Optimising Precast Bridge Girders for Sustainability with the use of High Performance Concrete

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Abstract The standard Super-T bridge girders used in Australia were developed to provide optimum performance at a time when the maximum concrete grade covered by the bridge design code was 50 MPa. This paper examines the opportunities for improved sustainability through the use of high performance concrete, considering the use of existing standard sections, modified sections optimised for higher strength grades, and the use of techniques such as hybrid pre-tensioned and post-tensioned girders, and precast girders used in continuous structures. These alternatives are compared for impact on CO_2 emissions within the context of current Australian precast and bridge construction practice. In addition, the designs of the sections are reviewed based on a series of alternative concrete mix designs covering a reference Portland cement concrete mix and a series of concretes incorporating a range of supplementary cementitious materials included at different levels of cement replacement to determine efficiencies in design and impacts on the embodied energy required to manufacture the elements.

Introduction

The standard precast "Super-T" bridge girders used in Australia have proved to be very popular, offering both an efficient design solution, and rapid construction. At the time of their introduction the maximum concrete grade covered by The Australian Bridge Design Code [1] was 50 MPa [2]. Since that time the maximum concrete grade for use in bridges has increased to 65 MPa in AS 5100 [3], and the latest Australian Standard Concrete Structures Code, AS 3600 [4], released late in 2009, covers concrete strengths up to 100 MPa. Use of these higher strength concretes offers potential for reduction in quantities of concrete and/or steel, offset by higher cement content, but the current range of standard girders are not necessarily optimal for use with higher strength concrete, and there is little data available on CO_2 emissions associated with different alternatives.

Super-T Bridge Girders were introduced in Victoria in 1993, and were quickly adopted by the other Australian States [2]. For the purposes of this study, open topped girders of type T3, T4 and T5 were used as standard sections, and modified type T2 and T3 were used for optimised designs. The Standard Type T5 Super-T open topped section is shown in Figure 1. Table I shows overall depths and bottom flange depths for standard sections T3 to T5 and the modified sections used in conjunction with post-tensioning and/or continuous construction, sections T3A, T3B and T2A.

In this paper the design of a typical two span freeway over-bridge is examined, comparing standard strength concrete and girders with higher strength grades and girders optimised for use with high performance concrete, post-tensioning, and continuous structures. These alternatives are examined for their effect on life-cycle CO_2 emissions.

Details of Study

This study examines the effect of the use different high performance concrete mixes on the life-cycle CO_2 emissions of a typical 2 span freeway overbridge. The reason for using the term performance instead of strength relates to the mechanical, serviceability and durability requirements of the concrete necessary for efficient design and manufacture of the structural elements. Key design features of the section are as follows:

- Two span freeway over-bridge
- Total length; abutment to abutment - 61 m (2 x 28.5 m span + 2.5 m link + 1.5 m ends)
- Carriageway width - 11.0 m; Footway / verge widths - 0.75 m both sides
- 5 or 6 open topped Super-T girders
- In-situ top slab of 160 mm depth.
- SM 1600 Loading
- Typical Sydney shrinkage and creep parameters
- Exposure class B1

Alternative concrete mixes selected for this study covered the following:

A. Reference case: 50 MPa characteristic compressive strength concrete made using Portland cement without supplementary cementitious materials (SCM's), defined in Australian Standard AS1379 (Specification and Supply of Concrete) [6], AS3972 (General Purpose and Blended Cement) [7], and AS3582 Parts 1 [8], 2 [9] and 3 [10] (Supplementary Cementitious Materials for Use with Portland and Blended Cements).
B. Typical current high strength concrete; characteristic compressive strength = 65 MPa.
C. High strength concrete having a characteristic compressive strength of 80 MPa

D. Very high strength concrete having a characteristic compressive strength of 100 MPa
E. High SCM concrete having a characteristic compressive strength of 45 MPa.

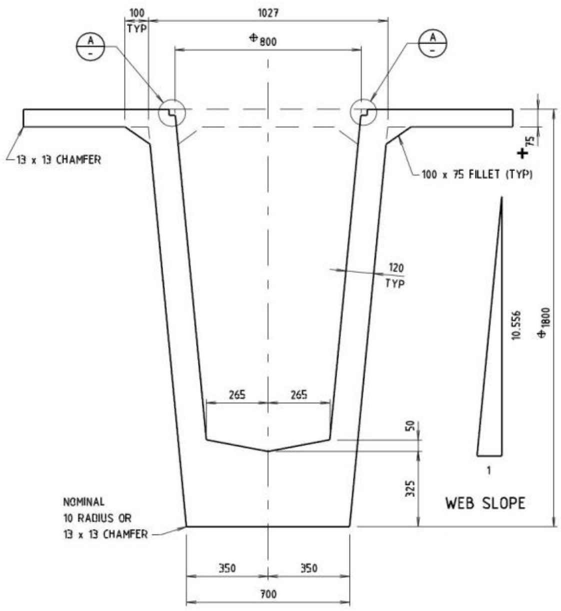

Fig 1: Type 5 Super-T Girder

Table I. Super-T Girder Dimensions

Type	O/A Depth, mm	Bottom Flange, mm	
		Base Width	Depth
T3	1200	814	260
T4	1500	757	260
T5	1800	700	325
Modified:			
T2A	1000	852	150
T3A	1200	814	200
T3B	1200	814	150

Details of the five mixes and design compressive strengths are shown in Table II. The emission data for the component materials used in the analyses are taken from earlier published work [11], and are given in Table III. Emission calculations are shown in Table IV. Calculations took the quantity of each component material and obtained a total emission quantity in the mix by multiplying by the corresponding emission factor given in Table III [11].

Table II: Mix Design Details

Concrete Property	**Unit**	**Mix A, Baseline 50 MPa**	**Mix B 65 MPa HPC Current**	**Mix C 80 MPa HPC**	**Mix D 100 MPa HPC**	**Mix E 45 MPa HPC High SCM**
Total Binder	kg/m^3	550	490	640	680	440
Portland Cement[1]	kg/m^3	550	350	500	540	245
Fly Ash[2]	kg/m^3		70	80	60	85
GGBFS[3]	kg/m^3		70			110
Amorphous Silica[4]	kg/m^3			60	80	
Coarse Aggregate[5]	kg/m^3	1120	1050	1050	1000	1100
Sand[5]	kg/m^3	590	675	630	650	670
Water[6]	kg/m^3	180	180	180	180	180
Water:Binder		0.33	0.37	0.28	0.26	0.41
28 Day Strength[7]	MPa	60	70	90	110	50
Transfer Strength	MPa	35	35	40	40	25
Shrinkage[8]	μstrain	700	600	550	550	650

Standard specifications: 1, AS 3972; 2, AS 3582.1; 3, AS 3582.2; 4, AS 3582.3; 5, AS 2758.1; 6, AS 1379; 7, AS 1012.9; 8, AS 1012.13

Table III: Concrete Component Emission Factors (11)

GP Cement	0.820	t CO_2-e/tonne
Fly Ash	0.027	t CO_2-e/tonne
GGBFS	0.143	t CO_2-e/tonne
Silica Fume	0.027	t CO_2-e/tonne
Basalt Coarse Aggregates	0.036	t CO_2-e/tonne
Fine Aggregates	0.014	t CO_2-e/tonne
Concrete Batching	0.003	t CO_2-e/m^3
Concrete Transport	0.009	t CO_2-e/m^3

Design Options

For each mix design 3 alternative structural configurations were considered:

- Type 1 - Fully Pre-tensioned Design: Typical current practice; Standard Super-T girders, fully pre-tensioned. Simply supported spans with in-situ top slab and link slab.
- Type 2 - Post-tensioned Design: Super-T optimised for use with High Strength Concrete. Pre-tensioned for transport and construction loads

with additional post-tensioning for live loads and long term effects. Simply supported spans with in-situ top slab and link slab.

- Type 3 - Post-tensioned Continuous Design: As 2, but with full structural continuity over the central support.

Table IV: Mix Emission Details (per cubic metre of concrete)

	Mix A 50 MPa Control	**Mix B 65 MPa Current**	**Mix C 80 MPa HPC**	**Mix D 100 MPa HPC**	**Mix E 45 MPa High SCM**
Portland Cement	0.4510	0.2870	0.4100	0.4428	0.2009
Flyash	0.0000	0.0019	0.0022	0.0016	0.0023
GGBFS	0.0000	0.0100	0.0000	0.0000	0.0157
Amorphous Silica	0.0000	0.0000	0.0016	0.0022	0.0000
Coarse Aggregate	0.0403	0.0378	0.0378	0.0360	0.0396
Sand	0.0083	0.0095	0.0088	0.0091	0.0094
Totals, t CO_2-e/m^3	**0.51**	**0.36**	**0.47**	**0.50**	**0.28**
% due to Portland Cement	**88%**	**80%**	**87%**	**88%**	**72%**
Portland Cement Reduction	**0%**	**36%**	**9%**	**2%**	**55%**

Note: As an example, for the Mix A Portland cement component, the emission derived is 550 x 0.82 / 1000 tCO_2 per cubic metre of concrete

Analysis and Design Procedures

Bridge Deck Analysis

The structures were analysed with the finite element package Strand7. The precast girders were modelled with beam elements, located on the precast section centroid, with the in-situ top slab modelled with plate-shell elements, connected to the beams with rigid links. A typical model is shown in Figure 2. Results of the structural analysis are shown in Table V.

Emissions Analysis

Component emission factors used to calculate embodied energy of concrete are presented in Table III and are taken from other studies conducted on concrete materials [11]. Concrete mix emissions for alternative mix designs A to E are given in Table IV and are expressed in tonnes of C02 emissions per cubic metre of concrete (tCO_2-e/m^3). These values were calculated using predetermined concrete emission factors for each of the concrete constituents [11]. An allowance of 5% of the Portland Cement content as mineral additions and or minor additional constituents has been made for the purpose of these calculations, though the recently published new edition of AS3972 (General Purpose and Blended Cement) [7] has increased this allowance to 7.5%.

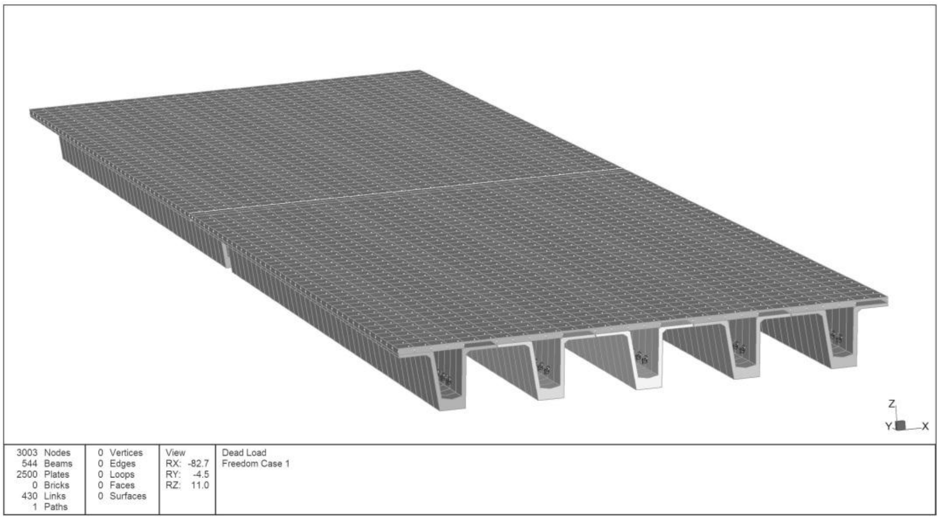

Figure 2: **Typical Deck Model**

Bridge Deck Sections

Six type four girders were required for the base case standard mix (Mix A), and the standard current high strength mix (Mix B). The high SCM mix (Mix E), with a lower strength at transfer, required six Type 5 girders. The higher strength mixes (Mix C and Mix D) allowed the number of girders to be reduced to five Type 4 girders.

The level of prestress was controlled by the standard bottom flange depth, so increasing the concrete strength from 80 to 100 MPa did not allow any further reduction in girder numbers or type. Use of post-tensioning allowed higher levels of total prestress and reduced prestress losses. This allowed the use of shallower girders and reduced depth of bottom slab.

Providing structural continuity over the central pier allowed a further reduction in the bottom flange depth and/or girder type, except for the Type D mix. Total concrete, reinforcement and prestressing quantities and total CO_2 emissions are summarised in Table VI. Emissions for the in-situ concrete were based on the Type A mix for Deck type 1A, and the lesser of Type B mix or the girder mix for all other deck types.

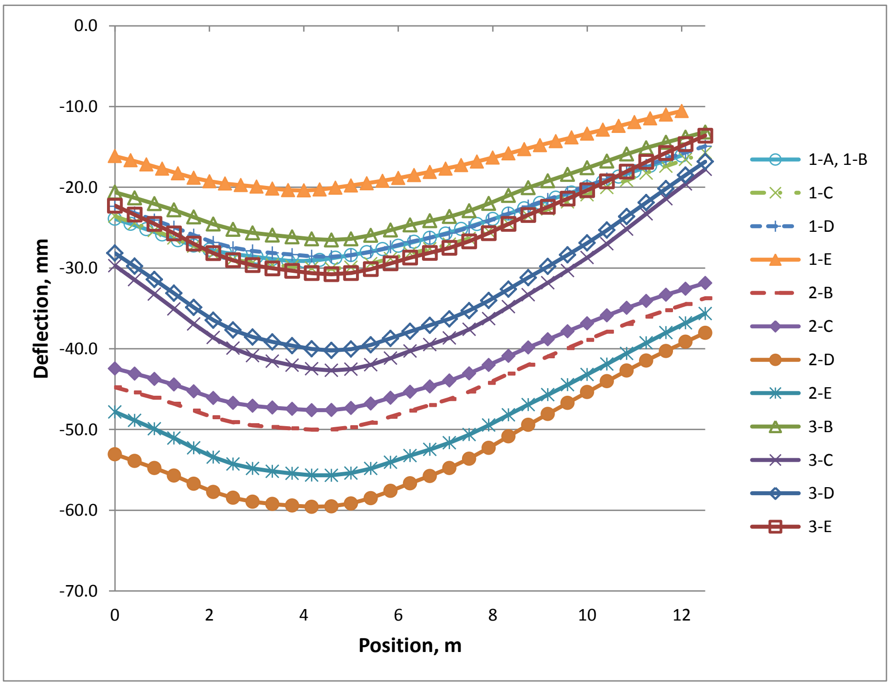

Fig 3: Maximum live load deflections

Bridge Deflection Results

Maximum deflections at mid span under SM 1600 loading [3] are shown for each deck and mix combination in Figure 3. The analyses used the mean modulus of elasticity of concrete specified in Cluse 3.1.2(a) of AS 3600 [4]. The maximum allowable deflection (averaged across the span width) specified in AS 5100 is Span/600 or 47.5 mm.

The smaller section depth used with the post-tensioned slabs (Decks Type 2 and 3) has resulted in significantly increased deflections, but this is reduced by the use of the higher strength grades, with an increased elastic modulus, and the provision of moment continuity over the central pier for Deck Type 3. Two of the deck / mix combinations studied in this paper were found to have deflections greater than that permitted by AS 5100; Type 2-E exceeded the limit by 3%, and Type 2-D by 11%. In practical applications these deflections could be reduced either by using the next deeper girder, using a higher strength concrete, or by providing moment continuity over the central pier.

Table V: Structural Analysis Output Summary

Deck/ Mix Type	Composite ULS Design Actions					
	Mid-Span			Link/Continuity Slab		
	Moment kNm	Axial load kN	Shear kN	Moment kNm	Axial load kN	Shear kN
1-A/B	8,930	-1,339	1,355	45	651	292
1-C	10,080	-825	1,481	99	-1,080	353
1-D	10,080	-825	1,481	99	-1,080	353
1-E	9,459	-693	1,371	40	-569	263
2-A/B	10,148	-737	1,573	10	-797	39
2-C	10,080	-737	1,573	10	-797	39
2-D	10,125	-885	1,427	10	-1,271	39
2-E	10,148	-737	1,573	10	-797	39
3-A/B	6,730	-580	1,854	4,874	-536	2,483
3-C	6,399	494	1,847	4,878	-529	2,499
3-D	6,331	636	1,847	4,943	-1,532	3,217
3-E	6,730	-580	1,854	4,874	-536	2,483

Resource and Emission Analysis Results

In Table VI, the volume of concrete resulting for each deck option was multiplied by the total C02 emissions per cubic metre of concrete (tCO_2-e/m^3) for the relevant mix to determine the total CO_2 emissions for each deck/mix type option. All options studied provided significant emissions savings compared with the Base Case (Mix Type A, Deck Type 1), with the greatest savings being provided by Mix Type E (High SCM mix). Savings were in the range of 15% to 19% for the fully pre-tensioned deck, increasing to 24% to 32% for the post-tensioned deck. A further 3% saving resulted from providing structural continuity at the pier.

This result suggests that by consideration of structural design options and adopting higher grade concrete, concrete volume can be reduced and the overall CO_2 emissions for a bridge deck, or potentially for any other structural element, can be decreased in a broader sense.

Table VI: Summary of Quantities and Emissions

Deck / Mix Type	Super-T Girders		Prestress; No. 15.2 mm dia. Strands		Total Quantities			Total Emmissions	
					In-situ	Precast	Reo.		
	Type	Num.	Pretens	Posttens	m^3		t	t CO_2-e	%Type 1A
1A	T4	6	40	0	147	224	65.06	376.9	100.0%
1-B	T4	6	40	0	147	224	65.06	320.1	84.9%
1-C	T4	5	42	0	147	186	59.58	312.3	82.8%
1-D	T4	5	46	0	147	186	58.62	315.3	83.6%
1-E	T5	6	28	0	151	243	67.26	304.2	80.7%
2-B	T3A	5	22	30	142	153	58.43	274.1	72.7%
2-C	T3B	5	20	30	142	146	57.76	286.1	75.9%
2-D	T2B	5	24	34	139	133	58.98	286.6	76.0%
2-E	T3	5	22	30	142	170	58.43	255.6	67.8%
3-B	T3B	5	22	10	159	146	54.25	265.5	70.4%
3-C	T2B	5	24	14	154	133	54.42	274.5	72.8%
3-D	T2B	5	24	14	154	133	53.15	275.0	73.0%
3-E	T3B	5	22	10	159	146	54.25	241.6	64.1%

Examples:

Deck Type 3-E, derived emission = $(159 + 146)m^3 \times 0.280 + 54.25t \times 2.88 = 241.6\ tCO_2$

Deck Type 1-C, derived emission = $147 \times 0.358 + 186 \times 0.472 + 59.58 \times 2.88 = 312.3\ tCO_2$

The push to replace the Portland Cement component of concrete mixes with an increased percentage of SCM's *per se* may not necessarily provide the optimum result in the context of reduced resource use and overall CO_2 emissions. In this investigation, it was found that the Type 2 deck (post-tensioned precast girders) resulted in reduced overall CO_2 emissions compared to Type 1 (fully pre-tensioned design), and the Type 3 deck (post-tensioned with moment connectivity at the central pier) resulted in a further reduction in emissions, with significantly reduced deflections. Further, the use of the higher strength concrete with all three deck types resulted in significantly improved efficiencies in regard to embodied energy, compared to the Type A mix (50 MPa with no SCM's). In addition, the options incorporating a high SCM content concrete (mix Type E) also gave favourable environmental results. This was not apparent when data for each concrete mix was considered independently of the design evaluation shown in Table V. One key factor that has been highlighted in this study is the error in assuming that reducing Portland cement content in concrete will necessarily achieve favourable environmental outcomes for a construction project.

Other factors that are not immediately obvious include constructability requirements. The use of high SCM concrete such as mix E will lead to reduced early age strengths that may not be suitable for the early application of prestressing, as required in fully pre-tensioned products. This may be overcome with more accurate means of measuring early age strengths [12] or with the provision of post-tensioned reinforcement. The effect on precast productivity therefore needs to be considered when selecting the optimum solution.

Consideration needs also to be given to how Portland cement reduction could be achieved using other inclusions such as chemical admixtures. These materials have a significant favourable impact on early age properties of concrete and should also be considered in the framework of options to produce enhanced impact on environmental outcomes.

Conclusions

The following conclusions can be drawn from this study:

- The use of SCM's allowed significant reductions in CO_2 emissions for all the concretes studied, when compared with the standard "reference case" concrete.
- The greatest reduction in emissions was found with the high SCM concrete, but this was associated with a reduced compressive strength at transfer, and increased curing period, which would increase the cost of precast operations.
- Emissions from the 80 MPa and 100 MPa concretes were equal to or only slightly higher than the 65 MPa concrete, and also allowed the use of a reduced depth of girder, which would often allow significant reductions in emissions and cost from associated works.
- The use of precast post-tensioned girders allowed significantly higher levels of prestress, with a resulting reduction in concrete volumes and total emissions.
- The reduced girder depth used with the post-tensioned options resulted in increased deflections, in two cases exceeding the allowable deflection specified in AS 5100.
- Provision of structural continuity over the central support allowed an additional small saving in total emissions, and also significantly reduced deck deflections.
- The overall reduction of CO_2 emissions was not a simple function of the reduction of Portland cement in the concrete, but was also based on how the material properties of the concretes used influenced the structural efficiency of the design.

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