, in Proceedings of the Tenth Annual Conference and Congress, Gladstone, QLD, Australia.
- [28] McLaughlin, D. (2021). Engineering, Judgement and Engineering Judgement: A Proposed Definition, in Engineering and Philosophy: Reimagining Technology and Social Progress (Z. Pirtle, D. Tomblin, and G. Madhavan, Eds.), *Cham: Springer International Publishing*, pp. 199–217. doi:10.1007/978-3-030-70099-7_10.
- [29] Yates, J., and Murphy, C.N. (2021). Engineering Rules: Global Standard Setting since 1880. in Hagley Library Studies in Business, Technology, and Politics. *Johns Hopkins University Press*, doi:10.1353/book.66187.
- [30] Bowker, G.C., and Star, S.L. (1999). Sorting Things Out: Classification and Its Consequences. *The MIT Press*, doi:10.7551/mitpress/6352.001.0001.
- [31] Higgins, W. (2005). Engine of change : Standards Australia since 1922. *Brandl & Schlesinger*, Blackheath, NSW, Australia, 390 pp.
- [32] Barry, A. (2001). Political machines : governing a technological society. London: *Athlone Press*, 305 pp.
- [33] Easterling, K. (2016). Extrastatecraft: the power of infrastructure space, *Verso*, London New York, 304 pp.
- [34] Schön, D.A. (2016). The reflective practitioner : how professionals think in action, *Routledge*, London, England, 374 pp.
- [35] Busch, L. (2011). Standards: Recipes for Reality, *MIT Press*, Cambridge, MA, 360 pp, doi:10.7551/mitpress/8962.001.0001.
- [36] Spruyt, H. (2001). The supply and demand of governance in standard-setting: insights from the past, *J. Eur. Public Policy*, Vol. 8, No. 3, pp. 371–391, doi:10.1080/13501760110056022.

- [37] Trevelyan, J., Towards a theoretical framework for engineering practice, Chapter 2, Engineering practice in a global context (in Williams, B., Figueiredo, J. and Trevelyan, J., eds), CRC Press, USA, FL, CRC Press, 2013, 302 pp.
- [38] Lord, M. et al. (2017). Rethinking cement: Zero carbon industry plan (Zero Carbon Australia report). *Beyond Zero Emissions Inc*, 95 pp.
<https://www.bze.org.au/research/report/rethinking-cement> (accessed 1 February 2026).
- [39] GBCA (2016), Green Building Council of Australia, Case Studies, Buildings, Pixel Building: Materials, 2016, <https://new.gbca.org.au/case-studies/building/pixel-building-materials/> (accessed 1 February 2026).
- [40] Aldred, J., and Foster, S. (2025), Development of Alternative Binder Concrete Systems and Their Implementation into Practice, *Concrete 2025*, 31st Biennial National Conference of the Concrete Institute of Australia, Adelaide, 7–10 September, 7 pp.
- [41] Castel A., Nguyen Q. D., Law D., Kim T., Samson G., Cyr M., Provis J. L. & Li W. (2025), Recommendation of RILEM TC 283-CAM: performance-based assessment of alkali-activated concrete durability using the 10 V rapid chloride permeability test. *Materials and Structures*, 58, article 219, 8 pp. (<https://doi.org/10.1617/s11527-025-02738-2>).
- [42] Mostazid, Md, I, Kim, T., Foster, S., Ben, B., Asadi, H., and Hajimohammadi, A. (2026), “Inconsistencies in Rapid Chloride Permeability Testing of Geopolymer Concrete: Insights into Binder Chemistry, Pore Structure, and Test Cell Configuration, *Cement and Concrete Composites*, Vol. 165, 106340, 20 pp.
(<https://doi.org/10.1016/j.cemconcomp.2025.106340>).
- [43] Mostazid Md.I., Kim, T., Foster, S., Ben, B., Asadi, A., and Hajimohammadi, A., “Performance-Based RCPT Specification for Geopolymer Concrete: Modified Voltage Protocol and Chloride Resistance Classification, *Cement and Concrete Composites*, 170, 2026, 106557, 23 pp., (<https://doi.org/10.1016/j.cemconcomp.2026.106557>).
- [44] Green Building Council Australia (GBCA), A Climate Positive Roadmap for the Built Environment, for Buildings and Fitouts, Rev. B July 2021.

- <https://new.gbca.org.au/green-star/green-star-strategy/carbon-climate-change/> [accessed: 19 March 2026].
- [45] International Sustainability Council, IS Ratings, <https://www.iscouncil.org/is-ratings/> [accessed 9 December 2025].
- [46] ISCA, Materials Life Cycle Assessment (LCA) Guideline, Infrastructure Sustainability Council of Australia (ISCA), Version 1.0, 2021, 19 pp,
- [47] Vickers, J., Sullivan, N., Davies, A., Kogileru, T., and Wouters, T. (2022), Embodied emissions: Technical report (v1.0), *Thinkstep Pty Ltd for NABERS*, https://www.nabers.gov.au/sites/default/files/2022-12/NABERS%20-%20Embodied%20Emissions%20-%20Technical%20Report.pdf?trk=public_post_comment-text [accessed 9 December 2025].
- [48] National Australian Built Environment Rating System. NABERS Embodied Carbon. <https://www.nabers.gov.au/ratings/our-ratings/nabers-embodied-carbon> [accessed 4 April 2025].
- [49] Australian Government, Net Zero - Built Environment Sector Plan, 2025, 26 pp., <https://treasury.gov.au/publication/p2025-698821> (accessed 23 March 2026).
- [50] Low Carbon Materials Hub (LCMH), <https://www.lcmhub.com/materials/concrete> [accessed 25 February 2026].
- [51] Lower Carbon Concrete Group (LCCG), Market Benchmark Data, 2025, United Kingdom, <https://www.lccg.uk/home/current-activities/lccg-market-benchmark> [accessed 25 February 2026].
- [52] ARUP, Embodied Carbon Classification Scheme for Concrete, Revision 1, 2023, 47 pp., <https://www.arup.com/insights/embodied-carbon-classification-scheme-for-concrete/> [accessed 19 March 2026].
- [53] Crawford, R.H., Stephan, A. and Prideaux, F. (2024). Environmental Performance in Construction (EPiC) Database, The University of Melbourne, Melbourne,

(https://figshare.unimelb.edu.au/articles/book/EPiC_Database/10257728 [accessed 25 February 2026].

- [54] Hammond, G.P., and Jones, C.I., Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers: Energy, Vol. 161, Issue 2, 2008, pp. 87–98 (<https://doi.org/10.1680/ener.2008.161.2.87>).
- [55] Circular Ecology (2025), Inventory of Carbon & Energy (ICE) Database. Version 4.1. Circular Ecology Ltd., <https://circularecology.com/embodied-carbon-footprint-database.html> [accessed 25 February 2026].
- [56] Boral's Environmental Product Declarations (EPDs), <https://www.boral.com.au/sustainability/borals-environmental-product-declarations-epds> [accessed 25 February 2026].
- [57] Ng, T.S., Voo, Y.L., and Foster, S.J. (2012). Sustainability with Ultra-High Performance and Geopolymer Concrete Construction, Innovative Materials and Techniques in Concrete Construction, Chapter 5 [Ed. M.N. Fardis], *Springer Science+Business Media B.V.*, 379 pp.
- [58] Richard, P. and Cheyrezy, M.-H. (1994). Reactive powder concretes with high ductility and 200–800 MPa compressive strength, ACI SP-144, Vol. 24, pp. 507–518.
- [59] Rangan, B. V. (2008). Fly ash based geopolymer concrete, Research Report GC 4, Curtin University of Technology, Perth.
- [60] Witherspoon, R., Wang, H., Aravinthan, T. and Omar, T. (2009). Energy and emissions analysis of fly ash based geopolymers, Proc. Society for Sustainability & Environmental Engineering Int. Conf., Melbourne, Australia.
- [61] Xie, Y., Liu, Y. and Long, G. (2008). Long-term durability of cement-based materials with very low w/b, J. Wuhan Univ. Technol. – Mater. Sci. Ed., Vol. 23, pp. 303–308.
- [62] Provis, J. L., Lukey, G. C. and van Deventer, J. S. J. (2005). Do geopolymers actually contain nanocrystalline zeolites? – A re-examination of existing results, Chem. Mater., Vol. 17, No. 12, pp. 3075–3085.

- [63] Voo, Y. L. and Foster, S. J. (2010). Characteristics of ultra-high performance ‘ductile’ concrete and its impact on sustainable construction, IES J. A: Civ. Struct. Eng., Vol. 3, No. 3, pp. 168–187.
- [64] Graybeal, B. A. (2006). Material property characterisation of ultra-high performance concrete, FHWA-HRT-06-103, Federal Highway Administration, United States.
- [65] Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C., Palomo, A. and van Deventer, J. S. J. (2007). Geopolymer technology: the current state of the art, J. Mater. Sci., Vol. 42, No. 9, pp. 2917–2933.
- [66] Juenger, M.C.G., Winnefeld, F., Provis, J.L. and Ideker, J.H. (2011). Advances in alternative cementitious binders, Cement and Concrete Research, Vol. 41, No. 12, pp. 1232–1243.
- [67] Fu, J., Bligh, M.W., Shikhov, I., Jones, A.M., Holt, C., Keyte, L.M., Moghaddam, F., Arns, C.H., Foster, S.J., and Waite, T.D., A microstructural investigation of a Na₂SO₄ activated cement-slag blend, Cement and Concrete Research, Vol 150, 2021, 106609, 13 pp.
- [68] Huntzinger, D. N. and Eatmon, T. D. (2009). A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies, J. Clean. Prod., Vol. 17, No. 7, pp. 668–675.
- [69] Muntingh, Y. (2006). Durability and diffusive behaviour evaluation of geopolymeric material, M.Sc. Thesis, University of Stellenbosch, South Africa.
- [70] Tuutti, K. (1982). Corrosion of steel in concrete, Swedish Cement and Concrete Research Institute, Stockholm.
- [71] Tanaka, Y., Kawano, H., Watanabe, H. and Nakajo, T. (2001). Chloride-induced deterioration and its influence on load carrying capacity of post-tensioned concrete bridges, Proc. 3rd Int. Conf. on Concrete under Severe Conditions, Vancouver, pp. 495–502.
- [72] National material emission factors database – V2026.1 [accessed 9 March 2026]:
<https://www.nabers.gov.au/publications/national-emission-factors-database>

- [73] Humes Precast and Prestressed Concrete Products, Environmental Product Declaration, EPD Registration no. S-P-01545, Version 1.0, <https://www.holcim.com.au/humes/sustainability/epd> [accessed 9 March 2026].
- [74] Muttoni, A., Fernández Ruiz, M., Bentz, E., Foster, S. and Sigrist, V., Background to the Model Code 2010 Shear Provisions – Part II Punching Shear, Structural Concrete, Vol. 14, No. 3, 2013, pp. 195–203 (<https://doi.org/10.1002/suco.201200064>).
- [75] Hanein, T. *et al.*, Calcined clays as a low-carbon substitute for cement: A state-of-the-art review, Materials and Structures, Vol. 55, No 3, 2022, 23 pp. (<https://doi.org/10.1617/s11527-021-01807-6>).
- [76] Zunino, F., Boehm-Courjault, E. and Scrivener, K.L, The impact of calcite impurities in clays containing kaolinite on their reactivity in cement after calcination, Materials and Structures, Vol. 53, No. 44, 2020, 15 pp. (<https://doi.org/10.1617/s11527-020-01478-9>).
- [77] National Cement Company of California, Environmental Product Declaration (EPD) for Cement Produced at Lebec, California Operation, 2025, 5 pp. https://www.astm.org/v3/assets/blt5eb0a2cb04534832/blta5be8e291148bf07/67f7c80371341502cbdfc6a7/EPD_Lebec_FINAL_040082025.pdf [accessed 20 March 2026].
- [78] Holcim Emirates Cement, Environmental Product Declaration, Calcined Clay Cement, 2025, 16 pp., <https://www.environdec.com/library/epd25703> [accessed 20 March 2026].
- [79] CCB SA, Cementir Holding, FUTURCEM® - CEM II/B-M (Q LL 52.5 N), Environmental Product Declaration, EPD-IES-0026434:001, CCB Cie Des Ciments Belges, 20 pp., 2025, <https://www.environdec.com/library/epd26434> [accessed 20 March 2026].
- [80] Scrivener, K., Martirenab, F., Bishnoic, S., and Maityd, S., Calcined clay limestone cements (LC³), Cement and Concrete Research, Vol. 114, 2018, pp. 49-56.
- [81] Gettu, R., Pillai, R.G., Santhanam, M., Rengaraju, S., Dhandapani, Y., Rathnarajan, S. and Basavaraj, A.S, Sustainability-based decision support system for choosing concrete mixtures, Materials and Structures, Vol. 51, No. 165, 2018, 16 pp.

- [82] VIDA Rail, Victoria's Big Build, <https://bigbuild.vic.gov.au/about/vida/vida-rail> (accessed 2 April 2026).
- [83] Victorian Government 2026, Level Crossing Removal Project, Victoria's Big Build, <https://bigbuild.vic.gov.au/projects/level-crossing-removal-project> (accessed 14 April 2026).
- [84] VIDA, Victorian Infrastructure Delivery Authority, Transport Infrastructure Decarbonisation Strategy, 2024, 20 pp, <https://bigbuild.vic.gov.au/library/victorias-big-build/decarbonisation-strategy> (accessed 2 April 2024).
- [85] Level Crossing Removal Project (LXRP), Low Carbon Concrete Project (LCCP), Plan on a Page, 2025 [private communications].
- [86] Level Crossing Removal Project (LXRP), Sustainability Strategic Plan 2024–2028, 20 pp. [private communications].
- [87] Science Based Targets, SBTi Corporate Net-Zero Standard, Version 1.3, 2025, 86 pp, <https://sciencebasedtargets.org/net-zero> (accessed 2 April 2026).
- [88] VIDA Rail, Low Carbon Concrete Project (LCCP) - Workstream 1 Materials and Technology, 2025, 12 pp. (Private Communications).
- [89] Berwick Star News, Multi-deck car park for Berwick Station, 29 October, 2022, <https://berwicknews.starcommunity.com.au/news/2022-10-29/multi-deck-car-park-for-berwick-station/> (accessed 4 April 2026).
- [90] Better Future Awards, Berwick carpark and bus interchange, GOV Design Awards, 2024, <https://betterfutureawards.com/gov24/project.asp?ID=31402> (accessed 4 April 2026).