Embodied Emissions Study plus Sustainability and Durability Optimised Materials Specification and Design on an Australian Transport Infrastructure Project

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Abstract: The infrastructure sector faces significant challenges in reducing its carbon footprint, despite almost a quarter of upfront emissions from construction activity over the next five years being potentially abatable at no additional cost by employing practical decarbonisation strategies. Until recently, project-level decarbonisation efforts often began, at best, late in the planning process, jeopardising realisation of full carbon reduction potential and reducing carbon reduction achievements quasi-exclusively to value engineering opportunities. Now, engineering design and construction companies are rapidly increasing their embedment of sustainability and emissions reduction considerations in all stages of a project lifecycle as industry participants, together, continue a journey towards net zero.

This paper presents an embodied carbon emissions study completed early in the detailed design stage of a recent Australian transport infrastructure project involving head contractor Laing O'Rourke and designer Arcadis. The study reviewed various innovative, low carbon concrete mixes, 100% renewable and recycled structural steels and alternative concrete reinforcing (high strength steel and glass fibre reinforced bar) products. Its aim was to investigate the technical feasibility of the options in terms of structural design, durability, supply chain and constructability risks and impacts (both positive and negative) and determine the greenhouse gas emissions reduction potential of each option.

This paper then discusses, building on this study, the final sustainability-optimised materials design on the project, the reasons for it, any effects of this on the structural and durability design and the greenhouse gas emissions reduction benefits of these design decisions relative to a typical base case design.

Keywords: Low carbon, concrete, steel, sustainability, infrastructure

1. INTRODUCTION

According to Infrastructure Australia's Embodied Carbon Projections for Australian Infrastructure and Buildings report (1), buildings and infrastructure are currently directly responsible for almost one-third of Australia's total carbon emissions, and indirectly responsible for over half of all emissions (Figure 1). The infrastructure sector faces significant challenges in reducing its carbon footprint, despite almost a quarter of upfront emissions from construction activity over the next five years being potentially abatable at no additional cost (1) by employing practical decarbonisation strategies, such as material substitution.

Until recently, project-level decarbonisation efforts often began, at best, late in the planning and design process. Given that over two-thirds of the total potential to reduce the carbon emissions over a project lifecycle occur in the planning and design phases (Figure 2) (2), this has meant an inability to realise the full carbon reduction potential of a project.

Thankfully, a growing number of asset owners, engineering design and construction companies are now rapidly increasing their embedment of sustainability and emissions reduction considerations in all stages of a project lifecycle as industry participants continue their journey towards net zero. Aligned with this aim, an embodied carbon emissions study was completed early in the detailed design stage of a recent Australian transport infrastructure project.

The study reviewed various innovative low carbon concrete mixes, 100% renewable and recycled structural steels and alternative concrete reinforcing (high strength steel and glass fibre reinforced bar) products. Its goal was to investigate the technical feasibility of the low carbon material options in terms of their risks and impacts (both positive and negative) on structural design, durability, supply chain and constructability considerations and calculate the greenhouse gas emissions reduction potential of each option.

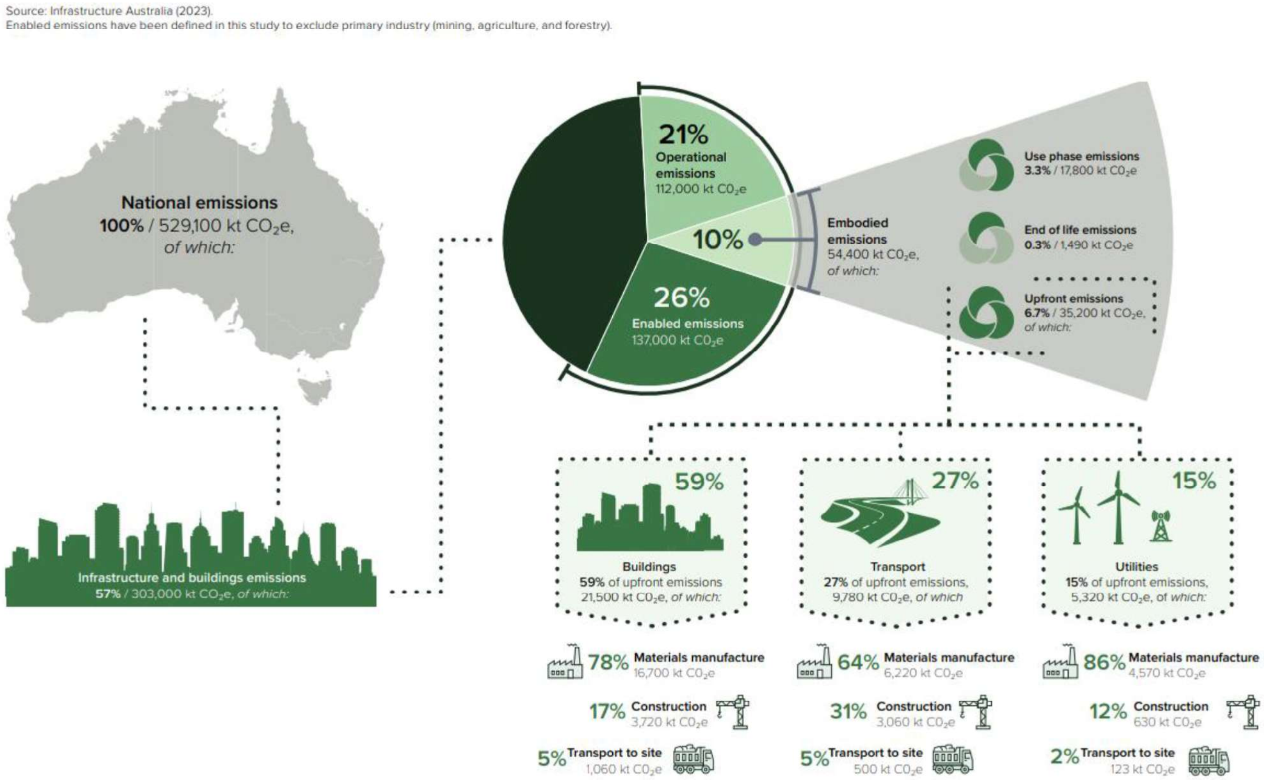

Figure 1. Carbon emission projections for Australian infrastructure and buildings, 2023.

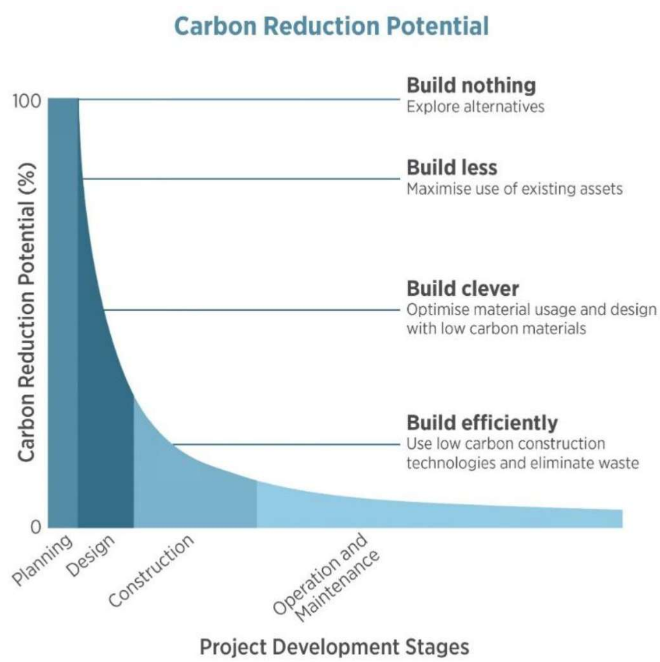

Figure 2. Opportunities to reduce embodied carbon from stages of a project's lifecycle (source: World Green Building Council: Bringing Embodied Carbon Upfront, 2019)**.**

The findings of this construction materials embodied emissions study were then considered collaboratively by the contractor and designer in the further development and finalisation of detailed design, and in procurement activities for the construction of the project. This paper discusses this embodied emissions study, the sustainability and carbon reduction requirements of the project in the owner's project specifications, the final sustainability-optimised materials design on the project, the reasons for it, any effects of this on the structural and durability design and the greenhouse gas emissions reduction benefits of these design decisions relative to a typical base case design.

2. ASSET OWNER PROJECT REQUIREMENTS

2.1 Sustainability Requirements

The owner's contractual specifications for the project contained numerous requirements with the aim of ensuring sustainability and carbon reduction in design, construction and materials use on the project, as well as for the operation phase. These are summarised in Figure 3.

25% min. GHG emission reduction	35% SCMs in project concrete (weighted average)	Max. cementitious contents for various concrete grades	Min. 40% of coarse agg. is crushed slag
Min. 50% of fine agg. is manufactured sand.	Min. 30% Fly Ash or 55% Slag cement content	Min. 50% Fly Ash or 70% Slag cement content in elements > 500mm (w/c < 0.4)	Triple blend mixes as alternatives
TfNSW Sustainable Design Guide V4 Gold Rating (Fig. 4) (3)	20% min. reduction in total annual operational energy consumption	100% offset of scope 1 and 2 emissions	Address impacts of climate change in design

Figure 3. Snapshot of the project's sustainability-related requirements.

The potential impacts of climate change needing to be considered are:

- an increase in the design serviceability limit state wind speed;
- a minimum unfactored load of 1 kPa must be applied for the weight of hail in the design of structures supporting surfaces on which hail can build up;
- an increase in the maximum and a decrease in the minimum values of ambient temperature for the purpose of calculation of thermal loads; and
- an increase in the concentration of carbon dioxide for the purpose of durability design.

There is also a requirement to minimise the use of materials where possible by encouraging the use of finished structural materials as the final face, avoiding layers of cladding and decorative materials where the appropriate quality of finishes can be achieved.

Rating	Percentage of points
Pass	All applicable P1 performance level requirements must be met.
Bronze	All applicable P1 performance level requirements and minimum 85% of the total applicable points in the P2 column.
Silver	All applicable P1 performance level requirements and minimum 85% of the total applicable points in the P3 column.
Gold	All applicable P1 performance level requirements and minimum 85% of the total applicable points in the P4 column.
Platinum	All applicable P1 performance level requirements and minimum 85% of the total applicable points in the P5 column.

Figure 4. Client Requirements to achieve Sustainable Design Guidelines ratings.

In the authors' experience, the owner's specifications for this project had a noticeably increased focus on sustainability and carbon reduction requirements, compared to most other Australian transport infrastructure and other built environment sector projects.

2.2 Sustainability Challenge

Contract requirements aside, Laing O'Rourke and Arcadis had early engagement with the asset owner to discuss the idea of delivering an exemplar low embodied emissions transport infrastructure project. The client encouraged the contractor and designer to go beyond the minimum requirements of the contract and to work with their sustainability teams to achieve the best possible outcome. This challenge by the end client was the true driver of the sustainability efforts that took place in this project.

2.3 Durability Requirements

In terms of whole of lifecycle carbon intensity of a built asset, it is advantageous to design and construct an asset that has high durability and hence a lower operational maintenance burden and longer time intervals between significant remedial measures to extend its safe operation service life. The owner's contractual specifications for the project understood this and contained the following key requirements related to durability:

- A long 120 year design life was required for most structures and built environment components, except where replaceable and maintainable.
- Design Life was defined in relation to each asset as:
    - the period specified for a listed asset commencing on the Date of Completion and ending on the day after expiry of the period specified for that asset; and
    - if the asset is replaced or refurbished during the Term, the period specified for that asset commencing on the date the asset is replaced or refurbished and ending on the day after expiry of the period specified for that asset.

3. LOW CARBON CONSTRUCTION MATERIALS EMBODIED EMISSIONS STUDY

Early in the detailed design phase of the project, Laing O'Rourke engaged Arcadis to complete an embodied emissions scenario assessment of selected innovative, low carbon construction materials and products. The purpose of the assessment was to investigate the high-level technical feasibility and greenhouse gas emissions reduction potential of a number of alternative material options. Materials investigated included low content to Portland cement-free concrete mixes, higher strength steel reinforcement and glass fibre reinforcement products, and low embodied emissions and/or high strength structural steel products.

A technical, comparative assessment factoring multiple criteria (Figure 5) was undertaken for the following products:

- Certain concrete lowest embodied emission products from various major project concrete suppliers in the local market, including: 40 and 50 MPa strength grade, B1 and B2 Exposure Classification (AS 5100.5), ternary blend concrete mixes containing varying percentages of GP or SL Cement, Fly Ash and Ground Granulated Blast Furnace Slag.
- Alkali-activated, Portland cement-free geopolymer concrete 40 and 50 MPa products available in the market.
- Reinforcement products including higher strength grade steels (600 MPa and 750 MPa grade) and glass fibre reinforced polymer (GFRP) and basalt reinforcing bar products.
- A low carbon structural steel product available in the market.

Figure 5. High-level criteria assessed in the embodied emissions study.

The outcome of the technical assessment for each assessed product was presented as a performance indicator on a performance scale compared to the Business As Usual (BAU) scenario:

- "Poor" indicates a performance level that is worse than the BAU case.
- "Comparable" indicates a performance level that is similar or equivalent to the BAU case.
- "Good" refers to a performance level that is slightly better than the BAU case.
- "Very good" indicates a performance level that is better than the BAU case.
- "Excellent" refers to a performance level that is significantly better than the BAU case.

Business As Usual scenarios used as the baseline to measure the assessment against included:

- Grade 300 structural steel and 500 MPa steel reinforcing bar.
- A concrete mix with a 25 per cent Supplementary Cementitious Material (SCM) content that complies with clause 4.4.1(A) and (B) of AS5100.5, and generally complies with AS 1379 and TfNSW QA Specification B80.

Emission factors and other calculation parameters used for calculating embodied greenhouse gas emissions were taken from the Sydney Metro Carbon Tool and, if not available in that resource for certain parameters, the Infrastructure Sustainability Council IS Materials Calculator.

3.1 Assessment Criteria – Concrete Mixes

Compliance with the requirements of applicable standards including TfNSW B80 Concrete Work for Bridges, AS 3600, AS 5100.5, AS 1379 and the contract specifications was assessed for concrete mixes as part of this embodied emissions study. Figure 6 shows the other criteria that were also assessed for concrete mixes.

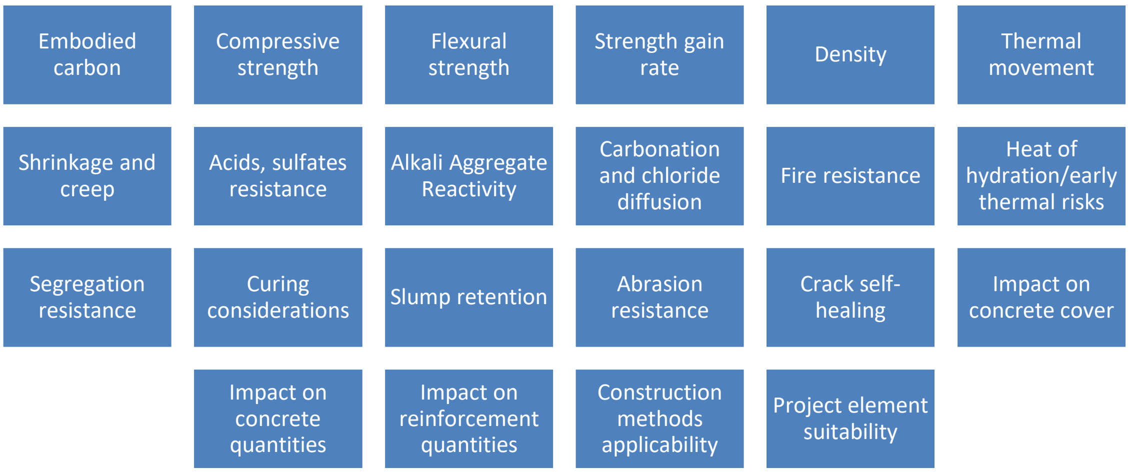

Figure 6. Criteria assessed for concrete mixes.

Compressive and flexural strength at both early age and 28 days were assessed.

3.2 Assessment Criteria – Steel and Reinforcing Products

Compliance with the requirements of the following applicable standards and the contract specifications was assessed for steel and reinforcing products as part of this embodied emissions study: AS 4100, AS 5100 series, AS 4600, AS 2312 series, TfNSW B220 and TfNSW T HR CI 12003 ST. Figure 7 shows the other criteria that were also assessed for steels and steel alternatives.

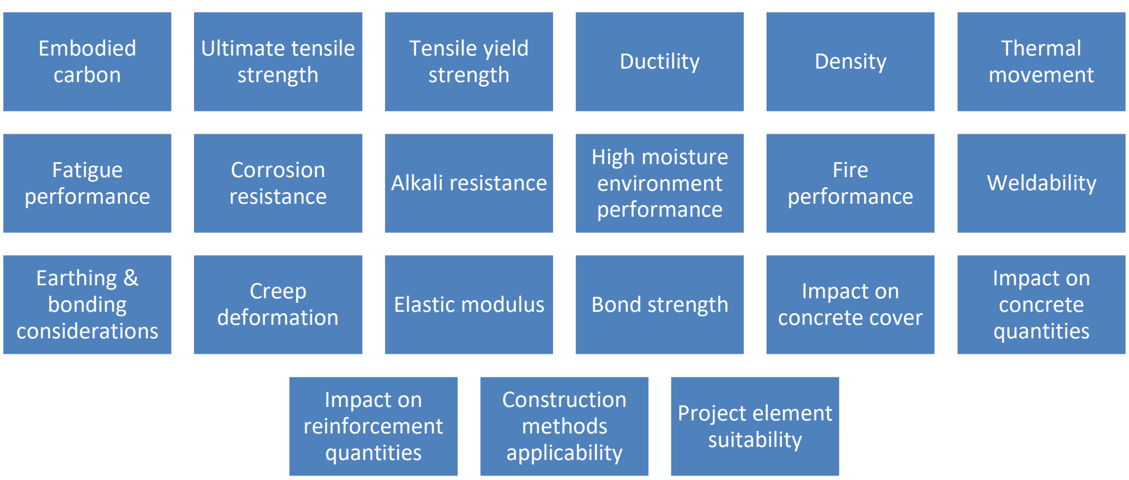

Figure 7. Criteria assessed for steel and reinforcing products.

3.3 Embodied Emissions Scenario Assessment Outcomes

Tables 1 shows the conclusions drawn from the embodied emissions assessment of available low carbon construction products.

Table 1. Embodied emissions scenario assessment outcomes.

Category		Technical Outcome	Greenhouse Gas Emissions Outcome
Below Ground Concrete Elements	Low GP cement concrete mixes	No significant technical due diligence risks identified.	Good
	Geopolymer mix	No significant technical due diligence risks identified. Potentially significant compliance risk due to inadequate development of standards covering this product.	Excellent
Above Ground Concrete Elements	Low GP cement concrete mixes	No significant technical due diligence risks identified. May require slight increase in concrete cover for carbonation durability design life compliance.	Good
	Geopolymer mix	Some low risks related to limited precedence of use, slab finishing considerations, carbonation durability and early strength gain in cool conditions (< 20°C).	Excellent
Reinforcing bar	GFRP bar	Medium risk identified relating to the lack of precedence of use and coverage within the Australian standards. Increased cover, quantity of concrete and reinforcement rate for resistance to blast and fire leads to poor GHG emissions outcome.	Poor
	Basalt bar	Medium risk identified relating to the lack of precedence of use and coverage within the Australian standards. Increased cover, quantity of concrete and reinforcement rate for resistance to blast and fire leads to poor GHG emissions outcome.	Poor
	600 MPa bar	No significant technical due diligence risks identified.	Good
	750 MPa bar	Significant technical risk: non-compliance with AS 5100.5 requirements for earthquake detailing (bars not deformed) hence not considered further.	N/A
Structural steel	Low carbon steel	No significant technical due diligence risks identified. A significant compliance/certification risk was identified due to product compliance testing not being to the required Standards.	Excellent

4. SUSTAINABLE MATERIALS SPECIFIED IN DESIGN AND USED IN CONSTRUCTION

Following the embodied emissions scenario assessment, the final detailed design for the project had several sustainable lower carbon materials specified.

4.1 Concrete Mixes

Following close collaboration between Arcadis (designer) and Laing O'Rourke (contractor) during the design phase, specification requirements such as concrete cover for durability (corrosion protection of reinforcement) for several concrete mixes were provided on the project's Drawing Notes. These included a 'baseline' 70% GP/SL cement + 30% Fly Ash concrete mix used in design plus several lower carbon, higher SCM concrete mixes. This allowed the contractor flexibility in concrete supply procurement and the option to select lower carbon construction materials.

Construction of the project is ongoing. At the time of writing, the project structural concrete elements constructed all used high SCM, lower carbon ternary blend concrete mixes which also complied with project requirements for reduced use of virgin materials for fine aggregates in concrete. Some examples are shown in Table 2.

Table 2. Examples of concrete mixes adopted in construction to date for foundations and walls.

Strength Grade (MPa)	GP or SL Cement (%)	Ground Granulated Blast Furnace Slag (%)	Fly Ash (%)	Water to Cement Ratio	Manufactured Sand as % of Total Fine Aggregate	Total Cementitious Content (SCM %) (kg/m^3)
40	44	32	24	0.44	64%	420 (56% SCM)
40	45	33	22	0.44	68%	420 (55% SCM)
50	45	33	22	0.4	68%	455 (55% SCM)

During the construction phase, at the request of the contractor the designer has reviewed numerous concrete mixes - mostly high SCM, lower carbon ternary mixes – to assess whether they are appropriate for use and would require any changes to the design (e.g. increased concrete cover) to ensure compliance with durability or any other project requirements.

4.2 Reinforcing bar

Higher strength 600 MPa reinforcing bar was specified for use in certain project concrete elements such as the footbridge superstructure. Additionally, an innovative 100% recycled, 100% renewable energy produced reinforcing bar product that was not part of the earlier embodied emissions study was specified for use for a significant portion of the steel reinforcement on the project.

4.3 Carbon Reductions in Final Design

Carbon measurement completed by the design team concluded that, in the final design, the most carbon reductions were achieved due to GP cement replacement in concrete. The purchase of GreenPower to offset operational energy use and procurement of 100% recycled, 100% renewable energy-produced reinforcing bars for a portion of the project concrete's steel reinforcement (Figure 8) were also major contributors to the achieved reduction in carbon emissions. Finally, optimising the design to reduce overall materials quantities in construction was also a significant contributor to carbon reductions.

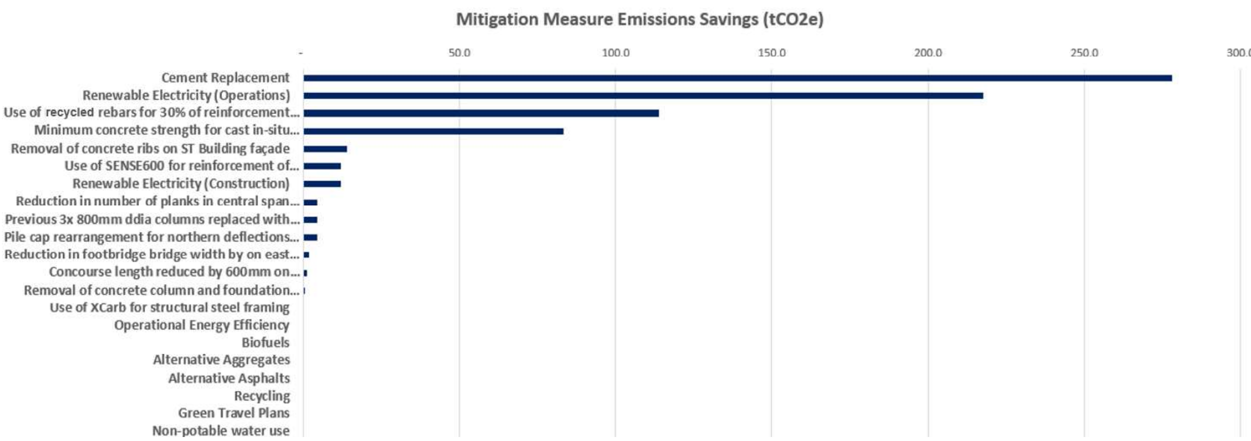

Figure 8. Carbon reductions in the final design relative to the base case.

5. DISCUSSION

The embodied emissions scenario assessment completed for selected novel low carbon construction materials and products on an Australian transport infrastructure project demonstrated that, for technical reasons such as structural and durability performance of the materials, almost all of the studied products were acceptable to use in construction. However, often it was found that the risk of using such products was unacceptably high due to a lack of precedence of use in similar applications or uncertainty around product compliance with applicable standards, especially for construction of higher risk structural members. For example, obtaining approval to use mixes that were outside the TfNSW B80 specification was a significant hurdle to using the lowest carbon mixes, even where a performance-based assessment indicated suitability. Working with supply chain, the team instead proposed four new low carbon mixes for approval under the specification, as well as maximised the use of low carbon concretes in suitable element exposure classifications, allowing for greater decarbonisation to be realised. For reinforcing steel products, a major challenge was an update being needed to Australian standards to allow greater flexibility in specifying improved, innovative structural steel materials. Even once updates to relevant standards were published after completion of the embodied emissions scenario assessment, the ability to use innovative steel products remained challenging as updates to material requirements for couplers were not included within the standards. Required adherence to prescriptive standards and specifications remains a limiter to industry being able to adopt these products going forward.

A secondary limiting factor for steel was that the Owner project specifications required a maximum of 50% imported materials to be used in construction. This limited the ability to use low carbon reinforcement products manufactured overseas, highlighting the need for Australian industry to continue to advance to maintain relevance in a changing marketplace.

These risks remain a significant barrier to innovation and to achieving the pace of transition to a net zero construction sector that is required. All construction industry stakeholders must work together to overcome these challenges and create settings that encourage, rather than impede, use of innovative, low carbon construction materials in construction projects. This starts, it can be argued, with the regulatory and project requirement settings established by government and standards authorities.

Although some of the products assessed in the embodied emissions study were not specified for use in construction of the project due to aforementioned barriers, many low carbon materials were utilised, including 600 MPa steel reinforcing bar, other low carbon reinforcing steel, and widespread use of high SCM, low carbon ternary concrete mixes.

One continuing challenge to adoption of high-SCM and alkali-activated binder, low carbon concrete on infrastructure projects with long design lives is that they carbonate faster. This may lead to increased concrete cover being required to achieve the required design life for carbonation durability. TfNSW B80 requires at least 240kg/m^3 of GP cement in B1 exposure environments for this reason. Industry may perceive this increased concrete cover to also mean increased concrete quantities and therefore potentially higher GHG emissions relative to specifying a higher GP cement concrete mix which can comply with the design life at the AS 5100.5 required concrete cover. However, on this project, refined carbonation service life analysis based on specific concrete mix data (where available) meant that only a small proportion of the assessed high-SCM concrete mixes required an increase in concrete cover to achieve design life compliance. Also, where there was slightly increased cover, the member sizes did not increase so there was no change in concrete quantities. Therefore, use of high-SCM mixes on this project resulted in a lower carbon outcome. These perceived knock-on effects need to be carefully considered, and their likelihood of occurrence assessed, in infrastructure project design. A lack of publicly available carbonation resistance performance data for Australian concrete mixes is currently a barrier to more widespread use of low or no Portland cement concrete mixes in construction. One partial solution to this is for project specifications to allow a corrosion propagation period (e.g. 10 or 20 years) as part of the design life for carbonation durability. Fib Model Code 2020 (4) now contains procedures for calculating the time to reinforcement corrosion-induced cracking and at least one Australian state transport agency already allows a period of corrosion propagation (20 years) in the definition of design life on projects (5). With the rapid movement towards a net zero construction industry, attention is needed on improving the accuracy of available carbonation service life design procedures for reinforced concretes with high percentages of SCMs.

6. CONCLUSIONS

An embodied carbon emissions scenario assessment of selected low carbon concrete mixes, steel and reinforcing products was completed early in the detailed design stage of a recent Australian transport infrastructure project. It demonstrated that, for technical reasons such as structural and durability performance of the materials, almost all of the studied products were acceptable to use in construction. However, in many cases it was concluded that the risk of using such products was unacceptably high due to a lack of precedence of use in similar applications or uncertainty around product compliance with applicable standards, especially for construction of higher risk structural members.

In the final design, sustainable materials were specified for use in construction. Selection of lower carbon concrete mixes resulted in the biggest reduction in project carbon emissions. Use of 100% recycled and 100% renewable energy produced reinforcing bars for parts of the project also lead to significant carbon reductions.

7. REFERENCES

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