

Article

Assessment of CO₂ Emissions by Replacing an Ordinary Reinforced Concrete Slab with the Void Slab System in a High-Rise Commercial Residential Complex Building in South Korea

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Abstract: The purpose of this study is to verify the environmental performance of the novel Void Deck Slab (VDS) system developed by the authors. The proposed VDS is a void slab system with enhanced design features that improve the constructability of the system through the elimination of additional works required to connect the void formers with the anchoring devices. The Life Cycle Assessment (LCA) technique was adopted to assess the carbon dioxide emissions of the void slab system with reference to the ordinary reinforced concrete slab. The system boundary of this study ranged from raw materials to pre-operation phase, in accordance with ISO 14044. The total CO₂ emissions of the ordinary reinforced concrete slab and the void slab system were 204,433.06 and 151,754.75 kg CO₂-eq, respectively, which equated to about 34% less emissions for the void slab system. In the case of the ordinary reinforced concrete slab, moulds accounted for approximately 62% of CO₂ emission, followed by concrete (~34%). The main source of CO₂ emissions for the void slab system was concrete that accounted for ~50%, followed by moulds and deck plates that accounted for roughly 27% and 19%, respectively. In the case of the void slab system, void formers would enable a lower amount of concrete, as well as the self-weight of the slab. Besides, although the void formers filled a significant volume of the slab, the contribution to CO₂ emissions was less than 1%.

Keywords: reinforced concrete slab; void slab; high-rise building; life cycle assessment; carbon dioxide

1. Introduction

Multi-storeyed buildings are increasingly preferred in both residential and commercial cases for the purpose of the effective utilisation of land, considering that cities have become more urbanised in recent years. According to Seto et al. [1], the rate of growth of global urbanisation is twice that of population on average. High-rise buildings help to resolve a number of issues related to urbanisation, apart from maximising the economic efficiency of housing development projects; nevertheless, there are a few disadvantages with respect to evacuation in the event of an emergency, and accessibility to the upper floors in general. In addition, there are environmental issues such as high energy consumption mostly related to fossil fuels [2–4], as well as wind funnelling and turbulence around the base of the buildings.

As global warming is a worldwide topic [1,2,5–8], there are a number of concerns applicable to high-rise buildings. In particular, the architecture, engineering, and construction (AEC) industry

has been the main contributor to global warming and mass energy consumption, considering that it accounts for up to 38% of annual CO₂ equivalent emissions, ~40% of the annual consumption of natural resources, and ~39% of the annual energy consumption [3,9–11]. Likewise, the environmental impacts of the AEC industry in South Korea, being similar to those in other countries [4,12,13], have prompted the industry to devise strategies for eco-friendly and sustainable design and construction methods.

Reinforced concrete is an ideal structural material with exceptional compressive and tensile strengths, owing to the combination of concrete and rebars. It exhibits a high use value as it can be shaped into different forms to match the specific architectural requirements, while it resists fire, corrosion, and adverse weather conditions. Furthermore, it is relatively inexpensive compared to steel and other construction materials. However, a number of studies have established that concrete not only consumes a large amount of energy and natural resources, but also emits a considerable amount of CO₂ during its manufacturing and transportation. The approaches suggested to reduce the environmental burdens of concrete include: use of high-performance materials, recycled items, and by-products, and replacement with low-carbon materials. Park et al. [4] indicated that the strength of concrete, as well as its seasonal attributes, influence CO₂ emissions. They observed that concrete works emit more CO₂ in winter than other seasons, in South Korea. According to Tae et al. [13], high-strength concrete is an effective solution for minimising CO₂ emissions, as it helps to reduce the size and quantity of rebars, especially the cross-section of the vertical members. Similarly, Kim et al. [14] showed that CO₂ emission was reduced by using high-strength concrete in buildings, despite the same floor area.

Apart from the use of high-strength concrete, optimal design and material selection are also considered to be important factors for lowering CO₂ emissions. González and Navarro [6] indicated that appropriate material selection in the early design stage would decrease CO₂ emissions by ~28%. Similarly, Chau et al. [15] asserted that a designer could prove to have significant role in reducing CO₂ emissions by selecting low-carbon materials. While various strategies to reduce CO₂ emissions involve the replacement of materials, there is another approach that considers the entire system of buildings whereby a complete structural system is replaced with a low-energy consuming and less CO₂-emitting system. A number of studies have shown that steel structures involve relatively less CO₂ emissions than reinforced concrete structures [12,16–18]. Han and Kim [16] examined the total CO₂ emissions of different structural systems used in the construction of apartments in South Korea. They concluded that a steel structure is more beneficial in terms of CO₂ emissions, compared to a conventional reinforced concrete structure. Nadoushani and Akbarnezhad [17] identified three main considerations for the comprehensive assessment of the environmental impact of a building: embodied carbon for selected materials, operating carbon during the operation and maintenance phase, and choosing the best structural materials.

The void slab system (Figure 1) is a new development that enhances the structural performance of a slab through reduced weight and increased stiffness [19–21]. It is a method to improve the strength of a slab in supporting a load, through the effective utilisation of its moment of inertia. In addition, the method enables the reduction of the slab weight by using lightweight void formers in its middle section, where the structural performance is less important compared to other portions in the slab. It is also recognised that the void slab system would be able to reduce the environmental impacts of concrete through reduced CO₂ emissions and energy consumption. However, research on environmental impacts of the void slab system is relatively scant compared to other topics such as structural performance (flexural and shear), optimal void ratio, and shapes of void formers [22–26].

The previous studies employed additional steel materials or devices to anchor the void formers securely in the slabs [22–26]; however, as the method of installation of void formers was slightly complicated, the accuracy and speed of installation strongly depended on the skill of the construction workers. Furthermore, Cho and Na [27] indicated that the utilisation of steel materials for anchoring the void formers to the lower and upper parts of the main reinforcement would cause more environmental burdens (~28% more CO₂ emissions) compared to ordinary reinforced concrete slabs.

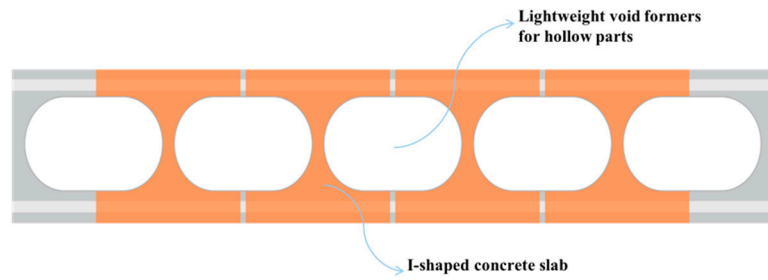


Figure 1. Conceptual diagram of the void slab system.

This research proposes a Void Deck Slab (VDS) system, a newly developed void slab system that eliminates additionally introduced steel materials for the prevention of buoyancy, and incorporates a newly developed device for anchoring the void formers to the reinforcement. As shown in Figure 2, the VDS is so devised as to avoid the use of steel materials for anchoring the void formers, thereby improving the precision of installation. Moreover, the VDS helps to simplify the construction procedures, so as to shorten the construction time and to secure economic efficiency. Figure 2 depicts the cross-sectional and schematic views of a VDS that is composed of T-shaped steel deck plates, lightweight void formers made of expanded polystyrene (EPS), and anchoring devices. It is evident from the cross-sectional view that the lightweight void formers are placed between the ribs of the T-shaped steel deck plates. The materials used for anchoring the void formers to the deck plates are also made of EPS, instead of steel. Moreover, the method of installation is so simple that the anchoring devices are just inserted into the slots, and fixed firmly by a 90° rotation, and even a novice worker can install and fix the void formers with a high degree of precision and improved workability (see Figure 2d).

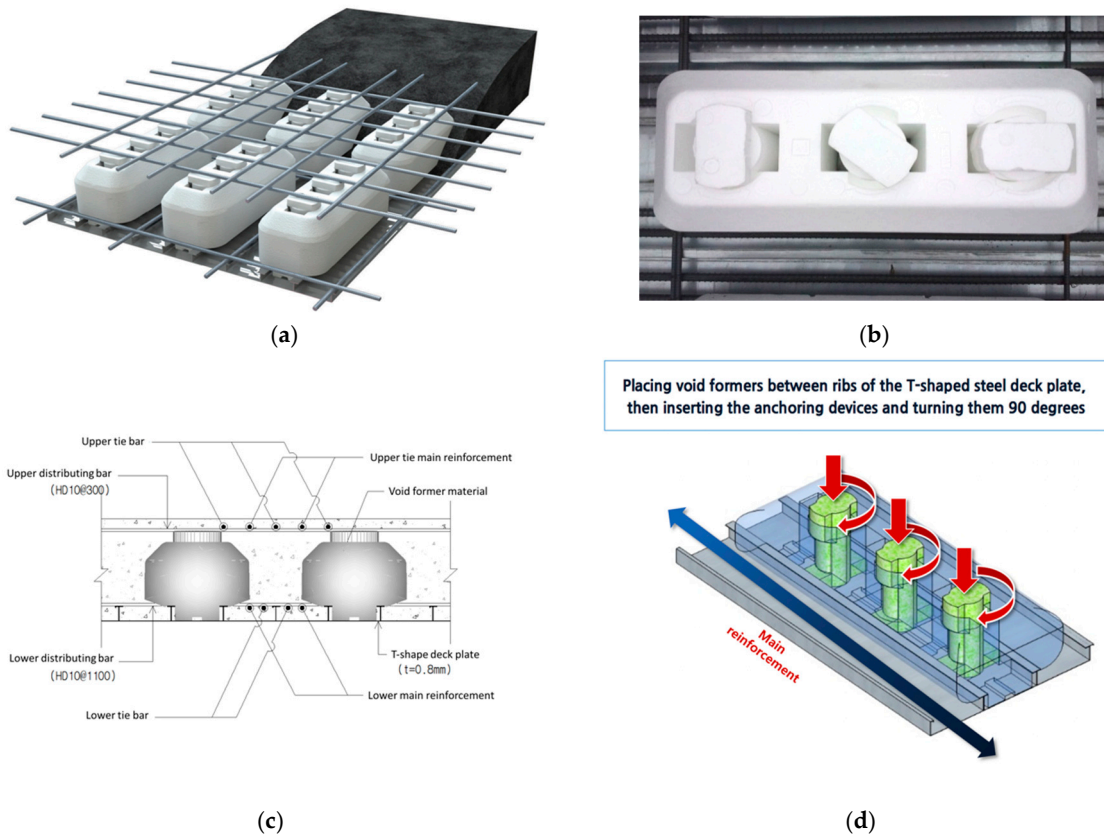


Figure 2. Illustrations of the void deck slab (VDS) (a) Schematic view of the VDS; (b) Void former and anchoring device; (c) Cross-sectional view of VDS; (d) Anchoring mechanism.

The additional steel materials or devices employed in the void slab systems discussed in the previous section are the main sources of carbon dioxide emissions [27]. In this regard, it is expected that VDS will produce less carbon dioxide, since both the anchoring materials and the void formers are made up of a common material other than steel. Based on this assumption, the purpose of this research is to investigate the environmental performance of VDS, which is considered to have lower environmental impacts compared to ordinary reinforced concrete slabs. In general, the life cycle assessment (LCA) technique is adopted to quantify and evaluate the environmental performance during the whole lifetime of a building, from raw materials to demolition [28–32]. In contrast, the LCA technique adopted in this research was focused on the evaluation of the environmental impacts of the ordinary reinforced concrete slabs and the void slab system on an exclusive basis.

2. Research Method

2.1. Lifecycle CO₂ Assessment

The purpose of this study was to compare the CO₂ emissions of two different slab systems, namely, the ordinary reinforced concrete slabs and the void slab system, in a high-rise commercial-cum-residential building located in Seoul, South Korea. For this purpose, the widely adopted LCA technique (as described in the previous section) was applied to our research for the assessment of the environmental impacts of the selected slabs. The LCA deals with the use of energy and CO₂ emissions occurring in all stages of the life cycle of a building. The life cycle, normally includes the following phases: (1) raw material; (2) transportation; (3) manufacturing; (4) construction; (5) operation and maintenance; and (6) demolition. Table 1 shows the descriptions of the phases to be considered in the evaluation of a building by LCA.

In the evaluation of CO₂ emissions, it is necessary to establish a system boundary for the life cycle assessment of the studied model. The system boundary envisaged in this study was from raw material to the pre-operation stage of the reinforced concrete slab and void slab systems (Figure 3) based on ISO 14044 [33] and ISO 21930 [34]. The production of both slab systems consisted of the stages: raw material, transportation, and manufacturing. Equation (1) was used for the calculation of the CO₂ emissions of each material of the two slab systems.

$$CO_2M = \Sigma(M(i) \times CO_2 \text{ emission factor } M) \quad (1)$$

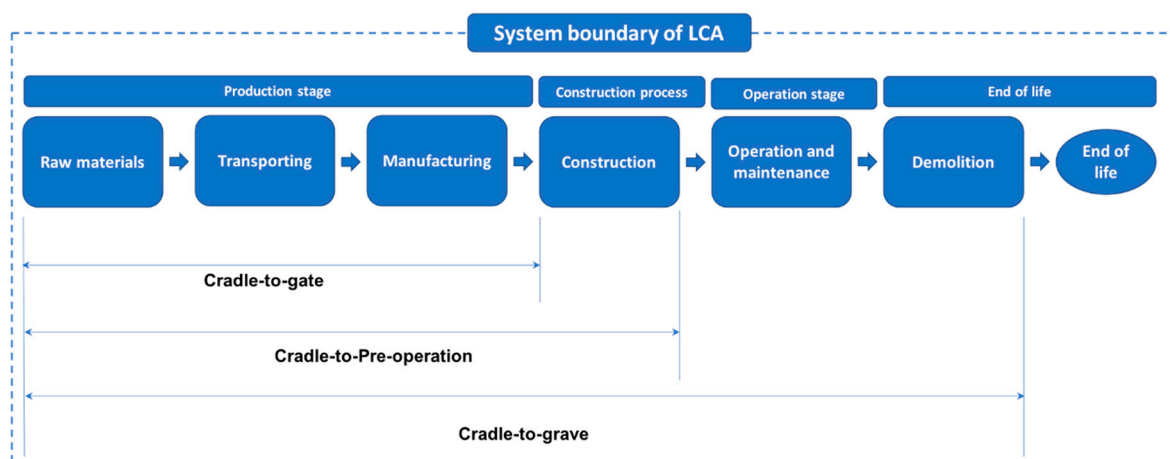


Figure 3. System boundary of life cycle assessment.

Table 1. Process and description of each phase in the LCA.

Phase	Process	Description
Raw material	Material processing and transportation	The manufacturing and handling of the raw materials; consuming resources and energy while manufacturing and handling the raw materials.
Transportation	Transporting individual materials	The process of transporting raw materials to the manufacturing plants; consuming energy while transporting the raw materials.
Manufacturing	Producing construction materials in a factory or by a supplier	The manufacturing of structure materials; consuming the raw materials and energy during the manufacturing of the structure materials.
Construction	Material transportation and construction works	The manufactured construction materials are transported from the manufacturing plants to the construction site; assembly of the structure materials to construct the building; operation of various types of construction equipment by construction workers; consuming resources and energy during the building construction.
Operation and maintenance	Utilising and maintaining the constructed building	The operation and maintenance of various types of equipment to ensure an indoor environment that is free of equipment downtime; consuming the resources and energy for maintenance and repair.
Demolition	Dismantling, transportation, and recycling of waste materials	Disassembly of the building; sorting the components for recycling or disposal; consuming resources and energy during the demolition.

The CO₂ emissions during the production stage indicate the occurrence of CO₂ from the major components used in the slab system. In this study, the major components of the ordinary reinforced concrete slab system were ready-mixed concrete, reinforcing bars, and moulds. Likewise, the major components of the void slab system were void formers, anchoring steel materials, and deck plates, as well as the ordinary reinforced concrete slab components. The environmental impact information of the construction materials applicable to this study was collected from the National Life Cycle Inventory Database (KLCI DB), as shown in Table 2 [35]. In the case of the construction materials not listed in KLCI DB, a foreign life cycle inventory database was applied [36].

Table 2. Life cycle inventory database of the major materials in this research.

Materials	Unit	Emission Factors (kg CO ₂ -eq/Unit)	Resource
Ready-mixed concrete (25-240-15)	m ³	4.20 × 10 ²	National LCI DB
Steel	kg	3.40 × 10 ¹	National LCI DB
Plywood	m ²	1.46 × 10 ²	National LCI DB
Expanded polystyrene (EPS)	kg	6.76 × 10 ⁻⁹	National LCI DB
Deck plates	m ²	5.83 × 10 ¹	National LCI DB
Diesel	kg	6.82 × 10 ⁻²	National LCI DB
Petrol	kg	8.32 × 10 ⁻²	National LCI DB
Electricity	kWh	4.95 × 10 ⁻⁵	National LCI DB

The CO₂ emissions of the transportation stage refer to CO₂ emissions during transportation of the materials to the manufacturing plants, which were calculated by using Equation (2). Here, M represents the materials used for each slab, L_T is the transported load (tons), and the CO₂ emission factor T is the CO₂ emitted due to the consumption of energy by the transportation method.

$$\text{CO}_2\text{T} = \Sigma[(\text{M}(i)/L_T) \times (d/e) \times \text{CO}_2 \text{ emission factor T}] \quad (2)$$

The CO₂ emissions from the construction stage were computed as the sum of petrol, diesel, and electricity consumed by the construction machinery and equipment, transportation equipment, and other facilities used at the construction site. In this study, the amount of energy consumed in

the construction stage was computed by applying the equation of the average energy consumption according to the total floor area:

$$DPA = 2.392 \times TFA \tag{3}$$

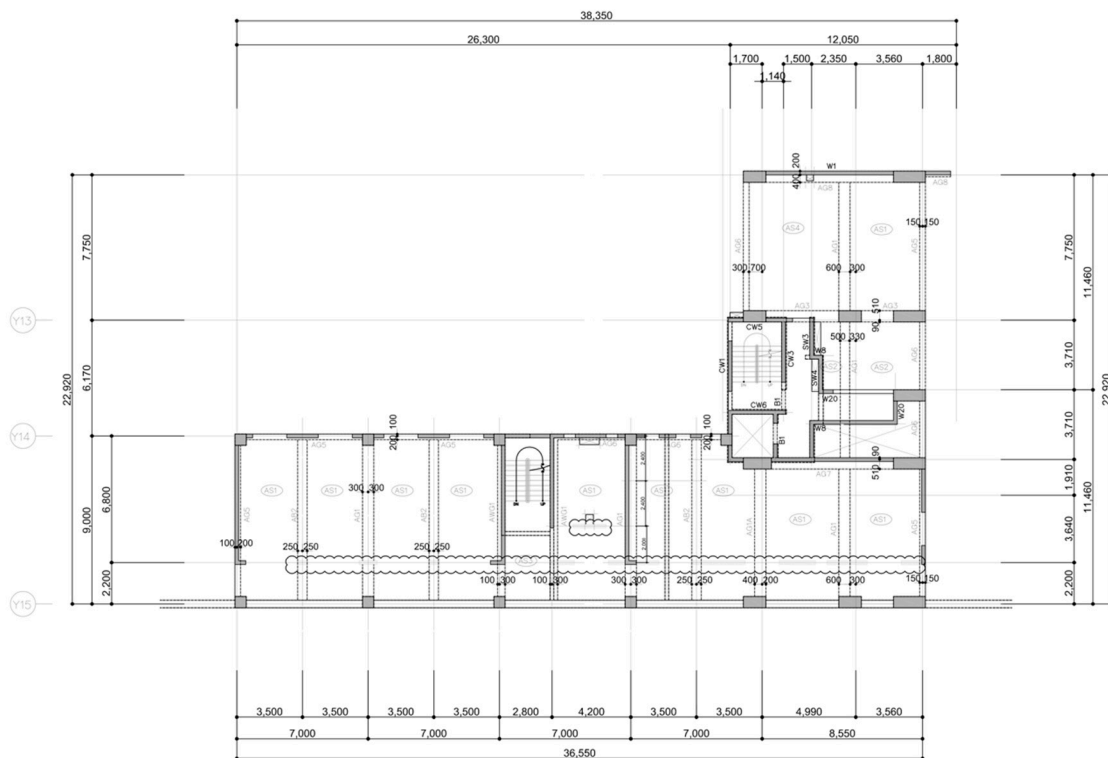
$$GPA = 0.048 \times TFA \tag{4}$$

$$EPA = 10.471 \times TFA \tag{5}$$

2.2. Overview of the Targeted Building

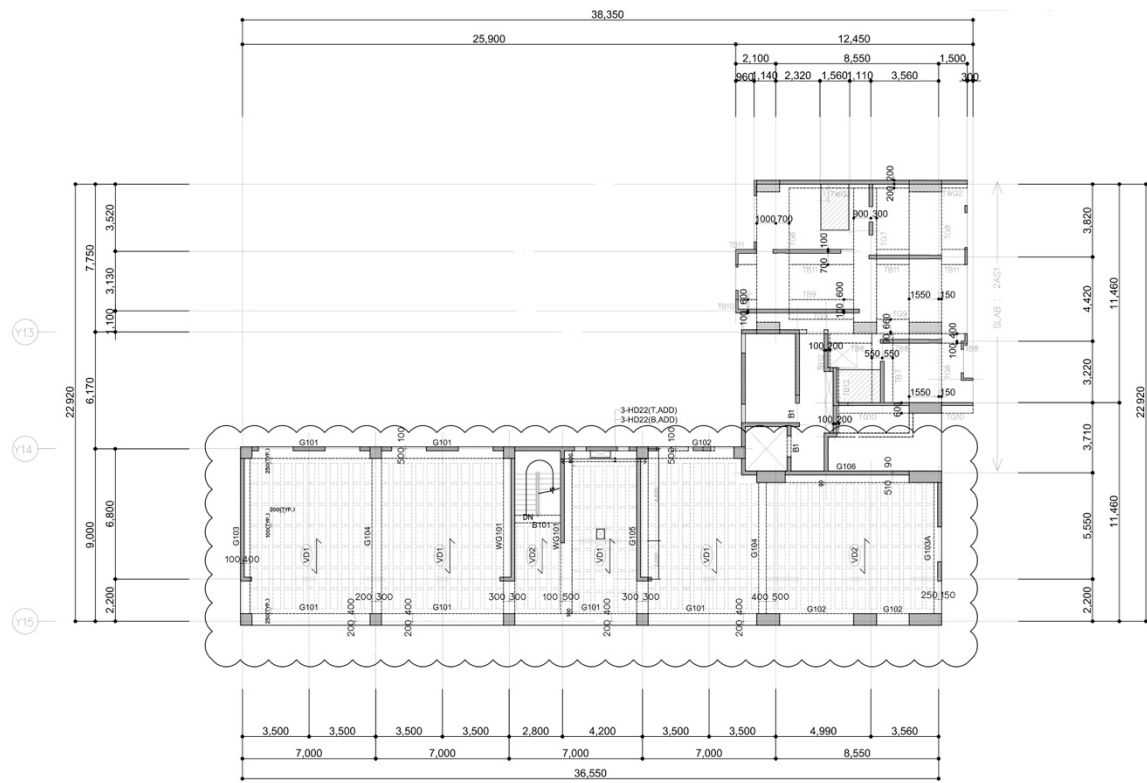
The studied building was a high-rise commercial-cum-residential complex building located in Seoul, South Korea. During the design development stage, value-for-money analysis was applied, in order to optimise the performance of the building for less cost and optimal materials. In this stage, the void slab system was suggested as an alternative system to reduce both the construction cost and the amount of construction materials. Moreover, applying the void slab system would enable the bearing walls to resist loads of the structure to be removed (see Figure 4). By replacing the ordinary reinforced concrete slab system with the void slab system, the span between the columns was extended to 9 m in length. Using the “value for money” analysis and structural design processes, the void slab system was accepted as a replacement for the ordinary reinforced concrete, because both structural requirements and economic aspects were satisfied.

The structural system was designed in accordance with the Korean Building Code [37], while the ACI 318-05 Building Code Requirement for Structural Concrete and Commentary [38] and ASCE/SEI 7-05 Minimum Design Loads for Buildings and Other Structures [39] were also referenced. The materials applied to both slabs were ready-mixed concrete with 25 MPa compressive strength and reinforcing bars with 400 MPa tensile strength.

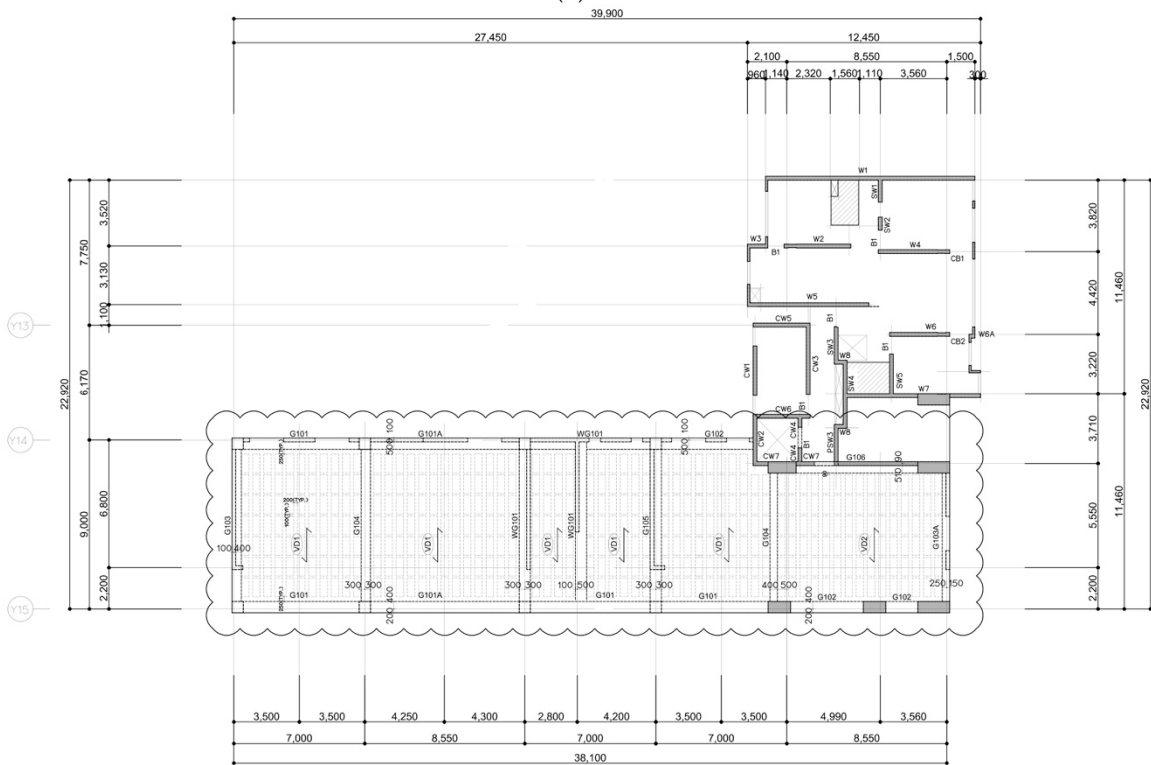


(a)

Figure 4. Cont.



(b)



(c)

Figure 4. Structural design of floors (a) Structural design of the first floor; (b) Structural design of the slab on the second floor; (c) Structural design of the slab on the third floor.

2.3. Analysis of CO₂ Emissions

The materials used for the ordinary reinforced concrete slab system were ready-mixed concrete, rebars, and waterproof-coated plywood moulds. In the case of the void slab system, expanded polystyrene void formers, steel anchoring materials, and deck plates were applied, in addition to the materials used in the ordinary slab system. The deck plates used in the void slab system served as a replacement for the moulds for the formation and curing of concrete. As a result of replacing the ordinary reinforced concrete slab with the void slab, the quantities of steel materials, including rebars and moulds were decreased by ~7% and ~211%, respectively (see Table 3).

Table 3. Comparison of CO₂ emissions between the ordinary slab and the void slab.

Materials	CO ₂ Emissions (kg CO ₂ -eq)		Variation (%)
	Ordinary Slab	Void Slab	
Ready-mixed concrete	70,043.40	75,381.60	7.08
Rebars and steel materials	5773.88	5409.40	-6.74
Moulds	128,615.78	41,259.60	-211.72
Deck plates	-	29,576.35	-
Void formers	-	8.82×10^{-6}	-
Transportation	110.07	127.80	13.09
Total	204,544.13	151,754.75	-33.99

On the other hand, the quantity of ready-mixed concrete used for the ordinary slab was 166.73 m³, which was 12.71 m³ less than that of the void slab system (see Tables 4 and 5). In the case of the void slab system, the thickness of the slab was 300 mm, which was twice the ordinary reinforced concrete slab (150 mm). Despite the 100% increase in thickness (two times), the total amount of ready-mixed concrete in the void slab system was increased only by ~7%. Since the concrete slab was filled with the lightweight void formers in the void slab, the increase in the ratio of concrete for the void slab was small.

Table 4. CO₂ emissions by input materials of the ordinary reinforced concrete slab system.

Materials	Quantity	Unit	CO ₂ Emissions (kg CO ₂ -eq)	Percentage
Ready-mixed concrete	166.77	m ³	70,043.40	33.6
Rebars and steel materials	16,982.00	kg	5773.88	2.8
Moulds	880.93	m ³	128,615.78	61.7
Transportation	-	-	111.07	0.1
Total			204,544.13	100.0

Table 5. CO₂ emissions by input materials of the void slab system.

Materials	Quantity	Unit	CO ₂ Emissions (kg CO ₂ -eq)	Percentage
Ready-mixed concrete	179.48	m ³	75,381.60	49.7
Rebars and steel materials	15,910.00	kg	5409.40	3.6
Moulds	282.60	m ³	41,259.60	27.2
Deck plates	507.40	m ²	29,576.35	19.4
Void formers	1305.92	kg	8.8×10^{-6}	0.0
Transportation	-	-	127.80	0.1
Total			151,754.75	100.0

Moreover, previous studies [23,24,26,27] showed that the void formers should be firmly installed and fixed to the lower reinforcement by using anchoring devices. These additional materials would increase the amount of construction materials. However, the anchoring materials adopted in this study were designed to be integrated with the void formers, and accordingly, both were manufactured by using the same materials. In addition, the anchoring mechanism involved inserting the fixers in the holes penetrating the void formers, and turning them by 90°. In this manner, they would be installed between the ribs of the deck plates (see Figure 2). Thus, the anchoring method for the void formers in this study would significantly lower the quantity of the reinforcing bars and the steel materials.

The CO₂ emissions of the ordinary reinforced concrete slab and the void slab systems are depicted in Tables 3 and 4. The total CO₂ emissions of the ordinary reinforced concrete slab system were observed to be 204,433.06 kg CO₂-eq (see Figure 5). The moulds for concrete curing represented the largest source of CO₂ emissions that accounted for 62.9%, followed by ready-mixed concrete (34.3%), and rebars and steel materials that accounted for the lowest proportion of CO₂ emissions (2.8%). The emitted CO₂ from transportation accounted for less than 1%, which was negligibly too low to be considered for an assessment of its impact. Besides, the CO₂ emissions from construction stage were 4040.38 kg CO₂-eq, which were calculated based on the consumption of diesel, petrol, and electricity.

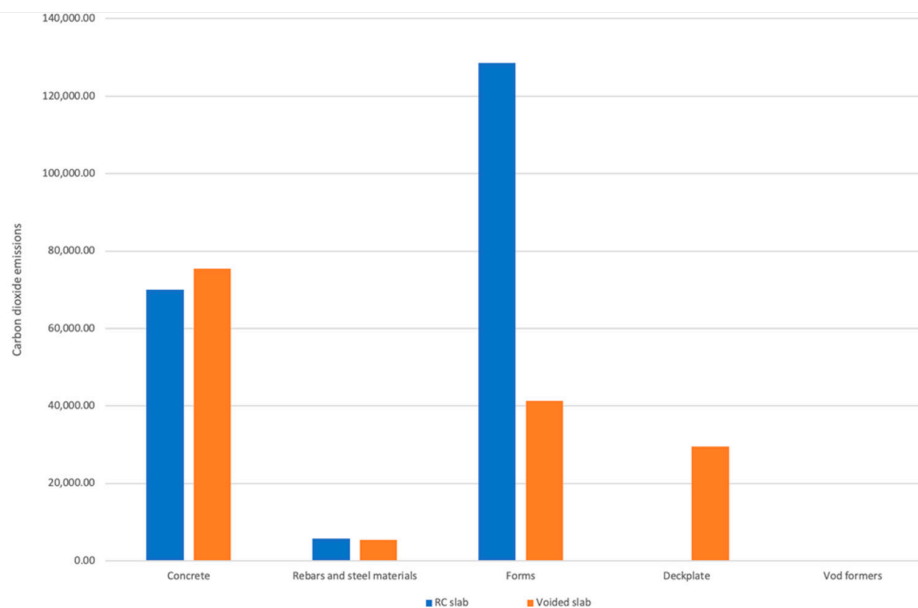


Figure 5. CO₂ emissions of the materials (Unit: kg CO₂-eq).

The CO₂ emissions of the void slab system were also computed, and the total emissions were observed to be 151,754.75 kg CO₂-eq. The greatest source of CO₂ for the void slab system was ready-mixed concrete, which accounted for ~49.7% (see Figure 6). Moulds followed the ready-mixed concrete; the CO₂ emissions were 75,381.60 kg CO₂-eq, accounting for ~27.2% of the total emissions. The use of deck plates constituted ~19.4%, as shown in Figure 7. The emitted CO₂ from transportation was less than 1%, similar to the ordinary slab data.

Comparing the CO₂ emissions of the ordinary reinforced concrete slab system with the void slab system, the total amount of CO₂ emitted from the void slab system was ~33.9% less than that of the ordinary reinforced concrete slab system (see Figure 7). In the void slab system, the use of ready-mixed concrete increased by 7.08%. When the quantity of the ready-mixed concrete in the void slab system was compared according to building member (i.e., slab, beams, and girders), the concrete used in the slab increased by ~34%, but the concrete in the beams and girders decreased by 33.23%. Since the application of the void slab system would reduce the self-weight of the slab, the number of beams and girders were reduced, which resulted in a reduction of total CO₂ emissions.

In this study, waterproof-coated plywood moulds were the most significant CO₂ emission source, which were used to form and cure the concrete for the ordinary reinforced concrete slab system, and the ready-mixed concrete for the void slab system. As seen in Tables 4 and 5, the amount of moulds used in the void slab system decreased by 211.72%, and reinforcing bars decreased by 45.12%. Additionally, deck plates were one of the main components for the void slab system, which served as moulds for the slab, and as anchoring devices for the void formers. Although the emission of CO₂ from deck plates accounted for ~28% of total emissions of the void slab system, the amount of CO₂ was 29,576.34 kg CO₂-eq. Moreover, the void formers had a significant role in reducing the self-weight of the slab, thereby enabling the expansion of the span between columns. Despite the fact that the

void formers played a crucial role in the void slab system, the occurrence of CO₂ was less than 1%, the impacts of which would be negligible (see Figure 8).

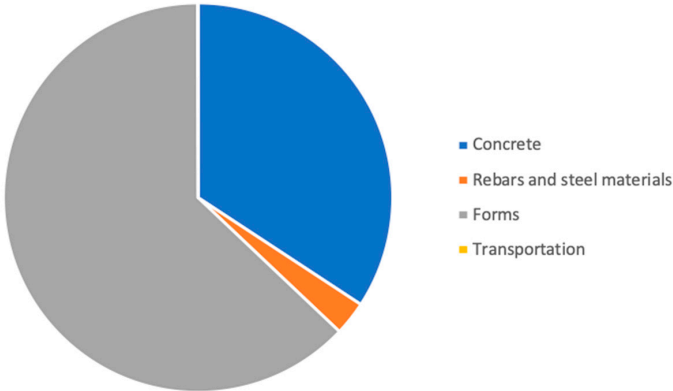


Figure 6. Percentage of CO₂ emissions for the ordinary reinforced concrete slab system.

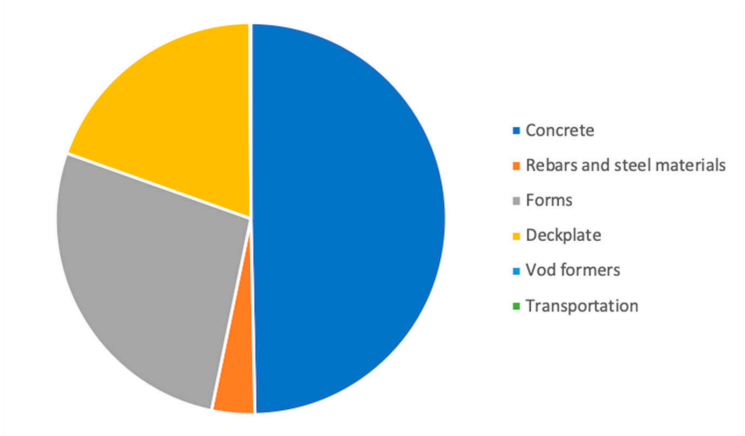


Figure 7. Percentage of CO₂ emissions for the void slab.

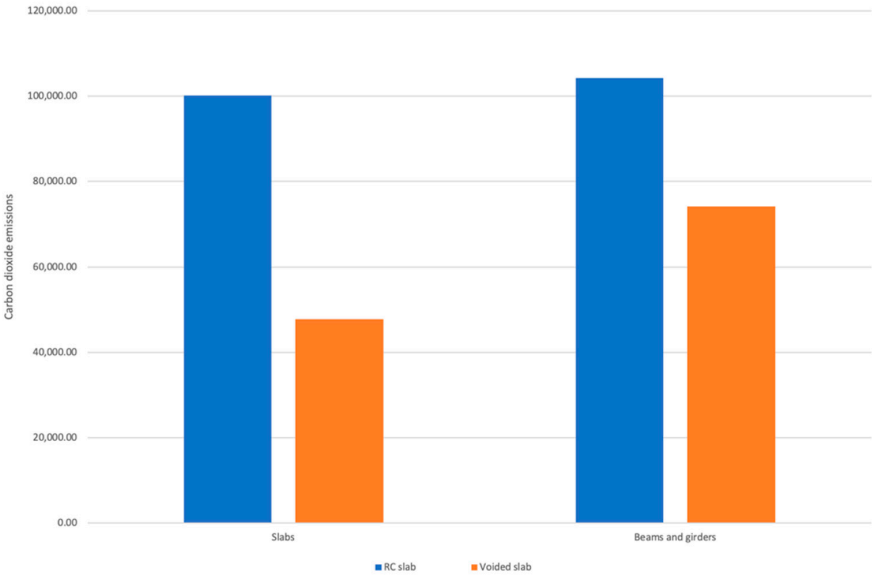


Figure 8. Comparison of CO₂ emissions by members (Unit: kg CO₂-eq).

3. Discussion and Limitations

In this study, the CO₂ emissions of an ordinary reinforced concrete slab system and a void slab system were evaluated and compared, for the lifecycle ranging from the raw materials to pre-operation stage. There are several limitations to mention prior to concluding this study.

While a number of studies maintain that concrete is one of the main sources that emits a large volume of CO₂ in the construction of high-rise buildings, the computed results of this study showed that the moulds used to form and cure the concrete slabs, beams, and girders accounted for the highest volume of CO₂ emissions in the ordinary reinforced concrete slab system. In the case of the void slab system, concrete was the largest source of CO₂ emissions, as it accounted for ~48% of the total CO₂ emissions, which was similar to other studies. However, the assessment of CO₂ emissions in this study only dealt with the slab system, rather than the entire building; hence, the results for the ordinary concrete slab system were different from those of other studies. In order to enhance the accuracy of the results, further research on the evaluation of CO₂ in the entire building is required. The operation, maintenance, and demolition phases should be considered, along with the evaluation of the entire building, so as to assess the environmental friendliness and sustainability of the void slab system.

In this research, the void slab system was applied only to the first three floors, which were designated as commercial areas in the commercial-cum-residential building. Based on the results of this research, the void slab system would reduce the number of beams, and girders and would enable the residents in the building to design and utilise their own spaces in a more flexible manner. Moreover, because of the lowering of the height of each floor caused by the removal of beams and girders, it is expected that a significant amount of construction materials and CO₂ emissions would be reduced in high-rise buildings. Moreover, the decrease in height would lead to a reduced basement floor height, which would in turn contribute to the reduction in CO₂ emissions through a reduced deployment of construction equipment for excavation works.

The concrete applied in both slab systems of this research was of the type most commonly utilised, which had 25 MPa compressive strength. According to Tae et al. [13], the application of high-strength concrete would contribute to a reduction in concrete and reinforcing bars. Moreover, high-strength concrete would help to extend the lifespan of the building, as well as to reduce the cross-section of the vertical members [12,13,40,41]. Along with the utilisation of high-strength concrete, the concrete mix design would have a significant role in decreasing CO₂ emissions from concrete, using by-products such as blast-furnace slag or fly ash [30]. If ordinary solid reinforced concrete slabs in high-rise buildings using normal-strength concrete were replaced with the void slab system by using high-strength concrete and by-products, then a considerable reduction in CO₂ emissions would be attained, according to the results of this study.

The results of the evaluation of this study indicated that waterproof-coated plywood moulds were the main source of CO₂ emissions in the ordinary reinforced concrete slab system. The processes of manufacturing plywood not only consume considerable amounts of resources and energy, but also emit a large volume of CO₂. If moulds for forming and curing the concrete were manufactured using other materials, then a significant reduction in CO₂ emissions would be obtained during the concrete works. Similarly, the CO₂ emissions from the void formers in the void slab were insignificant, and accounted for less than 1% of total emissions. However, using fewer petrochemical products and replacement of recycled materials are earnestly considered in recent trends. If the void formers were manufactured by recycled plastic components, then the environmental friendliness of the void slab system would be enhanced, even though the CO₂ emissions are small.

4. Conclusions

The purpose of this study was to assess and compare the CO₂ emissions of different slab systems in a high-rise commercial-cum-residential building. The system boundary of this study ranged from raw materials to pre-operation, in accordance with ISO 14044.

The total CO₂ emissions of the ordinary reinforced concrete slab and the void slab systems were 204,433.06 and 151,754.75 kg CO₂-eq, respectively. The void slab system emitted ~34% less CO₂ than the ordinary reinforced concrete slab system. In the case of the ordinary reinforced concrete slab system, moulds accounted for ~62% of CO₂ emissions, followed by concrete (~34%).

The main source of CO₂ emissions for the void slab system was concrete that accounted for ~50%, while moulds and deck plates accounted for ~27% and ~19%, respectively. In the case of the void slab system, void formers would lower the amount of concrete, as well as the self-weight of the slab. Although the void formers filled a significant volume of the slab, they accounted for less than 1% of CO₂ emissions. Thus, the void slab system would reduce the weight of the slab as well as enhance the environmental friendliness of the concrete structures.

Author Contributions: I.P. conducted the design of two structural systems of the studied building. S.N. carried out the assessment of carbon dioxide emissions of both systems. S.Y. designed the study and carried out the structural design of this study. All authors contributed to the analysis and conclusion of this study.

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Conflicts of Interest: The authors declare no conflict of interest.

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