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# Optimised design selection and environmental impact assessment of alternative concrete slab construction methods

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## ABSTRACT

This research has been conducted to compare the significant material reductions available through various slab systems to improve the sustainability attributes of a given building from a structural perspective. Specifically the study investigates the structural efficiency of a building that has been repetitively designed varying each of the slab systems and concrete construction types. These structures are designed in accordance with all relevant Australian standards. Each design is then graded in relation to the sustainable performance of the structure; more specifically its overall environmental performance. The outcomes of this study indicate that significant economic and environmental benefits are achievable through the selection of the most appropriate structural system type.

## 1. INTRODUCTION

Construction material consumption is greater than any time in history. Australia produces approximately 30 million tonnes of finished building products each year, with over 56% of this quantity, by mass, being attributed to concrete and a further 6%, steel (Walker-Morison *et al.* 2007). The cement industry alone has been shown to contribute more than 5% of global anthropogenic $CO_2$ emissions to the atmosphere annually (Flower & Sanjayan 2007). Globally, 23 trillion kilograms of concrete alone is consumed annually with growing population driving increasing demands (WGBC 2009, Schokker 2010). From a structural engineering perspective, the use of the most efficient solutions to any given task is poorly considered due usually to pressures from the architect and/or client. The aim of this paper is to investigate and identify the most efficient solution from a selection of slab system types and construction techniques to achieve a

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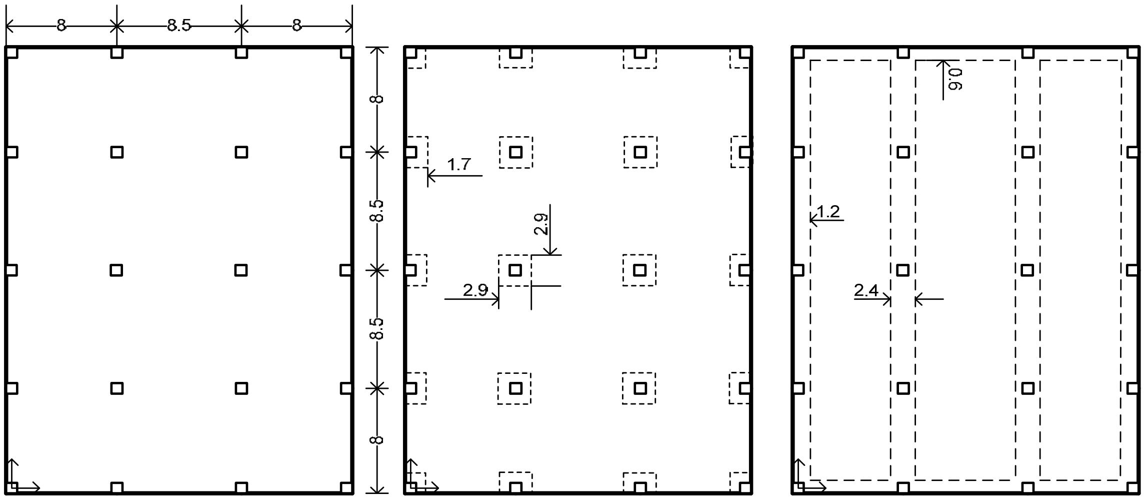
known structural outcome. Various slab construction systems were modeled and investigated to determine options through which embodied energy considerations are optimised to achieve a required outcome. The various slab systems available, all have unique properties requiring various depths, span lengths and other characteristics which all affect the final design and consequent performance of a structure from a sustainable perspective. Each slab system delivers its own strengths but the repetitive use of a design favourite often delivers inefficient solutions. The various slab systems investigated in this study include: beam & slab, flat slab and flat plates while concurrently considering the use of conventionally reinforced (RC) and post-tensioned (PT) construction techniques for a typical office building. Previous research focused initially on the effects of maintaining the material parameters and varying the span length (Miller *et al.* 2012), while further research investigated the relationship between the variation of both concrete strengths and span lengths (Miller *et al*. 2013). These papers studied the outcomes for both RC and PT construction techniques, but did not examine alternative slab design systems. These alternative slab systems have been investigated below.

## 2. DESIGN POST TENSIONED AND REINFORCED CONCRETE SLAB



(a)Flat plate (b) Flat slab (c) Beam & slab

Fig. 1 Typical slabs plan views

*2.1 Slab configuration*

A typical plan view of the slabs were modelled and analysed with four longitudinal and three latitudinal spans to achieve fixed structural dimensions. The only variations over the different designs were the changes in formwork, due to required adjustments to the slab depth or different slab system configuration. Fig. 1(a) illustrates the plan view that was used for the flat plate system. This plan was the basis for all designs and remained consistent excluding slab thickness and reinforcement requirement variations. The entire slab measured 25×32.5m and is supported on columns measuring 500×500mm. Each end span was shorter, (8.0m) while the interior spans measured 8.5m, a serviceability requirement, originating from the fact that end spans usually exhibit a higher overall deflection compared to interior spans, resulting in the need for either: 1) thicker slabs or 2) shorter end spans, the latter of which was chosen.

The flat slab (Fig. 1(b)) only differs from the flat plate by the additional drop panels over the columns. These panels measured 2.9m by 2.9m internally and 2.9m by 1.7m externally. The depth of these panels varied with normal slab depth at a ratio of approximately 1.6D for both RC and PT slabs. The beam & slab was chosen to have wide beams stretching in the longitudinal direction (Fig. 1(c)). The beams have a width of 2.4m internally and 1.2m for edge beams. Beams stretching in the latitudinal direction were added externally with a width of 600mm. This is usually done to create a better finish to the overall formwork. The depth of the beams varies with slab depth, similar to the drop panels for the flat slab. For a RC beam & slab the ratio for this depth was around 2.1D while a PT slab had a slightly smaller ratio at 1.75D. The selection of these ratios was based principally on extensive design experience of one of the authors in this field.

For comparative purposes, material parameters remained consistent across all designs, with concrete strength being 40MPa and a reinforcement yield strength of 500 MPa. Additionally, all designs were subjected to the same imposed loading. A live load of 3 kPa with a superimposed dead load of 1 kPa was applied in accordance with normal design loads for a typical office specified by the Australian loading code, structural design actions (AS 1170.1, 2002).

The design process was completed using traditional hand calculations, with verification via two modelling programs, RAM Concept and RAPT. This process resulted in the design of a total of 18 slabs for strength and serviceability based on the required criteria. The outcomes of these designs are discussed in detail below.

### *2.2 Design for serviceability*

Determination of the required slab thickness is an iterative process which continues through the analysis and is affected by numerous factors. The most efficient slab will display a minimum required thickness to control deflection and punching shear whilst maintaining acceptable reinforcement requirements.

A minimum control over long term deflection of $\frac{\Delta}{L_{ef}} \leq \frac{1}{250}$ is required for an office slab in compliance with Clause 2.3.2 in AS3600-2009. In addition to this, a minimum control over incremental deflection of $\frac{\Delta}{L_{ef}} \leq \frac{1}{500}$ for all floor slabs is required. This deflection is critical in members supporting masonry partitions and brittle finishes which are present in most multi-storey office structures of this height. Application of these minimum deflection limits using the deemed to comply span-to-depth ratio for reinforced concrete slabs, as detailed in AS3600-2009 - Clause 9.3.4, provides an initial indication of the required thickness for the reinforced concrete slabs. AS3600-2009 provides no methods to determine the thickness of a PT slab. In large spans, it is more effective to use a span-depth ratio to determine the slab thickness. While various span-depth ratios are suggested in a number of published literature, those quoted by the Cement and Concrete Association of Australia (CCAA, 2003) were used. It is suggested by the CCAA that the most economical span-depth ratio, L/D, for a PT flat plate slab is between 37 and 40. A value of 38 was adopted for the calculations conducted here.

### 2.3 Embodied Energy

After the completion of design and verification for modeling of each slab, a bill of quantities was generated in order to conduct an Environmental Impact Assessment (EIA). The data used for the EIA was obtained from an extensive literature review (Lawson 2000, Treloar *et al.* 2001, Norgate & Rankin 2002, Aye *et al. 2011,* Crawford 2011, Miller *et al.* 2011, Miller *et al.* 2012), in order to calculate an indicative value for the environmental impact of each structure in terms of Embodied Energy (EE). Unit values for each of the primary construction materials have been summarized from this review as shown in Table 1. While it is noted that high strength steel tendon fibers undergo different manufacturing procedures, there is significant limitations in identifying suitably accurate EE values for these. There was no value specified for embodied energy of the high tensile steel tendons, required for PT construction, in the study undertaken by Crawford (2011), or any of the other authors. However, EE for galvanised steel is included for the duct systems on bonded PT design. As a conservative estimate, the result of the addition of the EE of steel reinforcement and galvanized steel bar was adopted for the EE of high tensile steel tendons.

Table 1. Embodied Energy and $CO_2$ Equivalent values to be utilized in the Environmental Impact Assessment (Crawford, 2011)

| **Construction Material** | **Embodied Energy** |
|---|---|
| Concrete 40Mpa | 5670 $MJ/m^3$ |
| Steel bar | 85.46 GJ/tonne |
| Galvanised Steel | 38.00 GJ/tonne |
| High Tensile Steel Tendons | 123.46 GJ/tonne |

## 3. RESULTS AND DISCUSSION

To satisfy both long-term and incremental deflections, the deflection to span ratios were determined and presented in Table 2. As indicated in the incremental and long-term deflections, those minimum deflection limits will result in impractical deflections for some slab systems. These deflection to span ratios should be minimised as much as possible, given large deflections are visually unacceptable. For the RC flat plate slabs, depths of 250, 280 and 310mm were designed using two computer programs, however, the final instantaneous deflection for both the 250 and 280mm slabs were estimated to exceed the desired limit of 25mm using all methods for calculating deflection. Hence, the 310mm deep slab was therefore the most efficient choice of flat plate RC slab and could be used in the subsequent comparison. Initial selection of these three thicknesses (for all *Types*, see Table 2), was based on design experience. Given the iterative nature of the process, increasing slab thickness to obtain numerous comparative results for three satisfactory designs, above a thickness of 310mm was deemed unnecessary. An optimal outcome has obviously been achieved at 310mm thickness and hence adopted as the most efficient solution. Similarly, RC Flat slab 200 mm depth and Beam & Slab 170 mm depth do not meet incremental deflection requirements (Table 2). This outcome was also observed for the PT flat plate, with the 180mm thick slab not satisfying deflection requirements. For the remainder of the 18 slabs modelled, after satisfying all limit state and serviceability requirements, the minimum required depths for various slab systems of both RC and PT were determined developing the results presented in Table 2. Hand calculations were also attempted for verification purposes, with observed maximum deflection normally occurring in the corner panels. As a result, the optimum slab depth for each system with minimum steel reinforcement requirements to achieve the required structural outcomes have been summarised in Table 2. These floor system results were obtained to satisfy both serviceability and limit state design.

Table 2 Slab depths and material requirements

| Types | | Slab thickness ( Panel or Beam depth) mm | Concrete $m^3$ | Post-tension tonne | steel reinforcement tonne | Deflection mm | Long-term Deflection mm |
|---|---|---|---|---|---|---|---|
| RC Slab | Flat Plate | 250 | 209.4 | N/A | 19.56 | 50.8 (fail) | - |
| | Flat Plate | 280 | 234.5 | | 18.58 | 36.1 (fail) | - |
| | Flat Plate | 310 | 259.6 | | 18.06 | 19.00 | 30.6 |
| | Flat Slab | 200 (320) | 180.9 | | 19.36 | 37.8 (fail) | - |
| | Flat Slab | 220 (350) | 198.7 | | 19.32 | 21.20 | 40.6 |
| | Flat Slab | 240 (380) | 216.6 | | 19.12 | 16.90 | 34.6 |
| | Beam & Slab | 170(360) | 192.3 | | 19.69 | 28.0 | 34.7 |
| | Beam & Slab | 190 (400) | 214.3 | | 20.97 | 16.60 | 28.3 |
| | Beam & Slab | 210 (440) | 236.3 | | 21.48 | 12.60 | 23.9 |
| PT Slab | Flat Plate | 180 | 150.8 | 6.19 | 3.65 | 26.4 (fail) | - |
| | Flat Plate | 200 | 167.5 | 4.96 | 3.48 | 23.0 | 36.8 |
| | Flat Plate | 220 | 184.3 | 5.32 | 3.28 | 19.7 | 23.9 |
| | Flat Slab | 160 (280) | 147.4 | 2.99 | 2.43 | 20.8 | 27.4 |
| | Flat Slab | 180 (300) | 164.1 | 2.97 | 2.37 | 15.8 | 22.9 |
| | Flat Slab | 200 (320) | 180.9 | 3.24 | 2.09 | 11.3 | 25.3 |
| | Beam & Slab | 140 (250) | 146.1 | 3.55 | 10.63 | 24.6 | 30.8 |
| | Beam & Slab | 160 (280) | 165.5 | 3.55 | 11.09 | 17.1 | 23.1 |
| | Beam & Slab | 180 (310) | 184.9 | 3.35 | 9.75 | 11.8 | 25.0 |

Material requirements as determined from the bill of quantities generated from each design were applied factors to quantify the environmental impacts of materials in each floor (Table 1). These material requirements, as determined from the bill of quantities to EE for alternate slab construction techniques are presented below in Figs. 2 and 3. Results indicate a significant reduction in material requirements being achieved through the implementation of PT construction methods. Results also show that the selection of slab systems can provide significant variation in the final EE efficiency performance of a structural for a given task. The total environmental impacts in each slab are indicated as individual contributions of the concrete and steel components. Comparison of the unit environmental impacts for steel and concrete by mass, indicate the EE of steel and post-tensioning are at least 15 times that of concrete. As shown in Table 2, the only benefit of using a thicker flat plate and flat slab was less reinforcement requirements. Conversely, increasing the post-tensioning results in the total EE increasing as shown in Fig. 3. The PT flat slabs show the expected outcome that as slab depth increases, EE increases. On all PT slab systems, steel tendon inclusions were limited to the minimum necessary to satisfy deflection limit requirements.

Table 3 Percentage reduction of Embodied Energy for PT vs. RC construction systems

| Floor system | | Slab thickness (mm) | EE value (GJ) | % Steel reduction (compared to RC) | % Concrete reduction (compared to RC) | % EE reduction (compared to RC) |
|---|---|---|---|---|---|---|
| RC | Flat Plate | 310 | 3014.91 | - | - | - |
| | Flat Slab | 220 | 2777.28 | | | |
| | Beam & Slab | 190 | 3007.17 | | | |
| PT | Flat Plate | 200 | 1859.06 | 69.68 | 54.99 | 62.17 |
| | Flat Slab | 160 | 1412.57 | 186.17 | 34.80 | 96.61 |
| | Beam & Slab | 140 | 2174.68 | 33.11 | 46.68 | 38.28 |

Table 4 Proportional contribution of steel to structural system weight

| Floor System | | Slab Thickness | Concrete Weight (t) | Steel Weight (t) | Structural Weight (t) | Steel Contribution (%) |
|---|---|---|---|---|---|---|
| RC | Flat Plate | 310.00 | 623.04 | 18.06 | 641.10 | 2.82 |
| | Flat Slab | 220.00 | 476.88 | 19.32 | 496.20 | 3.89 |
| | Beam & Slab | 190.00 | 514.32 | 20.97 | 535.29 | 3.92 |
| PT | Flat Plate | 200.00 | 402.00 | 8.44 | 410.44 | 2.06 |
| | Flat Slab | 160.00 | 353.76 | 5.42 | 359.18 | 1.51 |
| | Beam & Slab | 140.00 | 350.64 | 14.18 | 364.82 | 3.89 |

Comparative analysis has been carried out between the most economical RC and PT for each slabs system. Table 3 displays the environmental impacts resulting from material requirements in the structure employing three PT slab constructions as a percentage of impacts resulting from the structure employing three RC concrete slab construction methods. These comparisons have been conducted against only the same type of design system i.e. flat plate RC vs. flat plate PT etc. Results indicate that in all cases PT slab selection was more efficient in terms of EE with a reduction of 38.3% to 96.6% in the EE values observed for the selection of a PT slab system over RC. Individual EE material contribution reductions of 34.8% to 55% for concrete as well as 33.1 to 186.2% for steel (reinforcement + high tensile tendons) were observed through the utilisation of a PT construction method (Table 3).

Despite the small contribution to structural system weight (less than 4% of total structural weight in all cases), environmental impacts in all slabs considered are shown to result mainly from the EE of steel making up approximately 51% to 60% for RC slabs and 20% to 52% for PT slabs (Table 3 & 4). This highlights a focus for EE reductions and optimisation in structural systems by minimising reinforcement requirements. From an optimisation perspective, given the known structural outcome required in this instance, the most efficient solution is that which consumes the least EE to achieve the required structural outcome. From the results presented in Table 3, the most efficient solution is the flat slab PT system consuming 1412.57 GJ of EE in comparison with the least efficient flat plate RC slab system consuming more than two times the EE at 3014.91 GJ.

Due to the disproportionate contribution of steel to the total EE value of a structure when compared to structural weight (Table 4), an increase in slab depth does not correspond to an increase in EE in all cases.

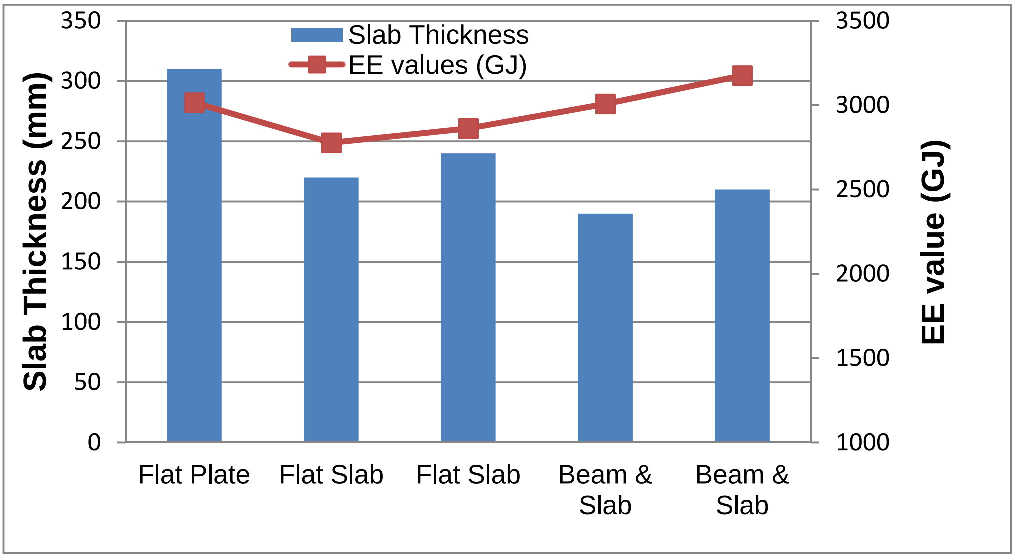


Fig. 2 Reinforced Concrete slab system vs thickness and Embodied Energy values

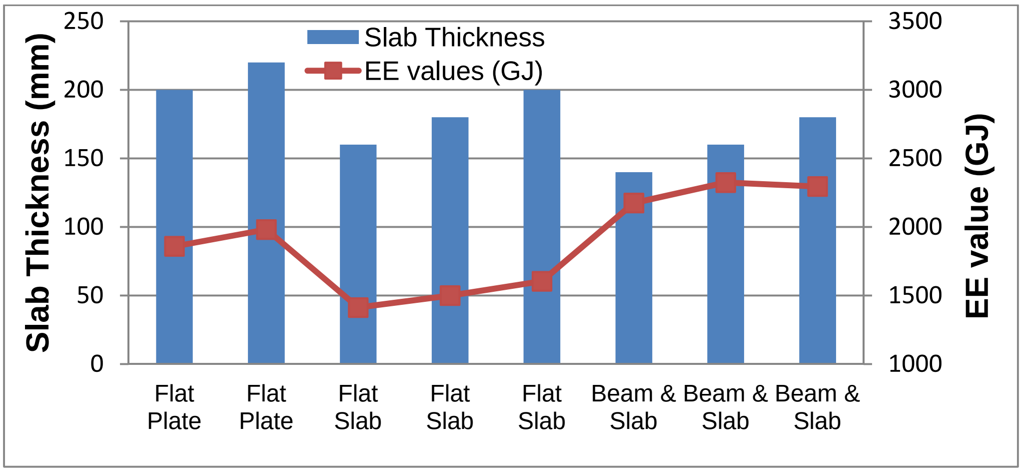


Fig. 3 Post-tensioned Concrete slab system vs. thickness and Embodied Energy values

## 4. CONCLUSIONS

The results obtained from this parametric study can be divided into two key components as determined from the structural analysis and the subsequent environmental impact assessment. The findings are divided into material requirements of the structures and the environmental impacts associated with these structures.

The findings obtained from the structural analysis indicate a significant reduction in material requirements can be achieved through the implementation of PT construction methods. The use of post tensioning is able to significantly reduce the concrete volume and more importantly in terms of its environmental performance - steel mass required for a structure. The variable results obtained from the selection of differing slab systems highlights the potential inefficiencies through the selection of an inappropriate system for a required structural outcome. Dissemination of these findings is important to increase the adoption of optimised structural systems.

Efficient structural systems will further result in significant overall building weight reductions leading to potential foundation material savings. From a practical perspective, the results of this study show that repetitive design favourites may not always lead to the most efficient structural system.

The outcomes from these results provide confirmation that PT construction techniques can achieve an advantageous EE cost being less than that of the RC option.

## REFERENCES

Aye, L. Ngo, T. Crawford, R.H. Gammampila, R. & Mendis, P. (2011), “Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules”, Energy and Buildings, (47) 159-168.

Cement and Concrete Association of Australia (CCAA) (2003), “Guide to Long-Span Concrete Floors”, Tech Media Publishing Pty Ltd, Sydney.

Crawford, RH (2011), “Life Cycle Assessment in the Built Environment”, Taylor and Francis, London.

Flower, D.J.M & Sanjayan, J.G. (2007), “Green House Gas Emissions due to Concrete Manufacture”, Int. J. of LCA, **12** (5) 282-288.

Lawson, B (2000), “Embodied energy of building materials”*,* BEDP Environment Design Guide, Melbourne.

Miller, D., Doh, J.H., Guan, H. (2011), “Environmentally Efficient and Sustainable Design Methodology of Concrete Residential and Office Buildings”, Adv. in Str. Eng. and Mech. (ASEM 11+), Seoul, Korea, September 18-23.

Miller, D., Doh, J.H., Guan, H., Fragomeni, S., McCarthy, T., and Peters, T. (2012), “Environmental Impact Assessment of Post Tensioned and Conventional Reinforced Concrete Slab Construction”, 22nd Australasian Conference on the Mechanics of Structural Materials (ACMSM), Sydney, Australia, December 11- 14.

Miller, D., Doh, J.H., and Peters, T. (2013), “Environmental Impact Assessment of Post tensioned and conventional reinforced concrete slab design”, International Structural Engineering and Construction Society (ISEC-7), Honolulu, Hawaii, June 18-23.

Norgate, T.E. & Rankin, W.J., (2002), “The role of metals in sustainable development”, The Int. Conf. on the Sustainable Processing of Minerals, May 2002.

Treloar, G., Fay, R., Ilozor, B & Love, P (2001), “Building materials selection: greenhouse strategies for built facilities”, Env. Mgt. and Health,**19**(3), 139-149.

Schokker, A. J., (2010) “The Sustainable Concrete Guide: Strategies and Examples”, United States Green Concrete Council (USGCC), Michigan.

Walker-Morison, A., Grant, T. & McAlister, S (2007), “The environmental impact of building materials”, BEDP Environment Design Guide, Melbourne.

World Green Building Council (WGBC) (2009), “How green building is shaping the global shift to a low carbon economy”, World Green Building Council, Ontario.