Carbon Footprint Assessment in the Life-Cycle Design of Concrete Structures in the Tropics: A Case Study of Residential Buildings in Malaysia

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With the exponential growth in development of cities and increasing demand for construction, which is one of the factors in environmental degradation, the need for CO2 emissions control is essential. In order to balance carbon emissions along the life-cycle of concrete structures; in this paper, we have analysed the carbon emissions and assessed the carbon footprint of selected concrete structures in a tropical city. For this purpose, the carbon footprint has been evaluated using Life-Cycle Sustainability Assessment (LCSA) approach at different stages concrete structures' life-cycle, which are production, construction, operation, and demolition stages, where the CO2 footprint of two residential buildings in Malaysia have been analysed as case studies. The findings indicated that the energy consumption, and the production phase in the life-cycle of a concrete structure are the main contributors of CO2 emission. In addition, detailed analysis of the carbon cycle in structures and their interaction with other components involved in the regional eco-system can lead to a significant reduction in CO2 emission, and thus to the improvement in reducing environmental deterioration and its consequences. Moreover, optimised design and customisation to the constituents of concrete, as well as improving citizens' consumption agenda can significantly reduce the carbon emission of concrete structures.

Keywords: *Carbon emission, CO^2 emission, Concrete structures, Life-cycle design, Life-Cycle Sustainability Assessment (LCSA).*

1. INTRODUCTION

The emission of greenhouse gases is one of the major problems facing civilisation in the modern world. To address this issue, it is essential to incorporate all the industrial sectors, which are responsible for the global CO2 emissions in the analysis process of carbon footprint contribution. This is certainly relevant to the cement manufacturing industry, which produces approximately 7% of the carbon dioxide emitted into the surrounding environment (Pradipto & Afif, 2019; Fantili et al., 2019).

Concrete structures contribute significant environmental impacts, which is rooted in its investment in terms of raw materials and energy (Sharif et al., 2017). In recent years, the need for sustainability in concrete structures and reducing its impact on the environment has been the attention centre and these issues are envisaged to intensify in the coming years. There are incontrovertible issues related to concrete construction, which results in it being viewed as a menace to the environment (Caruso et al., 2017). Energy consumption and carbon emission are the two most important environmental issues related to concrete structures (Latawiec et al., 2018).

As low carbon footprint and sustainable design solutions have root in design and material choices, there is an incumbency to study the contribution of concrete to the embodied energy and carbon footprint of a building during its production and construction phases of its life-cycle (Sulaiman et al., 2018). Substantial amount of research has been undertaken on the utilisation of concrete and its different ingredients, and cement replacements materials in concrete production (Rohden & Garcez, 2018). While many of these studies have

focussed on the environmental impact of residential concrete buildings, the studies focussing on concrete structures in tropical cities have been limited. Hence, it is necessary to assess carbon footprint, as well as the sustainability aspect over the life-cycle of concrete buildings comprehensively, through a detailed framework (Kajaste & Hurme, 2016).

In undertaking this study, the Life-Cycle Sustainability Assessment (LCSA) framework for assessing concrete residential building's footprint over their life span have been adopted, and CO2 emission resources in concrete structures have been analysed, and subsequently to develop an improved sustainability framework for concrete structures. Notwithstanding differing views on the exact life-cycle of a concrete structures, a 50 years' life-cycle for residential buildings have been considered in this study. Based on this definition, the life-cycle length of time can be construed as starting from the material production cycle until their end of life (Besten et al., 2018).

Basically, there are four main phases in a building's life-cycle; i.e. materials production, building construction, building operation and maintenance, and end of life phase (Chau et al., 2015). In order to determine the CO2 emission and environmental impact of a building, there is a need to study these components throughout all its life-cycle phases.

2. METHODOLOGY

In this study, the methodology for LCSA of concrete structures have been considered based on the principles defined in ISO 14040 (2006), ISO 14044 (2006) and corresponding sets of international standards. This framework examines the socio-economic and environmental impacts of a product to assess its sustainability and environmental impacts through its life-cycle. Basically, the LCSA framework is used to estimate the environmental impacts through a product's life-cycle and the changes on the ecosystems (Venkatarama Reddy, 2009). A number of researchers in the field of sustainability have adopted the LCSA methodology function in the CO2 emission assessment of a product life-cycle and its environmental impacts (Woon et al., 2019; Dakwale et al., 2011). The carbon emission of concrete building's life-cycle can be monitored using the Life-Cycle Carbon Emission Assessment (LCCEA) model, which has been developed in the LCSA method (Jahandideh et al., 2017).

2.1 *Method of Analysis of LCSA in the Construction Industry*

The approach of LCSA describes the key instrument used to measure adverse effects on different climate conditions and ecosystem modifications correlated with the life-cycle of the structure (Miller et al., 2018). LCSA study is typically described in the form of accumulation of environmental loads, impacts of economic aspects or impacts per unit of construction practices, and the social life-cycle assessment, without considering the possibility of their allocation in time and space (Sharma et al., 2012). Recently, related international practitioners and researchers have also acknowledged the successful role of the LCSA approach in the quantitative evaluation of CO2 pollution and its environmental and economic consequences (Kofoworola & Gheewala, 2008).

2.2 *Life-Cycle of Concrete Residential Building: Definition*

In this paper, a 50-year life span for concrete residential buildings have been adopted, in keeping with the predominant design criteria in Malaysia, irrespective of what a residential building's exact life-cycle is. Through a building life-cycle approach, the research phase ranges from the production of the raw materials used by structures to their final destruction where all sorts of waste are processed or reused (Ramesh et al., 2012). There are usually four sequential stages, such as the production phase, construction and reformation phase, service life phase, and building End-of-Life (EOL) (Giesekam et al., 2015). All of those stages must be applied to evaluate the CO2 and environmental pollution and the environmental effect of residential buildings on their life-cycle.

2.3 *Main Source of CO2 Emission in Concrete Structures*

According to the Intergovernmental Panel on Climate Change (IPCC) report (2018), emission of CO2 in residential buildings arise from three main sources; industrial and chemical activity, transportation, and energy consumption. Thus, it can be deduced that the occupation of land and making changes in preparation of construction, as well as the process of material production and transportation to the project site, and ultimately the energy consumption during the construction and operation phase are all contributing factors to CO2 emission of concrete structures (Hafizzudin et al., 2019).

Due to lack of data in the present case study, the land footprint CO2 emission were not considered in the analysis. Based on the information provided, the total life-cycle CO2 emissions of residential structures can be calculated through the Equations (1) to (3), as follows:

$$TE = \sum_{p=1}^{4} (IC_p + EC_P + T) \quad (1)$$

where, *TE* is the total emission during the building's life-cycle, *p* is the different phases of a building life-cycle, from Phase 1 to Phase 4, *IC* and *EC* are industrial and chemical, and energy consumption respectively. *T* also is a symbol of transportation.

$$IC_p = \sum_{m=1}^{2} (M_{pm} \times CF_m) \quad (2)$$

Eq. (2) above represents the calculation of the exact amount of industrial and chemical activities (*IC*). Here, *m* is the types of materials used in the structure that contribute to CO2 emission, where in this study, we have only considered cement and steel reinforcement. *M* is the intended material and *CF* is the conversion factor, where it is 0.396*t*/*t* for cement and 0.319*t*/*t* for steel (You et al., 2011).

$$EC_p = \sum_{k=1}^{n} (M_{pk} \times CF_k) \quad (3)$$

Energy consumption is computed using Eq. (3) above, where *k* is type of energy used in different phases of the building's life-cycle. *M* introduces the intended energy, which in this case is electricity, and as mentioned, *CF* is the conversation factor for *k*.

2.4 *Building Materials Production Phase*

As mentioned previously, the industrial and chemical process of the production phase, as well as the energy consumption in the production phase are the main sources of the CO2 emission in the production phase, i.e. since the inputs of materials and energy take place intensively in this phase (Fiala et al., 2013). The industrial and chemical process related to cement production emission, which is rooting in the limestone disintegration, and the energy consumption is referred to as emission from electricity and initial energy consumption during the life-cycle of the building (Nor et al., 2019).

2.5 *Building Construction Phase*

During the construction phase, a large amount of different building materials and resources are expanded to have a building constructed or retrofitted (Pui & Othman, 2019). Energy consumption to lighting, and using the construction machineries, as well as transportation of materials to the construction site, and landfilling the waste materials after or during the construction, are the main causes of CO2 emissions in this phase (Doan et al., 2017).

2.6 *Building Operation Phase*

Generally, residential buildings consume a considerable amount of energy during their life-cycle. In this phase, the electricity and water consumption by residents are the main sources of energy consumption and air conditioning is the main factor of electricity consumption and CO2 emission (Hakkinen et al., 2015).

2.7 *Building End-of-Life Phase*

By the end of shelf life of the building, which in this study is 50 years, we can call the building "out of use". This is the time to demolish the building mechanically or manually [4]. In this stage, the generated waste materials are divided for either recycling and reuse, or to be transferred to landfill. In this phase, energy consumption during landfilling is considered as the main source for CO2 emissions (Atmaca & Atmaca, 2015).

3. CASE STUDIES

The data analysis of this study was undertaken according to data on details of quantitative characteristics and utility bills of two concrete residential buildings, where the first is a 5-story reinforced concrete structure (Fig. 1) that can be considered as a medium rise structure, while the second is a masonry-concrete semi-detached house (Fig. 2), as a smaller sample. The main construction materials in both cases were cement, steel, gravel, sand and water.

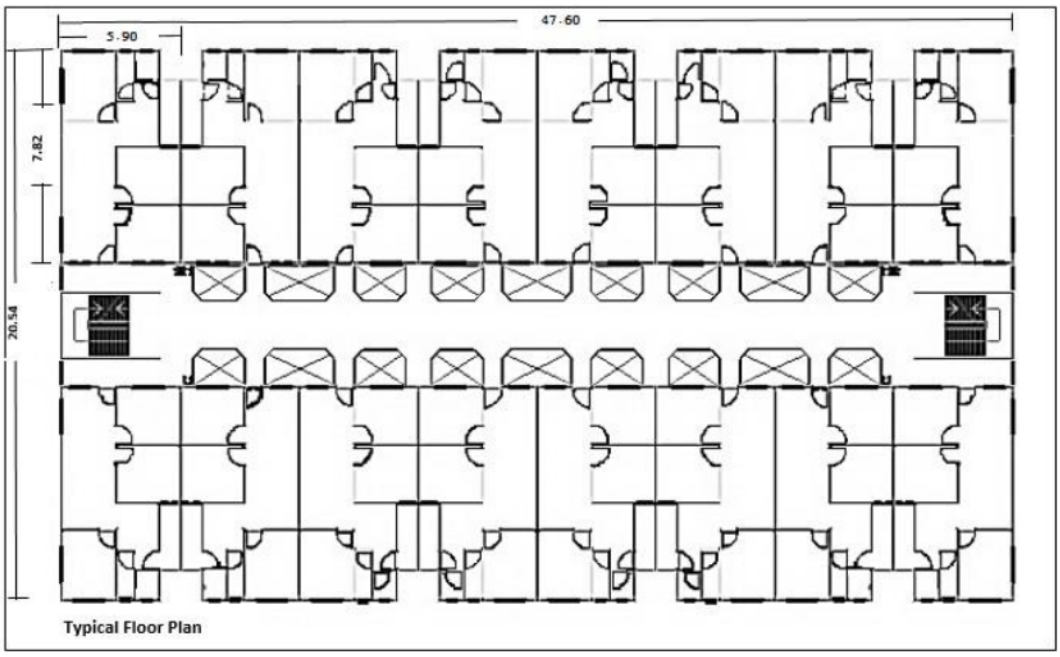

Fig. 1: Layout of reinforced concrete apartment building.

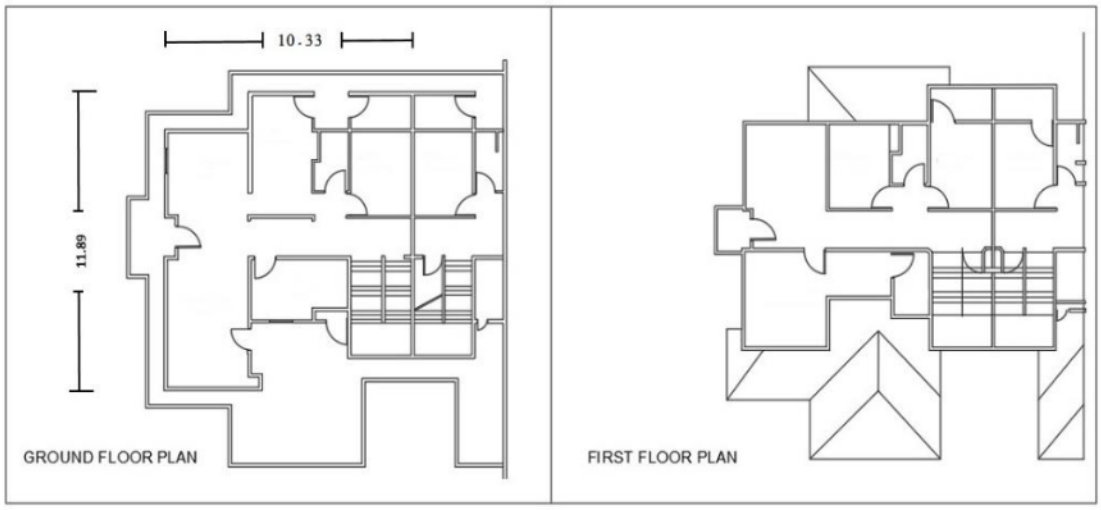

Fig. 2: Layout of masonry-concrete semi-detached house.

4. RESULTS AND DISCUSSION

The findings of the study indicated that concrete residential buildings' life-cycle CO2 emission of the medium rise reinforced concrete structure is 298.91 tons per 100 m^2, while for the masonry-concrete building was 318.67 tons per 100 m^2. During the life-cycle of a concrete residential building in Malaysia, it is evident that the building's operation phase contributed to almost 85% of CO2 emission, which is the highest impact on environment and ecosystem during the building's life-cycle. Second to that is the production phase, which contributed 8–10% of the CO2 emission. Construction and end of life of the life-cycle of a concrete structure contributed the least influence in climate change and environmental issues (Fig. 3).

Based on the findings from this study, as well as those reported in literature, it is evident that the best approach to reduce the carbon footprint in residential buildings is to reduce the energy consumption during the building operation phase.

Analysis results of the sources of CO2 emission in the present case studies indicated that, almost 80% of CO2 emission was rooted in the energy consumption, while the industrial and chemical

process with 15% was in second place, where it is contributed by cement and steel production. As shown in Fig. 4, other sectors have negligible contribution in CO2 emission and environmental issues.

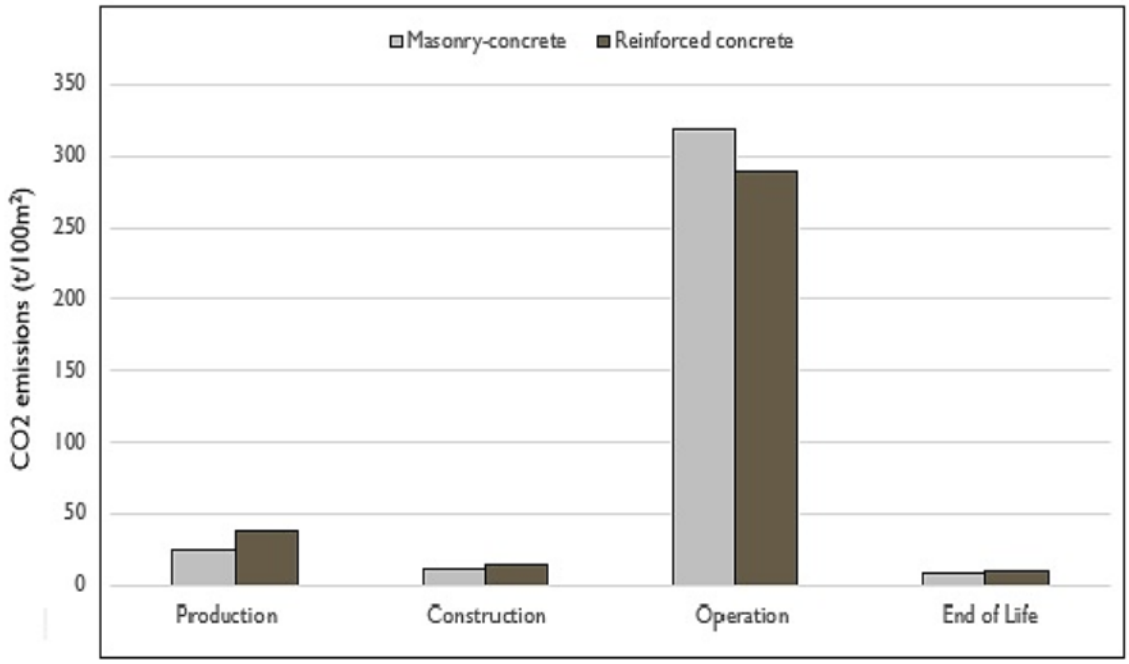

Fig 3: CO2 emission of different life-cycle stages of residential buildings

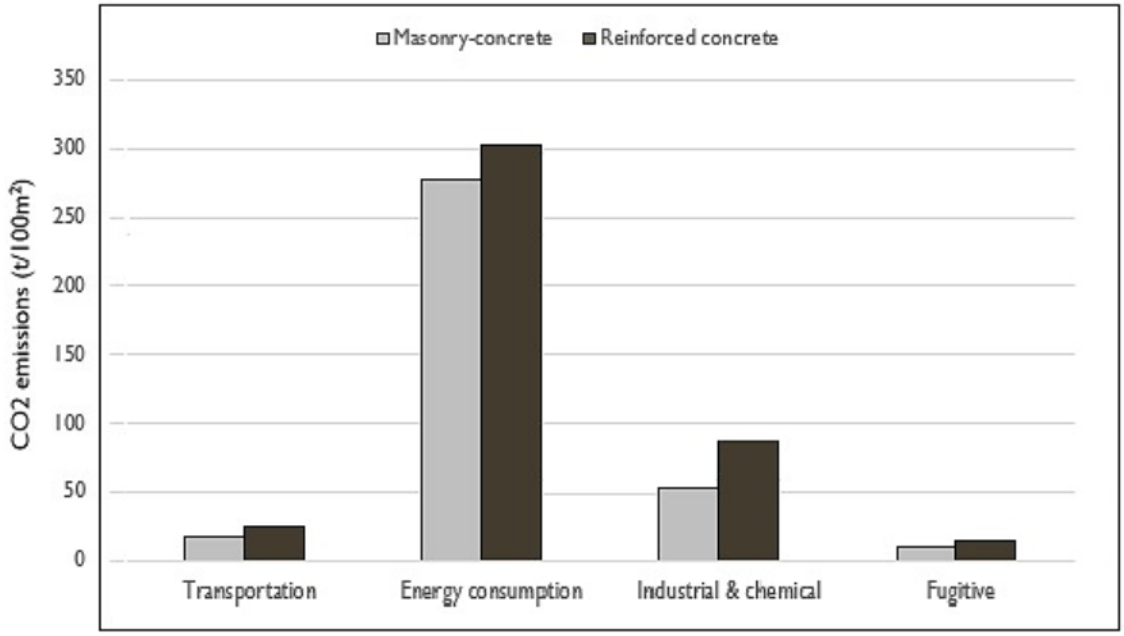

Fig 4: Source of CO2 emission in residential buildings

The results reported in Fig. 5 indicate that while CO2 emission of reinforced concrete residential building is almost four times higher than a masonry-concrete structure, but cement with 85% is the main source of CO2 emission. Therefore, it is essential to cut down on the usage of cement in the production of concrete and replace it with other supplementary cementitious materials.

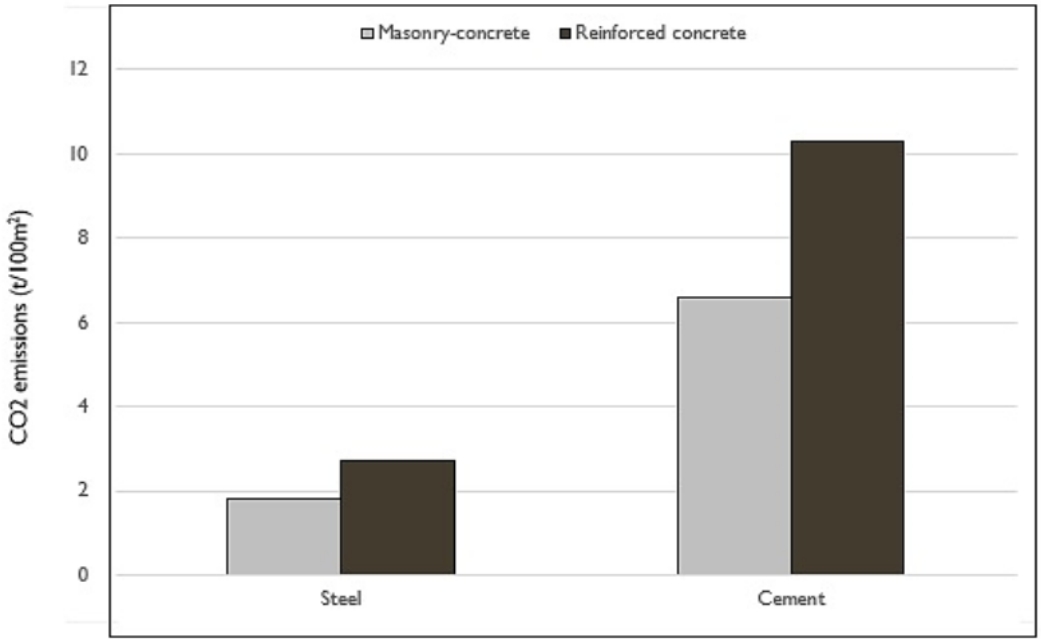

Fig 5: CO2 emission of different material

5. CONCLUSION

In general, concrete structures contribute substantial environmental impact and is one of the biggest sources of CO2 emission in cities. To analyse CO2 emissions of concrete structures based on the LCSA framework, we have used the LCCEA model in different phases of two concrete residential buildings' life-cycle in Malaysia. The findings have shown that the main source of CO2 emission of residential buildings is related to energy consumption during the operation phase, and in some cases, the land footprint. It can be concluded that optimised design and the use of natural ventilation in residential structures, as well as the use of renewable energy for electricity generation can contribute significantly in reducing CO2 emission and environmental impacts. Further, it is also essential to reduce on the usage of cement in the production of concrete in order to contribute positively towards reduction of CO2 emission and environmental impact.

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