Improved Sustainability in Bridge Design through the use of Factory Produced Pretensioned, Prestressed Concrete Girder and Beam Elements

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Abstract: There are several benefits that are associated with precast prestressed concrete including structural performance, cost, efficiency and improved sustainability. However, to facilitate efficient manufacture, the concrete needed for daily production cycles tends to have high Portland cement contents to achieve high early age strength for the transfer of prestress forces. This results in concrete having a higher embodied carbon per cubic metre when compared with more conventional in-situ concrete. In recent years a large emphasis has been placed on sustainability and reduction of carbon emissions in the concrete industry which contributes up to 8% of global emissions [1] [2]. One of the primary and most effective methods of reducing the embodied carbon in concrete is to increase the use of supplementary cementitious materials (SCM's) and reduce the amount of Portland cement. The reduction in Portland cement content reduces the early age strength, resulting in longer production cycle times, which reduce the efficiency of precast pretensioned prestressed construction [3]. This paper examines different girder construction methodologies, processes and materials used to construct a two-lane bridge in Newcastle NSW spanning 37m and the impacts they have on sustainability.

Keywords: Emission reduction, efficient construction, Sustainable construction

1. Introduction

Concrete is a versatile material and is used in a variety of applications due to its high compressive strength and durability. Per kilogram, concrete has lower embodied carbon emissions than other construction materials like steel this is illustrated in Figure 1. Due to the high usage of concrete, the concrete industry contributes up to 8% of global CO_2 emissions, 80-90% of these emissions comes from the manufacture of Portland cement. With the increase in urbanisation, cement production is forecast to increase by 25-50% globally [1] [2] [3], therefore there is a need for the construction industry to provide improved sustainability in design, construction methodologies and asset management.

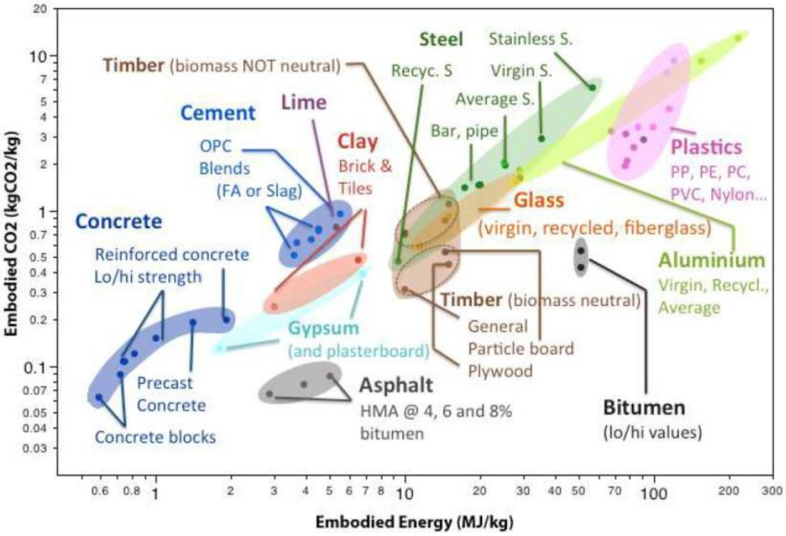


Figure 1. Embodied Emissions for materials per industry [2]

Initiatives and specifications have focused on improved sustainability performance of in-situ concrete through the reduction of Portland cement and its partial replacement with SCM's. While this is probably the most effective way to reduce CO_2 emissions in concrete, this approach has drastic effects on the sustainability outcome for the precast manufacturing process. The traditional approaches described above focus largely on material based embodied carbon criteria [4] [5], CO_2 per cubic meter / tonne. Studies have shown that such approaches do not necessarily provide the outcomes sought and further thinking on this is now required [6] [7] [8]. Consideration of concrete and component material properties need to be coupled with the engineering outcomes of a project, structure, structural element design, structural element construction and manufacturing criteria. Relatively little effort has gone into the assessment of different designs, construction methodologies, and manufacture of concrete and concrete structural elements on the sustainability (CO_2e) of structures. This is particularly the case with the manufacture of precast pretensioned prestressed concrete planks and girders, where sustainability specifications have applied the same sustainability criteria to pretensioned concrete as they have to in-situ concrete construction.

The standard precast pretensioned prestressed (PSC) Super-T girder has been widely adopted in preference to other girder manufacturing methodologies like steel and in-situ concrete in Australia since their introduction in 1993 due to their well-documented advantages over in-situ construction [7] [9]. The advantages are generated through the standard precast 24-hour manufacturing cycle and the technology of applying pretensioned prestressed forces on the structural element.

The design and manufacture of such structural elements is complex with many factors needing to be considered such as:-

- Optimising concrete and reinforcement volumes to meet load requirements;
- Optimising deflection limit requirements;
- Optimising structural and manufacturing efficiency;
- Ensuring efficient manufacturing processes that require;
    - Mould re-use within specific time limits to optimise production shifts and reduce cost;
    - Application of heat accelerated curing to ensure early strength requirements are met to achieve the customary daily production cycle;
    - Use of prestressed concrete in design to minimise girder sections;
    - Optimised concrete transfer strengths for required performance criteria.

Some of these processes require material properties to be compliant with design and manufacturing-imposed criteria. Changes in parameters such as reducing the total cementitious binder and/or reducing cement contents will have negative impacts on the above criteria.

There has been significant work done in Australia and other parts of the world on concrete binders and supplementary cementitious materials (SCMs). As examples, fly ash has been used in concrete since 1958 and ground granulated (iron) blast furnace slags have been used since the late 1960s and early 1970s [10]. Silica fume was used in Australia as far back as 1971 [11]. Significant work on durability of concrete and mechanical properties of concretes containing these materials can be found in the literature and standards covering these materials are now linked to structural design and construction. Recently, however, the requirement to reduce carbon on projects has resulted in prescriptive specifications nominating arbitrary levels (percentage replacement of binder with SCM) in concrete independent of imposed design and construction requirements.

There has been widespread use of Super-T concrete girders in construction, particularly for the fast and efficient construction of bridges. Standardised sections have been adopted throughout the industry allowing for optimisation of mould design and life cycles, plant production, energy, time, and materials [9].

Given current industry initiatives and the adoption of SCMs for in-situ concrete there is pressure for further consideration of sustainability performance initiatives to be directly adopted for pre-stressed concrete and in turn, for the manufacture of Super-T concrete girders.

As previously indicated, given the existing disconnect between material properties driven by “specifications for sustainable concrete” and design, manufacture and construction requirements, unnecessary problems are being faced in the construction industry. The goal of reducing carbon on projects may not be achieved unless changes are made in the way specification for sustainability is documented and this is particularly the case for precast prestressed concrete girders.

Designers, manufacturers, installers/contractors, and asset owners face a number of issues when considering the adoption of sustainability performance initiatives for prestressed concrete girders including the following:

- Design considerations required for performance of alternate mix designs such as cracking, creep, durability, lower concrete strength at transfer (application of prestress during manufacture) and geometry. These have the potential to depart from standardised sizing creating issues with manufacture and the known connection between theoretical performance and known performance of standardised designs.

- Adequate prediction of transfer deflections and service behaviour including crack distribution when using SCMs.
- Past optimisation of prestressed Super-T girders has considered several factors including efficiency of materials, reduced construction time (where elements are produced on a daily cycle minimising formwork and energy for curing), reduced wastage.
- While in-situ beam dimensions can be adjusted there can be issues with even minor geometric adjustment of prestress girders (i.e., Super-T girders) such as mould dimensions, void dimensions, tendon layout, etc. This can create issues for coordination between the designer and manufacturer.
- The use of SCMs typically results in lower early age concrete strength which requires additional curing time to reach the necessary transfer strength. These longer curing times result in higher energy consumption and reduced efficiencies for equipment (multiple casting beds required to maintain the required rate of production). The increase in cycle time may affect assumptions made by the designer.
- Use of geopolymers (and other alkali activated binders) not having a track record of successful use in the precast industry due to insufficient material (SCM's) to support widespread use and specifications like TfNSW B80 do not allow the use in the manufacture of bridges.
- Adoption of special purpose cements with higher performance than general purpose cements which are currently being used

2. Analysis and Design Procedure

2.1 Details of study

This study performs a comparative assessment of Embodied Carbon for different bridge superstructure types (construction methodology) for a two lane 38m single span bridge. Specifically, the study compares bridge girders of prestressed concrete, in-situ concrete and steel and evaluates their impact on sustainability and whether evaluating a sustainability target per material is appropriate rather than consideration of the life cycle of the structure.

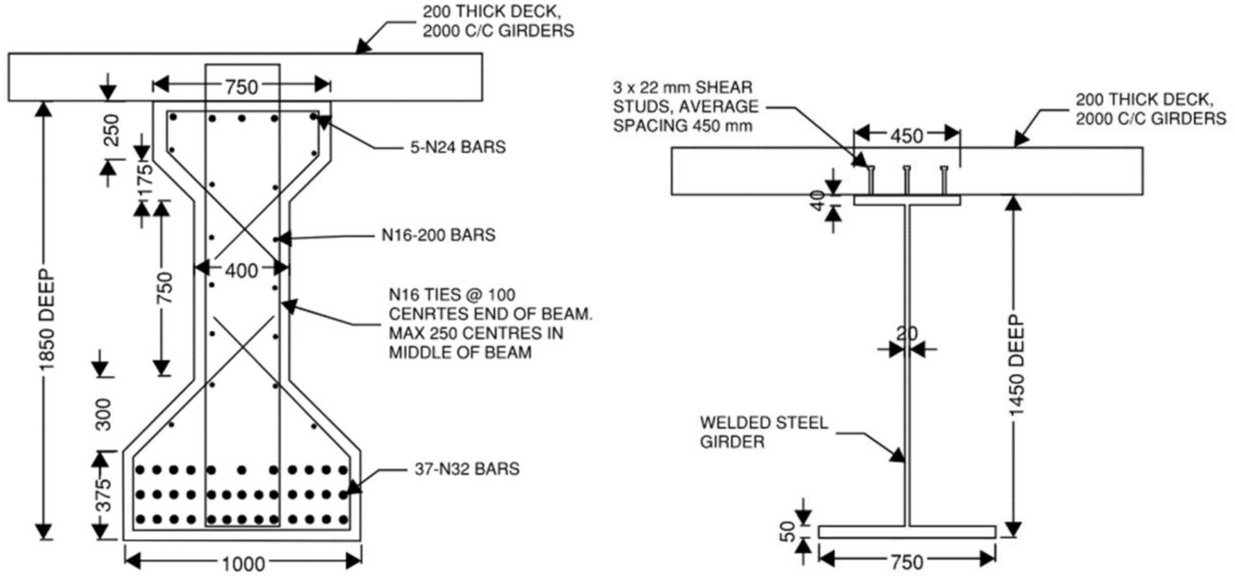
A bridge of the same configuration (i.e., span, width, etc.) has been utilised for the 3 assessed options, all of which utilise a 200 mm cast in-situ deck. The assessment is limited to the girder section only (Modules A1-A3 girder production only) and has not considered the in-situ concrete deck for embodied carbon calculations. Calculations for strength and deflection have considered composite action of the girder with the in-situ concrete deck. Table 1 provides a summary of the bridge arrangement for the comparative assessment.

Table 1. Bridge Information

Structure Type	Road Bridge
Track Alignment	Straight
Number of Lanes	2
Overall Length	38.5 m
Width	13.6 m
Number of Spans	1
Span Length	37.5 m
Deck Type	Concrete Deck
Girder Spacing	2.0 m
Number of Girders	7
Cast In-situ Deck	200 mm

2.2 Girder Configuration

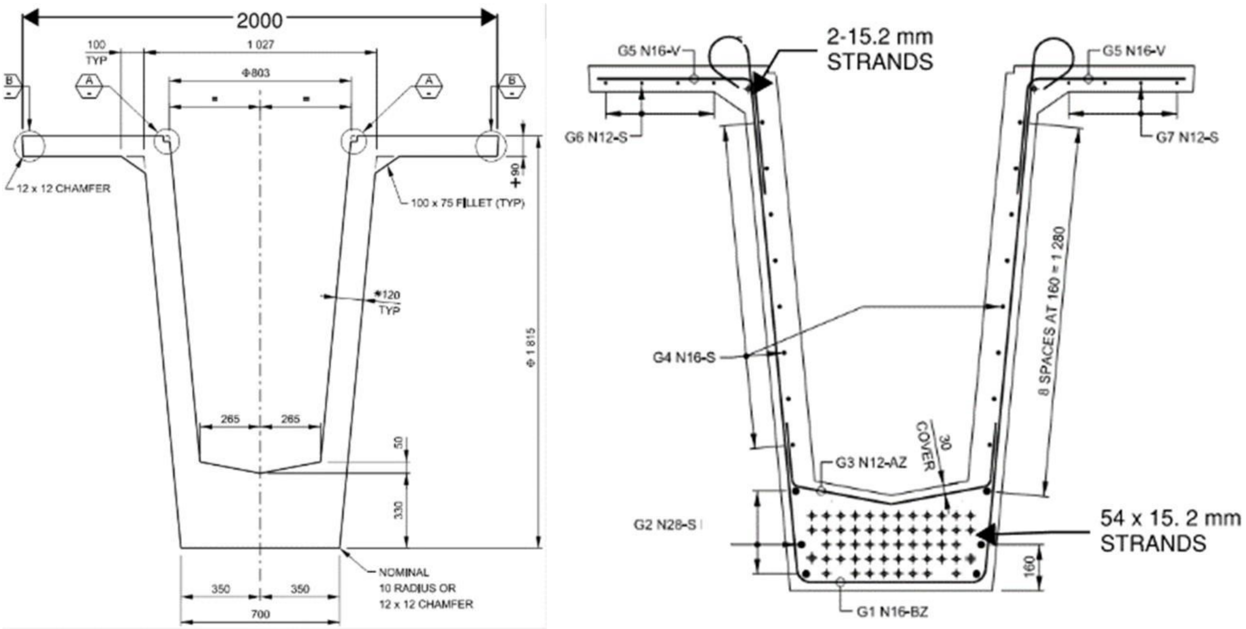
The details of the girder cross sections for the three different construction methodologies investigated in this study are presented in Figure 2&3.



1850 Deep Reinforced Concrete I Girder

1450 Deep Welded Steel I Girder

Figure 2.



1815 Deep Super T-Cross-section

1815 Deep Super T-Reinforcement & Strand layout

Figure 3.

Factory manufactured Super-Ts provide a very economical and sustainable solution to other forms of construction because they are able to be manufactured on a 24-hour cycle. To maintain this cycle, however, there is a need to utilize a concrete technology which is capable of the achievement of high early strength, nominally 35-40MPa in 12-15 hours. This is achieved by the use of high Portland cement content / low water cement ratio mix designs coupled with heat accelerated curing. Heat accelerated curing is provided by applying steam (or other heat source) to the PSC element at a temperature range of 50-70 °C for 8 hours. To avoid the risk of thermal cracking and DEF (Delayed Ettringite Formation) limits are imposed on the heat cycle, minimum pre-setting period 2hrs, maximum temperature rise of 24°C / hr and a maximum temperature of 70 °C. Transfer of prestress can occur when the element has achieved its minimum transfer strength (as determined by representative test specimens cured under identical conditions) and the cured maturity of the concrete is ≥ 350 °C-hrs. Factory manufactured reinforced concrete elements also need to achieve minimum strengths prior to demoulding sufficient to ensure that the element can support its own weight without unacceptable cracking due to demoulding and handling forces. In both cases the mix designs are controlled by the achievement of early strengths necessary to achieve these conditions rather than the ultimate 28-day strength criterion. [12] [13]

It is for these reasons that the CO_2 emission targets imposed on in-situ cannot be fairly compared to the precast alternatives. Put another way the 50MPa concrete specified for PSC Super T's is better compared to a 75MPa high early strength mix on the construction site.

A summary of girder material volumes is presented in Table 2.

Table 2. Girder Material Volumes

Parameter		**Girder Type**		
		In-situ Concrete	**Welded Steel Girder**	**PSC Super T**
Girder Depth	(mm)	1,850	1,450	1,815
Concrete	Total Volume (m^3/girder)	45.2	N/A	31.9
Steel[1]	Total Mass (kg/girder)	N/A	26,815	N/A
Reinforcement[2]	Total Mass (kg/girder)	15,543	N/A	7,018
Strand[3]	Total Mass (kg/girder)	N/A	N/A	2,985

2.3 Design Criteria for Bridge Girders

Design of girders was undertaken in accordance with AS5100 (2017) for deflection and strength. The deflection criteria is presented in table 3.

Table 3. Deflection Criteria

Girder Type	**Deflection Limit (Long Tern Permanent Loads)**		**Deflection SLS + DLA**
Steel	L/300 Pre-camber limit[1]	No Sag	L/600
In-situ Concrete	L/300 Pre-camber limit[1]	No Sag	L/600
Super-T	Hog L/300	No Sag	L/600

[1] L/300 pre-camber limit assumed based on AS5100.2 Clause 7.11 requirements for hog deflection limits.

Design was undertaken considering deflection requirements for the girders where calculated pre-cambers and deflections are presented in table 4.

Table 4. Girder Deflection

Girder Type	**Pre-camber/ Hog (mm)**	**$DL_{Long\ term}$ Deflection (mm)**	**Permanent Sag (mm)**	**LL Deflection (mm)**	**Total LL + Permanent Sag (mm)**
Steel[1]	-94[2] Min	94	0	61	61
In-situ Concrete[1]	-114[3] Min	114	0	53	53
Prestressed Concrete Super-T	-51[4]	24[5]	-27	61	34

[1] Beam pre-cambered to achieve AS5100 requirement for no sag under permanent loads (i.e. minimum pre-camber to match deflection for $DL_{Longterm}$).

[2] Prior to application of girder self weight and weight of deck slab (i.e. girder fabricated on its side).

[3] Slab cast integral with beam.

[4] Hog at 28 days without concrete slab.

[5] Includes long term creep/hog under permanent loads (100 years).

2.4 Girder Strength

The bending strengths of the girders were calculated in accordance with AS 5100.5 and AS 5100.6. The capacity of the girders may be compared through the use of a rating factor, which presented in table 5.

Table 5. Girder Load rating Summary

Girder Type	Rating Factor (ULS Bending M1600)
Steel	1.66[1]
In-situ Concrete	1.03
Pre-stressed Concrete Super-T	1.06

[1] Steel beam controlled by deflection under live load.

2.5 Emission Analysis

This assessment has focused on the production phase of a product only as outlined in BS EN 15978:2011 (Sustainability of construction works - Assessment of environmental performance of building - Construction method.) referred to as Module A1-A3 see Figure 4 below.

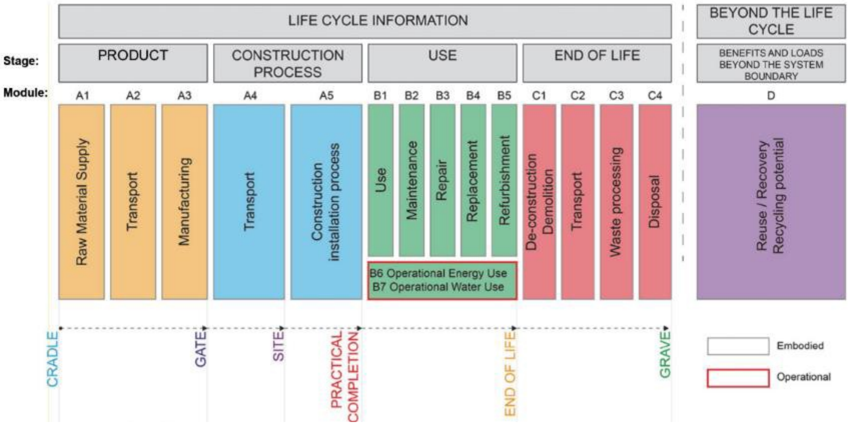


Figure 4. Carbon Emissions for Life Cycle Stages (BS EN 15978)

2.5 Embodied Carbon Assessment

Embodied Carbon for concrete materials was based on component emission factors and other studies conducted on concrete materials. Manufacturer supplied Environment Product Declarations (EPDs) were utilised for elements such as reinforcement, structural steel, strands/tendons, and natural gas; with emissions calculated for steam generation. Design parameters for embodied carbon assessment are presented in Table 6. Whilst values for various materials have been provided, it is noted that material properties impact many manufacturing processes that impact cost and structural efficiency. It is standard practice in precast girder manufacture to have three staff shifts per day, in part to monitor steam application and production processes, and thus provide efficiency.

Table 6. Material Emissions Data

Material	Emission Factors
Structural Steel	2.0 tCO_2e/t
Reinforcement Steel	1.7 tCO_2e/t
Strand/Tendons	2.2 tCO_2e/t
50 MPa concrete using Portland cement only[1]	0.5 tCO_2e/m^3
TfNSW B80 (including 25% fly ash by mass of binder)[2]	0.5 tCO_2e/m^3
Steam Curing for S60 Grade 8 hrs @ 70ºC[3, 4]	0.5 tCO_2e

50 MPa Concrete with 450kg Binder with 55% SCMs	0.3 tCO$_2$e/m^3
Steam for 50 MPa Concrete 450kg Binder with 55% SCMs 60 hrs @ 70ºC[4, 5]	9.1 tCO$_2$e

Results

Embodied Carbon values were calculated for girder components and are presented in Table 7 for a single girder and the total for seven girders required for the bridge. The analysis presented considers the options described previously with additional bridge design variations as follows:-

- A steel girder bridge
- A reinforced concrete bridge made with concrete containing 100% GP cement;
- A reinforced concrete bridge with concrete composed of 70% slag by mass of binder;
- A prestressed Super-T bridge with concrete incorporating a binder composed of 25% fly ash by mass of binder, and
- A prestressed Super-T bridge with concrete incorporating a 450 kg/m^3 total ternary binder composed of 55% SCM by mass of binder.

In addition to the above, bridge options have been assessed for embodied carbon relative to the prestressed Super-T bridge (from which the embodied carbon values have been normalised to ease comparisons). Also presented in Table 7 is an estimate of the required production cycle (in days) for girders manufacture within each bridge option

Table 7. Embodied Carbon Results for A1 to A3

Embodied Carbon (tCO$_2$e)	Girder Type				
	Steel Girder	Reinforced Concrete (100% GP)	Reinforced Concrete (70% slag)	PSC Super-T (25%	PSC Super-T (High SCM[1])
Concrete	N/A	23	11.3	14.7	11
Concrete Curing	N/A	N/A	N/A	0.56*	9.1*
Steel	53.6	N/A	N/A	N/A	N/A
Reinforcement	N/A	26.4	26.4	11.7	11.7
Strand	N/A	N/A	N/A	6.5	6.5
Total per Girder	53.6	49	37.7	33.5	38.6
Total for 7 Girders	375.4	343.4	264.1	234.2	270.2
Ratio to PSC Super-T (25% FA)	1.6	1.45	1.12	1	1.14
Days Required to Produce One Girder Element	5	14[2]	28[2]	1	3[3]

1 High SCM concrete investigated had ternary blend binders having 450kg/m3 total binder with minimum 55% SCM content.
2 Estimated time based on achieving a standard 7-day compressive strength.
3 Estimated based on time required to achieve transfer strength criteria.
* Heat accelerated cured in accordance with TfNSW B80

Further analyses on embodied carbon of the various design options were carried out and are summarised in Figure 5. Embodied carbon results for the bridge have been normalised and compared with the reference value for the Super-T bridge. The design options are those set out in Table 7 with further analyses presented for Super-T girder bridges including:-

- Steel with improved properties that are relevant to facilitating optimised girder design;
- Having the ability to improve concrete batching to optimise concrete performance, and
- Enabling higher and improved binder types specific to precast applications and enabling early age strengths to facilitate more efficient production.

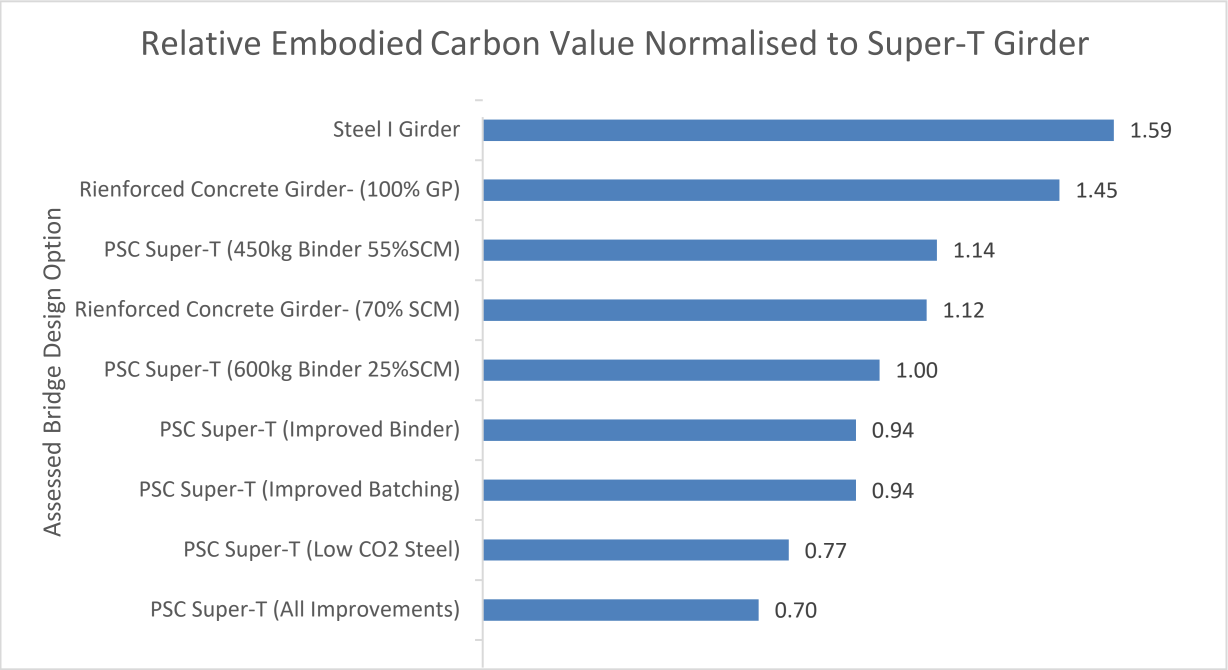


Figure 5. Evaluation of Bridge Design for Embodied Carbon Normalised to Super-T Girder

3. Discussion & Recommendation

It is noted that the reinforced concrete girders are not a viable solution for a 38m single span bridge, this option would generally be excluded during the design phase, due to constructability, design difficulties and cost. Concrete is the primary ingredient in the manufacture of PSC girders making up 90-95% of the mass, due to its high volume, it generally has the highest embodied carbon value compared to other materials. A large emphasis has been placed in sustainability specifications on reducing cement in concrete with the aim to reduce concrete embodied carbon for this reason because in in-situ construction it is the easiest and most efficient solution. As indicated from previous studies [6] [7] [8], this strategy has shortcomings as the engineering factors required to produce outcomes covering design (which includes design for durability), construction and manufacture are not considered which is validated in this study.

In this study where precast prestressed girders have been analysed for their sustainable application in bridge assets, the following has been observed:-

- Appling a universal CO2 target to materials or material components is not applicable to all design and construction methods, and more importantly, these can lead to perverse sustainability (carbon) outcomes;
- For the bridge selected for this study, standard precast pretensioned Super T girders are more efficient through optimised design and manufacture than is the case for in-situ concrete, steel design or high SCM precast Super T girder options;
- Extended curing times required with high SCM replacement have design implication such as relaxation in tendons, thus early loss in prestressing forces resulting in changes in design hogs
- Reducing the cement content of concrete used in the PSC Super-T girders (as is the case with many current specifications) increases the embodied carbon in the bridge investigated due to the reduced early age strength thus requiring increased amounts of heat accelerated curing to achieve the required strength which is not viable from sustainability, cost or program time frame aspects;
- Specifying the concrete mix to solely reduce CO_2 emissions does not mean that the bridge girder will have a lower carbon content. In the cases investigated, the carbon increases in the girder and the bridge itself even though the concrete mix had a low CO_2, and
- Sustainability criteria need to consider design requirements (which includes durability requirements), manufacturing requirements and construction processes. This is critical for future design options to be both sustainable and cost effective.

- Sustainability specifications need to be considered prior or during design phase, not during the construction phase where they can adversely effect engineering outcomes and manufacturing process.

4. Conclusions

The study concluded that simple cement reduction or maximum binder content limits for concrete construction can be detrimental to carbon reduction in structures, the direct opposite impact being sought for infrastructure. Precast pretensioned prestressed concrete has been used successfully in Australia for some 70 years. The cementitious content limits noted above impact negatively on the optimised design, manufacture, construction and long-term durability of such components. A new method of assessing carbon reduction in precast pretensioned prestressed concrete is required. Some suggestions towards achieving that have been suggested in this work.

5. Acknowledgement

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