Optimising Building Design for Sustainability Using High Performance Concrete

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Synopsis: The need to reduce CO_2 emissions in all parts of the building cycle has seen a push to use reduced cement contents in concretes and an increased use of supplementary cementitious materials in building construction. The roles of supplementary cementitious materials on concrete performance, whilst well understood, are not clearly defined in a sustainability context in building construction. In addition, a new Australian Standard for General Purpose and Blended Cements has recently been published with additional constituents allowed for in the broad definition of GP cement and other cement categories. The Green Building Council of Australia has recently published a proposed revised concrete materials credit that will in future form part of its published Green Star specification for residential and commercial buildings.

Whilst these developments are welcomed, there has been little examination of the potential interaction between cement content, binder composition, binder content, concrete strength, other mechanical and serviceability properties of concrete, required constructional properties and the total material usage in typical building structures. This paper examines the opportunities for improved sustainability through the use of high performance concrete in building construction, considering the use of existing typical designs, and modified designs optimised for higher strength grades or other critical concrete performance parameters. These alternatives are compared for impact on life-cycle resource requirements, CO_2 emissions, durability, and constructability, within the context of current Australian building design and construction practice. Guides are provided to design groups who may be confronted with sustainability related requirements on building projects.

Keywords: sustainability, Green Star, cement, supplementary cementitious materials, embodied energy, fly ash, ground granulated iron blast furnace slag, binders, concrete, performance.

1. Introduction

This paper examines the effect of concrete strength on the design of a typical flat slab structure. Reinforced concrete flat slabs were originally developed in the USA at the start of the 20th century, with prestressed flat slabs being introduced in the USA and Australia from the 1960's (1). In Australia development focussed on bonded prestress systems, which are now widely used in floor systems for multi-story buildings (1, 2). In order to provide a valid comparison between reinforced and prestressed designs, with a structure where changes in concrete performance will have a significant effect, the subject structure was chosen to have spans at the upper end of the range where reinforced concrete is typically used.

The span arrangement for the slab investigated is shown in Figure 1. This arrangement is a metricated version of an example design to ACI 318 (3), provided in a PCA publication (4). For the purposes of this paper the design has followed the requirements of AS 3600-2009 (5), and follows typical Australian practice for arrangement of prestressing tendons and reinforcement detailing.

2. Details of study

This study examined the effect of the use of different concrete mixes on the embodied energy (CO_2 emissions) of a typical continuous multi-span flat slab structure, constructed in either reinforced or prestressed concrete. Key design features of the structure are as follows:

- Three x four span flat slab building floor structure supported on square columns,
- Span arrangement: 4 x 7.5m longitudinal, 7.5 m, 9.0 m, 7.5 m transverse,
- 2.5 x 2.5 m drop panels over 400 mm square columns,

- Design to AS 3600 using an equivalent frame analysis and non-linear analysis for deflections,
- Deflections were limited to Span/250 for all members and Span/500 for long term plus live load deflections, in accordance with AS 3600, Table 2.3.2,
- Loading to AS 1170.1(6) with 3 kPa live load,
- Typical Sydney shrinkage and creep parameters, and
- Exposure Classification A2 as defined in AS3600 Section 4 on Design for Durability (5).

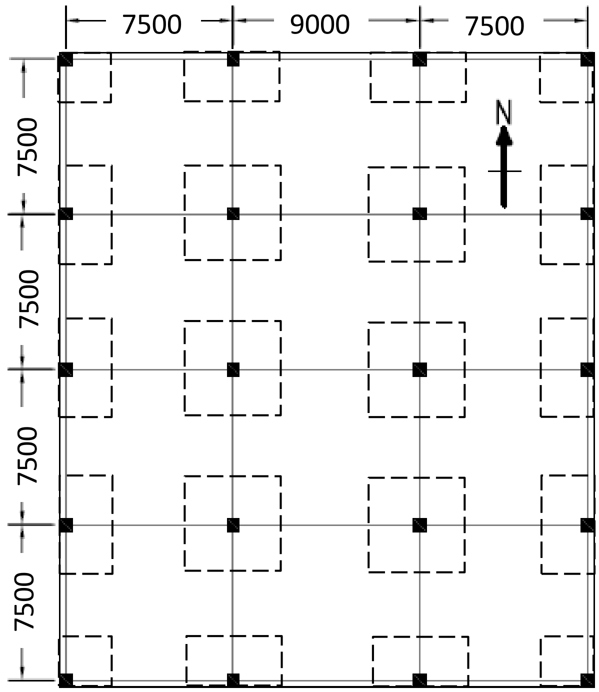

Figure 1, Flat Slab Layout

Two alternative structural configurations were considered as follows:

- Type 1 – Reinforced concrete flat slab.
- Type 2 - Post-tensioned concrete flat slab.

Alternative concrete mixes conforming to Australian Standard AS1379 (Specification and Supply of Concrete) (7) were selected for this study. These covered a reference case concrete mix made using Portland cement alone and, whilst based on draft guidelines prepared by the Green Building Council of Australia (8), adopted more typical cement contents required to achieve the performance criteria described above. Other concrete mix options considered had binders containing cement and supplementary cementitious materials (SCMs) defined in AS3972 (General Purpose and Blended Cement) (9), and AS3582 Part 1 (Fly Ash) (10) and Part 2 (Ground Granulated Iron Blast Furnace Slag) (11). The following concrete mixes were evaluated in this study:

A. **Reference case:** 25 MPa characteristic compressive strength concrete made using Portland cement alone,
B. Typical current standard structural concrete; characteristic compressive strength of 25 MPa incorporating SCMs,
C. Typical prestressed concrete having a characteristic compressive strength of 40 MPa required for post-tensioned construction (12, 13)
D. Typical high strength concrete having a characteristic compressive strength of 65 MPa,
E. High SCM concrete having a characteristic compressive strength of 40 MPa.

Typical mix designs details for concrete mixes A to E are provided in Table 1. The reinforced concrete designs were provided with spandrel beams in order to meet deflection requirements. Concrete mixes used were A, B, C and E. The slab depth for the reinforced concrete design was governed by deflections, and the higher strength of mix Type D was found not to provide any significant advantage.

Table 1: Concrete Mix Design Details

Concrete Mix Property	Concrete Mix Constituent/ Performance Parameter	Unit	Standard Specification	Mix A: 25MPa Reference case mix (OPC only)	Mix B: Typical 25MPa mix containing SCM's	Mix C: 40MPa prestressed mix	Mix D: 65MPa HSC mix	Mix E: 40MPa mix with high SCM content
Nominal Concrete Mix Design	Total Binder Content	kg/m^3		290	310	395	500	420
	GP Cement Content	kg/m^3	AS3972	290	250	335	350	255
	Flyash	kg/m^3	AS3582.1	0	30	60	70	80
	GGBFS	kg/m^3	AS3582.2	0	30	0	80	85
	Coarse Aggregate	kg/m^3	AS2758.1	980	990	1000	1035	1000
	Sand	kg/m^3	AS2758.2	945	900	830	690	785
	Water	kg/m^3	AS1379	185	185	180	180	180
	Total Binder Content	kg/m^3		290	330	435	530	420
	Water:Binder Ratio			0.64	0.60	0.46	0.36	0.43
Concrete Mechanical Property	Typical 28 day Compressive strength (f_{cm})	MPa	AS1012.9	28	28	50	75	45
	Transfer Strength	MPa	AS1012.9	-	-	25	30	25
	Nominal Drying Shrinkage	Microstrain	AS1012.13	750	750	650	550	600

The prestressed concrete designs did not require spandrel beams. Concrete mixes used were C, D and E. The standard strength mixes (A and B) were not suitable for prestressed concrete use because of performance criteria required as discussed elsewhere in the literature (12, 13). Details of slab design using the various options considered are summarised with estimated concrete volumes for each design in Table 2.

Table 2: Slab Design Details

Slab-Mix Type	1-A,B	1-C	1-E	2-C	2-D	2-E
Slab depth, mm	300	250	250	180	170	180
Drop panel depth, mm	90	90	90	100	80	100
Drop panel O/A width, m	2.5	2.5	2.5	2.5	2.5	2.5
Spandrel beam depth, mm	300	300	300	0	0	0
Concrete vol: slab	216.0	180.0	180.0	129.6	122.4	129.6
Drop panels	6.8	6.8	6.8	7.5	6.0	7.5
Spandrel beams	13.0	13.0	13.0	0.0	0.0	0.0
Total	**235.7**	**199.7**	**199.7**	**137.1**	**128.4**	**137.1**

4. ANALYSIS AND DESIGN PROCEDURES

4.1 Structural Analysis

The structures were designed to the simplified method given in AS 3600, and checked using the equivalent frame method, following the procedures given in Warner et. al. (14). Prestressing strand was provided to balance approximately 85% of the structure self-weight, and was checked to ensure compliance with the Code requirements for the Ultimate and Serviceability Limit States. Slab deflections were checked with a non-linear finite element analysis, using a moment-curvature relationship taking account of cracking, tension stiffening, loss of tension stiffening, creep and shrinkage (15). Further details of the deflection analysis are given in Section 6.

4.2 Concrete Emissions Analysis

Component emission factors used to calculate embodied energy of concrete are presented in Table 3 and are taken from other studies conducted on concrete materials (16). Concrete mix emissions for alternative mix designs A to E are given in Table 4 and are expressed in tonnes of $C0_2$ 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 (16). 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) (9) has increased this allowance to 7.5%.

Table 3: Concrete Component Emission Factors (16)

Concrete Component	Emission Factor	Unit
GP Cement	0.82	t CO_2-e/tonne
Fly Ash	0.027	t CO_2-e/tonne
GGBFS	0.143	t CO_2-e/tonne
Amorphous Silica	0.027	t CO_2-e/tonne
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

Table 4: Mix Emission Details (per cubic metre of concrete)

Constituent Emissions $tC0_2$-e/m^3	Mix A: 25MPa Reference case mix (OPC only)	Mix B: Typical 25MPa mix containing SCM's	Mix C: 40MPa prestressed mix	Mix D: 65MPa HSC mix	Mix E: 40MPa mix with high SCM content
Portland Cement	0.2259	0.1948	0.2610	0.2727	0.1986
Flyash	0.0000	0.0008	0.0016	0.0019	0.0022
GGBFS	0.0000	0.0043	0.0000	0.0114	0.0122
5% Mineral Add's/Minor Constituent Mater	0.0012	0.0011	0.0014	0.0015	0.0011
Coarse Aggregate	0.0353	0.0356	0.0360	0.0373	0.0360
Fine Aggregate	0.0132	0.0126	0.0116	0.0097	0.0110
Concrete Batching and Placement	0.0120	0.0120	0.0120	0.0120	0.0120
Totals tCO_2-e/m^3	0.2877	0.2612	0.3236	0.3464	0.2730
% due to Portland Cement	79%	75%	81%	79%	73%
% Reduction in CO_2 Emissions compared with 25MPa Reference Case		9%	-13%	-20%	5%

Note: As an example, for the Mix A Portland cement component, the emission derived is (0.290 t cement/$m^{3)}$ x (0.82 tCO_2tonne) x 0.95 = 0.2259 tCO_2 per cubic metre of concrete, allowing for 5% mineral additions in the cement.

The value of total CO_2 emissions for a mix is mostly influenced by the Portland Cement content due its relatively high emission factor; a result of the relative energy intensive process required for its manufacture. The total mix CO_2 emissions increases with strength grade, however it can be effectively reduced with the replacement of the Portland cement component with SCM's. Data in Table 4 suggest that based on the mix designs and in the context of maximising Portland cement content reduction, the 25 MPa standard structural concrete mix (Mix B) and the 40 MPa high SCM mix (Mix E) might provide the most favourable options when compared with the reference case concrete mix in terms of embodied energy reductions. The 40 MPa prestressed concrete mix and the HSC mix appear to provide less opportunity for reducing embodied energy based on materials related criteria alone.

5. SLAB SECTIONS

Details of slab depth, drop panel depth and spandrel beams for this analysis have been provided previously in Table 1. The minimum thickness for the reinforced slabs (Type 1) was controlled by deflections. The minimum thickness for the prestressed concrete slabs (Type 2) was controlled by punching shear criteria at the column locations. Reinforcement and prestressing strand requirements are shown in Table 5. Using the embodied energy calculations for each mix described in Table 4, a summary of quantities and total CO_2 emissions for each of the structural designs, reinforced concrete and post-tensioned concrete, were calculated. Results have been summarised in Table 5. Recapping the analysis, the following were used for analysis:-

- Reinforced concrete design
  - 25 MPa reference case Portland cement concrete (1-A),
  - 25 MPa concrete containing SCMs (fly ash and ground slag) (1-B),
  - 40 MPa concrete containing SCM's (1-C), and
  - 40 MPa concrete containing high SCM content (1-E)
- Post-tensioned concrete design,
  - 40 MPa concrete containing SCMs (2-C,
  - 65 MPa concrete containing SCMs, and
  - 40 MPa concrete containing high SCM content

A graphical representation of the data is presented in Figure 6.

6. DEFLECTION ANALYSIS AND RESULTS

Slab deflections were checked with a non-linear finite element analysis, using 4-noded plate-shell elements. One quarter of the finite element model is shown in Figure 2. Non-linear behaviour for the reinforced concrete slabs was modelled using a stress-strain curve formulated to give the correct moment-curvature behaviour of the slab, allowing for cracking of the concrete and long term creep and shrinkage effects. Deflection results at mid-span are shown in Figures 3 to 5 for Slabs 1-B, 1-C and 2-C. Long term deflections for the reinforced slabs (1B and 1C) are greatly increased compared with the short term deflection under self-weight, due to the effects of flexural cracking, shrinkage and creep. Deflections for the prestressed slabs (2C) are greatly reduced, and the increase in deflections with time is reduced because the slab remains uncracked.

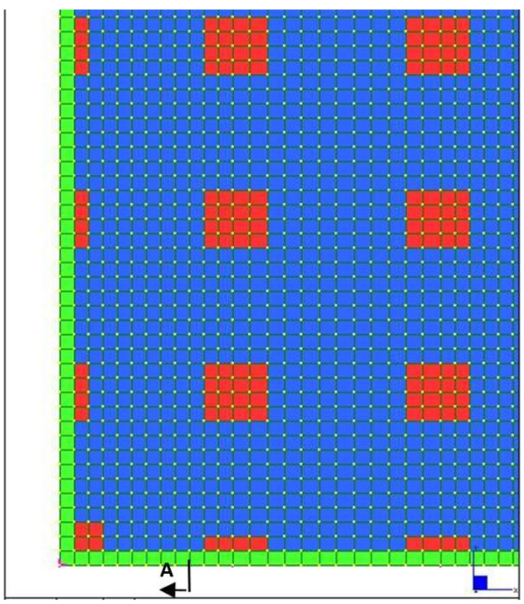

Figure 2, FEA Mesh (part)

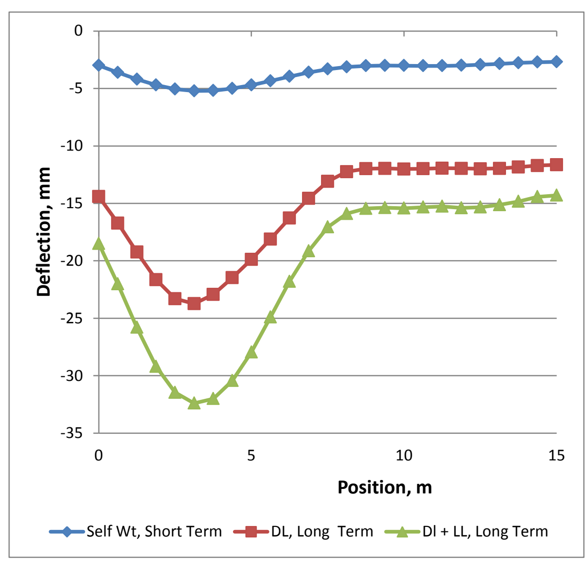

Figure 3, Vertical Deflections, Slab 1-B

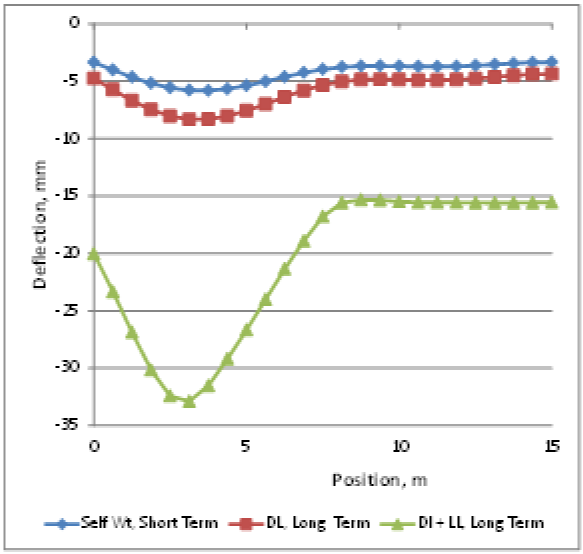

Figure 4, Vertical Deflections, Slab 1-C

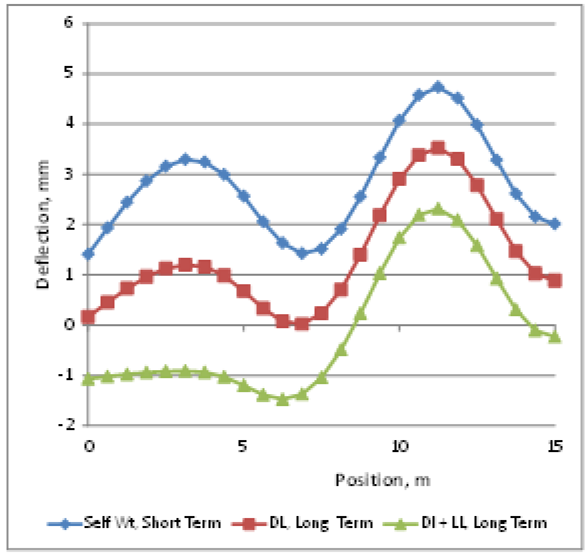

Figure 5, Vertical Deflections, Slab 2-C

Table 5: Summary of Quantities and Emissions

Summary Calculations	Unit	Slab-Mix Type						
		1-A	**1-B**	**1-C**	**1-E**	**2-C**	**2-D**	**2-E**
Total Concrete Volume	m^3	233.3	233.3	197.3	197.3	147.6	129.6	147.6
Total kg of Portland Cement	kg	64274	55409	62791	47796	46974	43092	35756
Concrete Mix Emissions per m^3	t CO_2-e/m^3	0.2877	0.2612	0.3236	0.2730	0.3236	0.3464	0.2730
Total Concrete Emissions	t CO_2-e	67.1	60.9	63.9	53.9	47.8	44.9	40.3
Passive reinforcement wt	kg	12,242	12,242	12,242	12,242	1,962	1,902	1,962
Prestress strand and anchorage wt	kg					4,008	3,340	4,008
Reinforcement emissions	t/kg	0.00288	0.00288	0.00288	0.00288	0.00288	0.00288	0.00288
Total reinforcement emissions	t CO_2-e	35.3	35.3	35.3	35.3	17.2	15.1	17.2
Total Emissions	t CO_2-e	**102.4**	**96.2**	**99.1**	**89.1**	**65.0**	**60.0**	**57.5**
% Reduction in CO_2 Emissions compared with Slab/Mix Type 1-A			**6%**	**3%**	**13%**	**37%**	**41%**	**44%**
% Portland Cement Reduction compared with Slab/Mix Type 1-A			**14%**	**2%**	**26%**	**27%**	**33%**	**44%**

7. RESOURCE AND EMISSIONS ANALYSIS RESULTS

In Table 5, the volume of concrete resulting for each slab option was multiplied by the total $C0_2$ emissions per cubic metre of concrete (tCO_2-e/m^3) for the relevant mix to determine the total CO_2 emissions for each slab/mix type option. All options studied can be seen to provide significant emissions savings when compared with the reference case concrete (Mix A, Slab Type 1). 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 slab, or potentially for any other structural element, can be decreased in a broader sense.

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 structural configuration Type 2 – Post-tensioned concrete flat slab resulted in reduced overall CO_2 emissions compared to Type 1 – Reinforced concrete flat slab design. Further, the use of high strength concrete as per Slab Type 2 with Mix D resulted in one of the most efficient options in regard to embodied energy. In addition, the post-tensioned slab option incorporating a high SCM content concrete (slab/mix option 2-E) resulted in another favourable environmental design option. This was not apparent when data for each concrete mix was considered independent of the design evaluation shown in Table 4. 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 but need to be considered include constructability requirements, The use of high SCM concrete such as mix E will lead to reduced early age strengths (12, 13) that may not be deemed suitable in the case of prestressed applications where 1 and 4 day minimum compressive strength criteria apply. While this may be overcome with more accurate means of measuring early age strengths (12), it could lead to increased project timelines all the same. The applicability of higher strength concretes in some elements must also be considered as in this case, the option of 65 MPa for a slab application has been included to highlight potential benefits of such concretes in designing for sustainability. It is recognised that it may not be feasible in some cases to apply such materials to projects due to other design and/or performance constraints.

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.

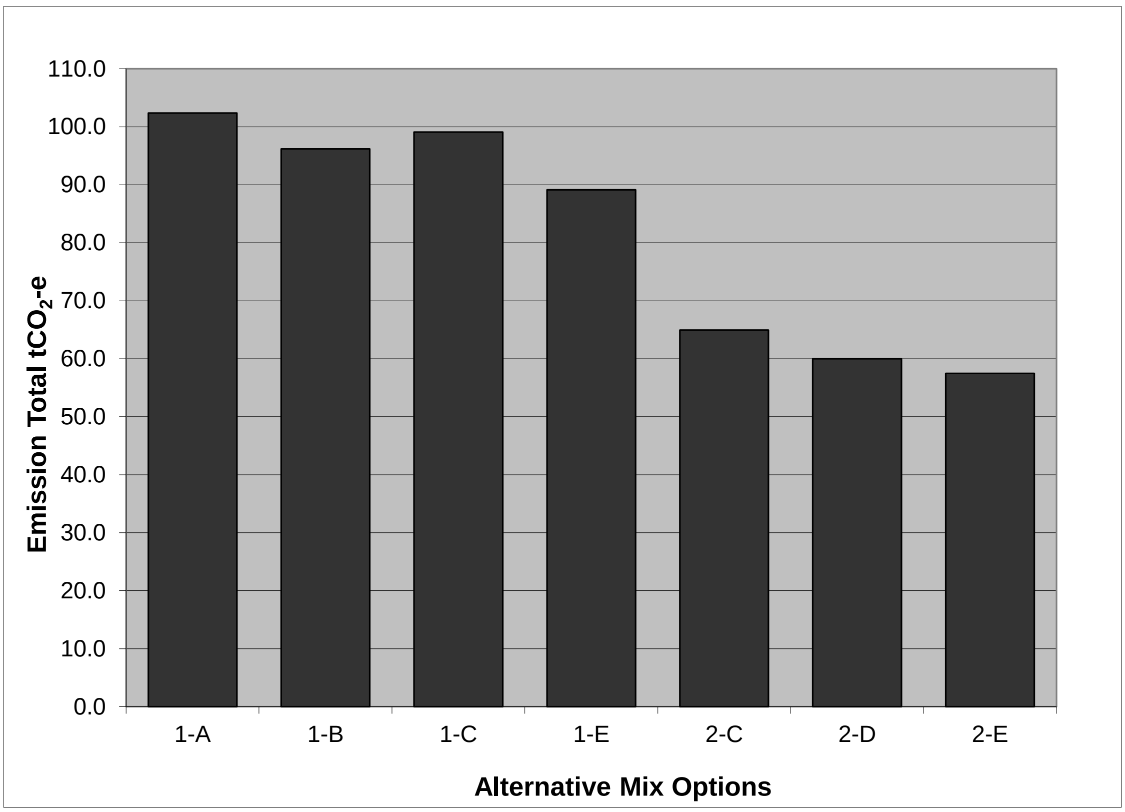

Figure 6: Embodied Energy (CO_2 Emissions) Derived from The Design and Concrete Materials Related Analyses

7. CONCLUSIONS

The following conclusions can be drawn from this study:-

- Both reinforced concrete design and post-tensioned concrete design for slabs in buildings can result in efficient solutions on building projects for sustainable construction.
- Tools are available to determine with reasonable accuracy the embodied energy involved in producing and supplying a cubic metre of concrete.

- Supplementary cementitious materials can be efficiently used to produce concretes that have appropriate design and construction characteristics required for building projects.
- The simple reduction of Portland cement content in a concrete mix, by whatever means, will not necessarily result in an efficient design and thus in an efficient environmental outcome.
- The analysis showed that using higher strength concretes having more Portland cement than would be used on other design options resulted in more efficient design options with respect to favourable environmental outcomes, both through the reduction in the total volume of concrete and a reduction in total steel quantities.
- The use of a high SCM content in association with a prestressed, post-tensioned design may require changes to current construction practices, particularly at the stage of initial stressing, and the choice of optimum system will require review of the effects on the construction programme and cost, as well as direct materials emissions and costs.
- For floor slabs in the span range examined in this study or greater, the use of a relatively high strength, high SCM concrete, in conjunction with prestressing, is likely to result in substantially greater reductions in total emissions than can be achieved by focussing on reduction of cement content alone.
- In addition to the reduction in CO_2 emissions, the use of a prestressed concrete design for slabs in this span range also had other benefits including reduced construction depth, greatly reduced long term deflections and reduced flexural cracking, which should also be taken into account in the choice of structural system.

8. ACKNOWLEDGEMENTS

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