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ENVIRONMENTAL IMPACT ASSESSMENT OF POST TENSIONED AND CONVENTIONAL REINFORCED CONCRETE SLAB DESIGN

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This research determines environmental advantages achievable through application of alternate concrete slab construction methods for a typical concrete office building. The collaborative pilot study has been conducted to compare the significant material reductions on alternate slab systems to improve sustainable design methods. These structures were designed in accordance with all relevant Australian standards, incorporating various concrete strengths and various geometric parameters such as the number of columns, spans and the associated effect on slab thickness influencing environmental performance. The results indicated that environmental advantages are achievable through the application of alternate concrete slab construction methods for the typical office structure. Analysis results indicated a 21.5 to 34.4 % reduction in concrete volume and 23% to 44% reduction in steel mass for the post tensioned structure compare with the conventional reinforced structure.

Keywords: Sustainability, Embodied Energy, Global Warming Potential, Post tensioned Slab, High Strength Concrete, Reinforced Concrete.

1 Introduction

Sustainability is derived from the Latin term, sustinere, which translates literally as: “to up hold”. This term has seen increasingly extensive global popularity and the development industry is no exception. Sustainable Development (SD) has been comprehensively discussed for over thirty years. SD, from a structural perspective needs to take appropriate consideration of these dimensions. The construction industry has been referred to as the lifeblood of the economy across the developed world and as such, satisfaction of the economic consideration of SD is unquestioned (Miller *et al.* 2011). In Australia, the construction industry is valued at $151.3 billion, contributes 7.0% of GDP and employs 9.1% of our workforce making it our fourth largest industry (ABS 2010a). The social benefits of concrete buildings are also extensive, providing: good quality indoor living environments; structural integrity; low vibration; a high degree of weather protection; high fire resistance; good thermal resistance and sound acoustic performance (CCAA 2010). It is more difficult however to present a strong case for such buildings in satisfying the environmental consideration of SD. The construction, operation and maintenance of buildings are estimated to account globally for between 30-50% of all energy usage and 30-50% of all anthropogenic Greenhouse Gas (GHG) emissions (Yeo & Gabbai 2011). In Australia, this accounts for 40% of GHG emissions (Hood, 2004). Studies have identified the cement industry alone contributes more than 5% of global anthropogenic CO_2 emissions (Flower & Sanjayan 2007). These emissions will increase with growing demand through population pressures unless alternatives can be identified, that deliver sustainable structures. Australia’s population is predicted to increase to approximately 35.5 million by 2056 (ABS 2010b) and global population growth is expected to continue through the first half of this century (IPCC 2007). In order to keep pace with the associated increasing demand, 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). Globally, 23 trillion kilograms of concrete are consumed annually, and this number is increasing due to demand (Schokker 2010).

The aim of this paper is to utilise sustainable design methodologies to compare corresponding environmental impacts of equivalent office mid-rise structures in the South East Queensland region in Australia, when post tensioning and conventional reinforcing construction methods are implemented. The results of this study will facilitate improvement of the environmental efficiency of office buildings, helping instigate the need for national design codes and rating systems, targeting embodied energy. Using an appropriate quantification technique and a relative measure (embodied energy) a comparison between different designs can be made which enables the selection of the optimum design solution for a slab system in a typical office structure.

2 Methodology

A multi-stage research methodology was formulated. This methodology categorised into two major components, Structural Design and Environmental Analysis. The Structural Design consisted of several distinct components: 1) Design Definition stage involved formulating the design of the specific building to be analysed and identified with any assumptions that were necessary to undertake the analysis; 2) Manual Calculations were then undertaken to provide a detailed design of the structural element (slab), that was used for inputs into the two dimensional computer analysis program, RAPT; 3) The structural 2D designs were finalised using the results obtained from the computer analysis that were verified with the manual hand calculations to ensure accuracy, economics and suitability of the design; 4) The reinforcement requirements for each structural element were subsequently detailed in accordance with Australian Standards (AS3600-09) and guidelines that allowed a detailed bill of quantities to be formulated.

2.1 *Design Post Tensioned and Reinforced concrete slab*

The typical office structure investigated comprised of a 10 story building. This was designed and analysed using both post tensioned and conventional reinforced concrete slabs with the concrete strengths of 32, 40, 50 and 65 MPa. The slab span was varied to evaluate four column centre spacings of 6.67, 8, 10 and 13.33 metres. This layout resulted in the analysis of the building containing 3-6 clear spans for the total exterior building footprint of 40.5×40.5 metres. Typical flat plate slab construction system was used, which was supported on a square grid of 500×500 mm^2 columns with 3.5 m floor to floor heights. To meet all relevant standards including structural adequacy, durability, fire resistance and acoustic performance, a minimum slab depth of 200mm was required along with a minimum clear cover of 29mm to provide a minimum axis depth of 35mm when N12 bars are utilised. For the post tensioned slabs, the code specifies an additional 10mm concrete cover to tendons than that required for typical reinforcement. This requirement was accounted for by allowing 30mm clear cover to the duct. The additional cover is available within the void, therefore this design meets all relevant requirements.

2.2 *Design for Serviceability*

Determination of the required slab thickness is an iterative process which continues through the analysis and is affected by many 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 $\frac{\Delta}{\square_{\square\square}} \leq \frac{1}{250}$ 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 $\frac{\Delta}{\square_{\square\square}} \leq \frac{1}{500}$ 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 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 post tensioned 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 (2003), were used. It is suggested by the CCAA that the most economical span-depth ratio, L/D, for a post tensioned flat plate is between 37 and 40.

2.3 *Embodied Energy*

Using the bill of quantities, an Environmental Impact Assessment (EIA) was undertaken using data obtained from the extensive literature review (Miller *et al.* 2012, Treloar *et al.* 2001, Lawson 2000, Norgate & Rankin 2002, Aye *et al. 2011*, Crawford 2011), to calculate an indicative value for the environmental impact of each structure in terms of embodied energy. The values published by Crawford (2011) were used in this study as shown in Table 1. While it is noted that high strength steel tendon fibres undergo different manufacturing procedures, there is significant limitations in identifying suitably accurate values. There was no value specified for embodied energy of steel tendons in the study undertaken by Crawford (2011).

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

Construction Material	Embodied Energy
Concrete 32MPa	4880.4 MJ/m^3
40MPa	5670 MJ/m^3
50MPa	7182 MJ/m^3
65MPa	10348.8 MJ/m^3
Steel bar	85.46 GJ/tonne
Galvanised Steel	38 GJ/tonne

3 Results and Discussion

Material requirements as determined from the bill of quantities were applied factors to quantify the environmental impacts of materials in each floor and roof slab. Slab results were combined together with concrete columns to form results for whole building material requirements. These slab thicknesses, as determined from limit state and serviceability design for alternate slab construction techniques are presented below in Figures 1 and 2. Results indicate a significant reduction in both roof and floor slab thicknesses achieved through the implementation of post-tensioned construction methods.

It was found that the percentage reductions in the floor slab thickness, through the use of post tensioning, ranging from approximately 25% to 37.4% and 22 to 32 % for concrete strengths of 32 MPa and 65 MPa, respectively. Also it was observed that the significant reduction of slab thickness occurs for the increasing in column to column spans. Similar results have been observed for the reduction on the roof slab. The percentage reduction resulting through the use of post tensioned roof slabs range from 14 to 37% for the 32 MPa concrete, and 0 to 36% for 65MPa. Figures 1 and 2 illustrated that the use of post tensioning in large spans is more efficient in terms of material reductions.

Figure 3 indicates that the use of post tensioning is able to significantly reduce the concrete volume required for a structure, resulting in significant reductions in the overall weight of the structure. It was found that both span length and concrete strength influence the achievable reductions in concrete usage when post tensioning is utilised. It was found that the reductions in concrete volume through the use of post tensioning increases with increasing span length, ranging from approximately 21.5% for a 6.67m increasing up to 34.4% for a 13.33m span, indicating that the use of post tensioning in large spans is more economical in the sense of material reduction. It is also evident that as the concrete strength increases, the reduction in concrete volume decreases. This highlights that the use of post tensioning in high strength concretes is less economical than lower strength concretes as the use of this construction method becomes less effective in minimising concrete usage.

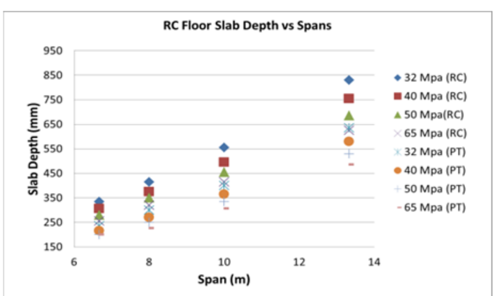

Figure 1 RC & PC floor slab depth vs span

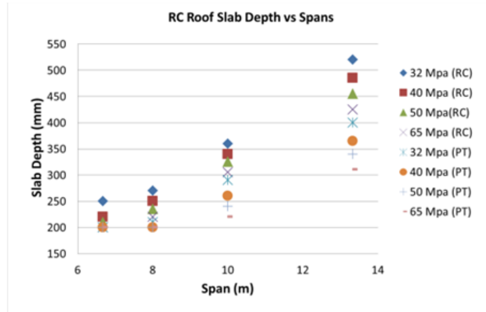

Figure 2 RC & PC roof slab depth vs span

Figure 4 indicates that the use of post tensioning is able to significantly reduce the steel mass required for the structure. It is evident that the concrete strength, in the exception of the 8m span, has little to no impact on the reduction in steel mass that is achievable when post tensioning is used. It is also observed that the span length plays a large role in this, being able to reduce the steel mass by between 23% and 44%. In the exception of the 6.67m span, the reduction in steel mass increases with span length, which was also observed with concrete volume. This indicates that the usage of post tensioning in structures with large spans is very economical in minimising the material requirements for that particular structure. In the case of the 6.67m span, it is apparent that a very large reduction in steel mass is obtainable due to design reasons which have been discussed in a previous study (Miller *et al.*, 2012).

These highlight the improvements possible by the incorporation of one, of a number of the anticipated improved efficient design methods. The results have also highlighted the importance of the contribution of steel to a structures environmental performance. For this structure investigated, steel accounts for between 1.5% and 3.1% of the structure's weight but accounted for 30% to 50% of its embodied energy.

The results indicated that environmental advantages are achievable through the application of alternate concrete slab construction methods for this 10-storey office structure. Analysis results indicate reductions of embodied energy from 28.4 to 40.5% as shown in Figure 5. Comparison of the unit environmental impacts for steel and concrete by mass, indicate the embodied energy of steel is at least 25 times that of concrete.

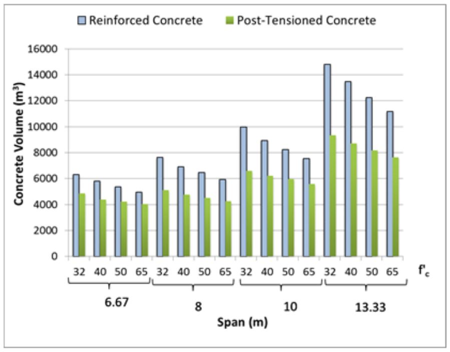

Figure 3 Total concrete volume of building.

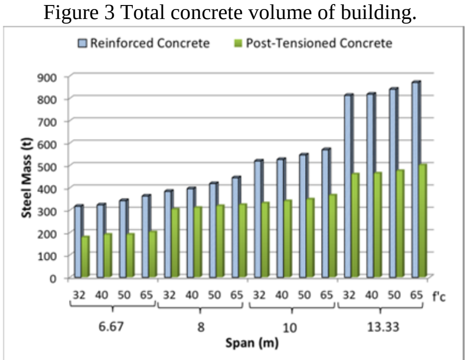

Figure 4 Total steel mass of building.

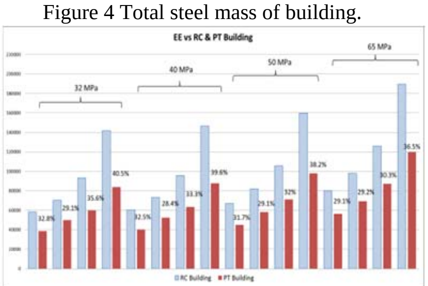

Figure 5 Embodied energy contributed by construction usage

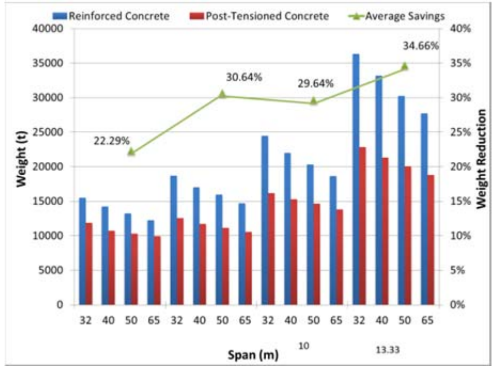

Figure 6 Reduction in the weight of building

Environmental impacts in both structures can be seen to result mainly from the concrete, which contributes approximately 51% to 63% of the embodied energy. This variation occurs as a result of the greater contribution from concrete in the overall structure mass (over 97%). Results indicate environmental efficiencies are achieved through both the material reductions of steel and concrete in the post tensioned structure. Overall, a 28.8% to 40.9% reduction in the Embodied Energy was observed as well as a 23% to 37% reduction in construction materials through the utilisation of post tensioned construction methods.

Not only is the use of post tensioning able to reduce the embodied energy of a structure, it is also able to dramatically reduce the weight of the structural frame (Figure 6). It is important to consider the reduction in embodied energy and weight concurrently. It is evident that while the 6.67m span experiences larger reductions in embodied energy than 8m spans through post tensioning, the reduction in weight in the 6.67m span is considerably less than other spans, approximately 22.29% compared to the 8m span of 30.64%. A reduction in weight of the structural frame results in significant reductions in material requirements of other structural components including foundations, walls, and columns that contribute significantly to the structure's overall embodied energy. Therefore, the overall reduction in embodied energy of the entire structure through the use of post tensioning and its overall effectiveness may be equal to or higher than that experienced in the 6.67m span. However, this cannot be quantified at present as this is outside the scope of this research and would require the design of these other structural elements.

4 Conclusion

This study suggests that not only is the post tensioned office building more efficient in its material use, but also in terms of the main EIA criteria of embodied energy. Findings indicate that the effectiveness of post tensioning is the greatest for spans exceeding 10 metres, with the highest reduction in environmental impacts achieved being over 40%.

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