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Evaluation of Carbon Dioxide Emissions amongst Alternative Slab Systems during the Construction Phase in a Building Project

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Abstract: Global warming is now considered to be one of the greatest challenges worldwide. International environmental agreements have been developed in response to climate change since the 1970s. The construction industry is considered one of the main contributors to global warming. In order to mitigate global warming effects, the construction industry has been exploring various approaches to mitigate the impacts of carbon dioxide emissions over the entire life cycle of buildings. The application of different structural systems is considered a means of reducing the carbon dioxide emissions from building construction. The purpose of this research is to assess the environmental performance of three different slab systems during the construction phase. In this study, a process-based life cycle assessment (LCA) method was applied in order to evaluate the level of performance of the three slab systems. The results showed total CO_2 emissions of 3,275,712, 3,157,260, and 2,943,695 kg CO_2 eq. for the ordinary reinforced concrete slab, flat plate slab, and voided slab systems, respectively. The manufacturing of building materials is by far the main contributor to CO_2 emissions, which indicate 3,230,945, 3,117,203, and 2,905,564 kg CO_2 eq., respectively. Comparing the building materials in the three slab systems, reinforcing bars and forms were significant building materials to reduce the CO_2 emissions in the flat plate slab and voided slab systems. In this study, reinforcing bars were the main contributor to lowering the carbon dioxide emissions in the flat plate slab and voided slab systems. The results of this study show that amongst all the three different slab systems, the voided slab system shows the greatest reduction potential. Moreover, replacing the ordinary reinforced concrete slab system by alternative methods would make it possible to reduce the carbon dioxide emissions in building projects.

Keywords: construction industry; carbon dioxide; life cycle assessment; reinforced concrete slab; flat plate slab; voided slab

1. Introduction

Global warming is considered one of the greatest challenges worldwide. International environmental agreements have been developed in response to climate change since the 1970s. The construction industry is considered to be one of the main contributors to global warming. According to the Intergovernmental Panel on Climate Change (IPCC) report [1], not only is the construction industry responsible for about 40% of global energy consumption, it is also responsible for 30% of global greenhouse gas emissions per annum. Furthermore, it is common for most countries to construct high-rise buildings and larger-sized facilities, due to the rapid growth of population, and scarcity of land in urban areas [2–4]. Since high-rise and larger-sized buildings and structures consume greater amounts of energy and materials per unit area, the total energy and carbon dioxide emissions associated with the construction industry are expected to grow. For example, it is reported that in South Korea, over 40% of the energy consumption and annual CO_2 equivalent emissions are related to the construction industry [5–7]. From the perspective of sustainable development, it is undoubtable that reducing energy consumption and carbon dioxide emissions from the construction industry would be one of the most sustainable measures [8–12]. Likewise, the construction industry has been exploring various approaches to mitigate the impacts of carbon dioxide emissions over the entire life cycle of buildings, which includes the manufacturing of building materials, transporting of the building materials, construction and installation, operation and maintenance, and eventual demolition [12–14].

The reduction of carbon dioxide emissions in the construction industry has a unique characteristic compared to other manufacturing or service industries. Due to the relatively long life span of buildings of over 30 years, the mainstay of reducing the carbon dioxide emissions in the construction industry is focused on the CO_2 emissions from the operation and maintenance stage of buildings [14–18]. A number of studies have maintained that approximately 70% of the life cycle CO_2 is generated from the operation phase for a typical office building, whereas only about 25% of carbon dioxide emissions are from the pre-operation stage, and less than 5% is emitted from the demolition and other stages [14,18,19]. Recent studies regarding carbon dioxide emissions in the construction industry [3,4,19–22] report that energy consumption and carbon dioxide emissions during the operation stage of a building are gradually decreasing, due to the newly developed technologies to enhance the energy efficiency and optimisation of heating, ventilation, and air conditioning (HVAC) systems. Even though the carbon dioxide emissions from the pre-operation stage are smaller than the CO_2 emissions from the operation and maintenance stage, various studies have tried to mitigate the occurrence of carbon dioxide in this phase. Furthermore, when the different time frames of life cycle are considered, the carbon dioxide emissions from the pre-operation stage might become more significant [23]. As the service life of buildings is reducing to less than 30 years, the contribution of CO_2 emissions from pre-operational stages would become larger at up to 50% [21,23]. As a consequence of the decreased carbon dioxide emissions from the operational and maintenance stage of buildings, the embodied carbon that is generated from manufacturing building materials to the construction stage becomes more significant, and from an entire life cycle perspective, has more potential to be mitigated [14,18,24–27].

Recent research in terms of carbon dioxide emissions from the pre-operational stage has focused on various aspects of the building to mitigate their impacts. Numerous studies have claimed that the CO_2 emissions from building material production are the most dominant contributor during this phase [24,27–30]. As building material production is the main source of carbon dioxide emissions, various approaches are being taken to alleviate the impacts from building materials. According to Goverse et al. [31], replacing building materials to low embodied carbon materials in Dutch residential buildings might achieve almost 50% reduction of carbon dioxide emissions, compared to the traditional method. Likewise, one of the most effective and prevalent approaches to lower the emissions of carbon dioxide emissions in the construction stage is the application of high-strength building materials. High-strength building materials not only lessen the input amount of building materials, but also enhance the durability of the entire structure or building [6]. Moreover, the strengthening of building materials would be beneficial to prolong the lifespan of buildings from the whole life cycle perspective. Tae et al. [6], for example, maintained that high-strength concrete would make it possible to reduce the emissions of carbon dioxide, owing to the quantity reduction of concrete and rebars, as well as the extension of building life span. In a similar vein, Cho and Na [32] indicated that the utilisation of high-strength rebars would contribute to reduction of the carbon dioxide emissions regardless of the structural type of office buildings in South Korea, even though the amounts of splice and development in reinforcement were slightly increased.

Along with the utilisation of high-strength building materials, it is important to produce building materials with high recycling potential to mitigate the emissions of carbon dioxide. For instance, Gao et al. [33] studied three buildings with different recycling ratio of building materials. The results indicated that approximately 25% of CO_2 could be decreased with the maximum recycling ratio. Moreover, Quack [34] maintained that from a theoretical perspective, about 12% CO_2 emissions reduction would be achieved, when the recycling rate increased to 100%. While various studies have claimed the usefulness of increasing the recycling ratio for building materials production, application of by-products is also suggested to mitigate the environmental impacts from building materials. As stated in the previous section, enhancement of material strength is a practical method to reduce the carbon dioxide emissions to a certain extent. According to Tae et al. [6], high-strength concrete of more than 24 MPa compressive strength would have a negative consequence, compared to high-strength concrete of less than 24 MPa. In order to deal with this matter, the authors suggested that applying industrial by-products, such as fly ash or blast furnace slag, would not only enhance the strength of concrete, but also reduce fuel consumption during the manufacturing of the concrete.

While a number of studies have considered replacing conventional building materials by alternative ones, approaches to the design of structural systems to mitigate the amount of building materials have been suggested. Structural systems are one of the core elements for the entire building to sustain the external forces, such as lateral loads, and service and permanent loads. According to Nadoushani and Akbarnezhad [35], comprehensive assessment of embodied carbon and operating carbon during the structural design stage would be a significant factor to assess the life cycle carbon of a building. The authors indicated that the embodied carbon from steel structure buildings is less than that from reinforced concrete structure ones, but the operating carbon of steel structure buildings is higher than that of reinforced ones. Similarly, Baek et al. [36] compared apartment buildings with different structural systems and building materials. Building materials, as well as design, would be one of the important factors to lower the carbon dioxide emissions during the construction phase. Likewise, optimal design of a building with high-strength building materials would result in superior performance in terms of carbon dioxide emissions and structural reliability [26]. Therefore, selecting the structural design and building materials would make it possible to reduce carbon dioxide emissions during the construction phase.

As the efficient use of land and urbanisation has become prevalent in recent years, it is common to construct high-rise buildings in urban areas around the world. Slabs in a building not only provide occupants with a flat surface, but also transfer various loads, such as service and permanent loads, through beams, girders, and columns, to the ground. Furthermore, the self-weight of slabs in high-rise buildings would significantly grow as the height of a building increased. Given the significant role of slabs in a building, the main focus of research regarding slab systems is to corroborate the structural performance and reliability, such as the flexural, shear, and seismic performance [37–40]. Compared to studies on the structural performance of slabs, studies that evaluate the environmental impacts of slab systems are relatively scarce. For example, Ferreiro-Cabello et al. [41] examined the carbon dioxide emissions from reinforced concrete slab of different thickness. The authors analysed the relationships amongst the distance between columns, the thickness of slabs, and the carbon dioxide emissions. However, this research only dealt with the conventional reinforced concrete slab system, rather than newly developed slab systems. In order to reduce the self-weight of slab systems, the flat plate slab and voided slab systems are applied to buildings for enhanced serviceability and ease of construction. Although the application of flat plate slab systems and the voided slab systems is prevalent, there is little research to compare and verify their environmental performance.

The purpose of this research is to assess the environmental performance of three different slab systems (i.e., the ordinary reinforced concrete slab, flat plate slab, and voided slab systems) during the construction phase (see Figure 1). In this study, the process-based life cycle assessment (LCA) method was applied, in order to evaluate their level of performance. The comparison amongst the three slab systems was carried out for the following three stages: building material production before transportation to the construction site; transportation of the building materials to the construction site; and utilisation of construction equipment during the construction and installation. The analysed data were further discussed to illustrate the respective environmental performance of the ordinary reinforced concrete slab, flat plate slab, and voided slab systems during the construction phase.

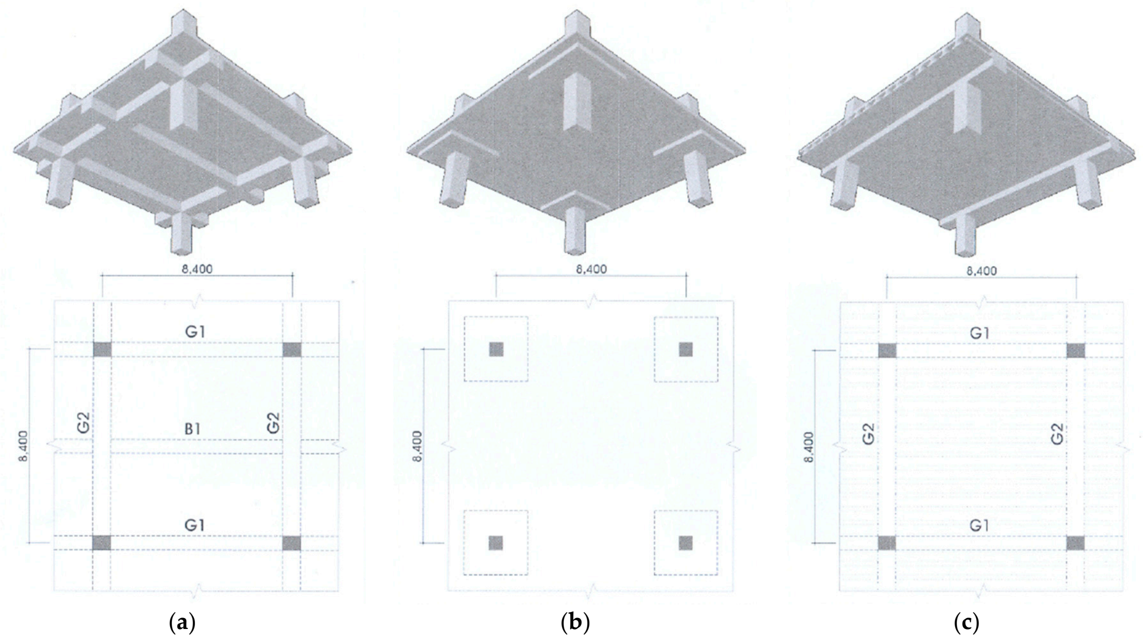


Figure 1. Schematic of the slab systems in a building: (**a**) Ordinary reinforced concrete slab system, (**b**) Flat plate slab system, (**c**) Voided slab system

2. Research Methodology

2.1. Description of the Assessment Method

This study assessed the environmental impacts of the three different slab systems during the construction stage. The construction stage included building material production, transportation of the building materials to the construction site, and utilisation of construction equipment. While there are several quantitative evaluation methods for the environmental impacts, the quantification methods could be categorised into two prevalent approaches, which are the economic input–output, and process-based, analyses.

The former approach, economic input–output analysis, is an assessment method to consider both direct and indirect environmental impacts on the targeted products or services [42–44]. In this approach, the data are normally accumulated from statistical ones related to manufacturing a product or delivering a service. Even though this method is time consuming and expensive to collect extensive data from all relevant areas, it would be useful to predict the direct and indirect impacts of products or services. For example, Suzuki and Oka [43] evaluated the energy consumption and CO_2 emissions of buildings through economic input–output analysis. Similarly, Chen et al. [44] accounted for detailed carbon emissions applying to a multi-scale input–output analysis method. Cho and Na [32] evaluated the carbon dioxide emissions of three different structural systems in South Korea, which applied to high-strength reinforcing bars as a means of reducing CO_2 emissions. In order to enhance the accuracy of the environmental impacts, it would be necessary to collect as much data as possible. Because of the accuracy of data collection in input–output analysis, this method is widely applied in the USA and Japan.

The latter method, process-based analysis, is a bottom-up approach that investigates a product's relevant data from manufacturing to demolition, and subsequently accumulates the data of the energy consummation, as well as carbon dioxide emissions [14,18,21,24,45]. This method is normally in compliance with ISO 14044 [46] and ISO 21930 [47] standards. In this method, the emissions of carbon dioxide of a product would be evaluated by the amount of materials and energy consumed during the production processes. Moreover, when the economic input–output data are unavailable, process-based analysis would be impossible to utilise for the environmental assessment. For example, Mao et al. [14] adopted this approach to compare greenhouse gas emissions between conventional construction and off-site prefabrication methods, since prefabrication was a newly applied construction method in China, so the data related to prefabrication in China was sparse and new. In a similar vein, Hong et al. [18] and Yan et al. [24] analysed the greenhouse gas emissions during the construction phase of buildings in China and Hong Kong using process-based analysis. For process-based analysis, the system boundary of a targeted product or services should be determined to assess the impact.

2.2. System Boundary

Few studies have dealt with the carbon dioxide emissions during the construction phase. The system boundary of the construction phase of a building has been determined by various researchers. According to Yan et al. [24], the GHG emissions in building construction are from six sources, which are the: (1) manufacture of building materials; (2) transportation of building materials; (3) transportation of construction equipment; (4) energy consumption of construction equipment; (5) transportation of workers; and (6) disposal of construction waste. However, the carbon dioxide emissions of the present study mainly considered the embodied carbon of the three different structural systems for slabs. Accordingly, the system boundary of this study was selected as the manufacturing of building materials (E_1), transportation of building materials to the construction site (E_2), and the carbon dioxide emissions from the energy consumption of construction equipment (E_3) in compliance with ISO 14044 [46] and ISO 21930 [47]. Figure 2 shows the system boundary for the construction process of different slab systems in this study.

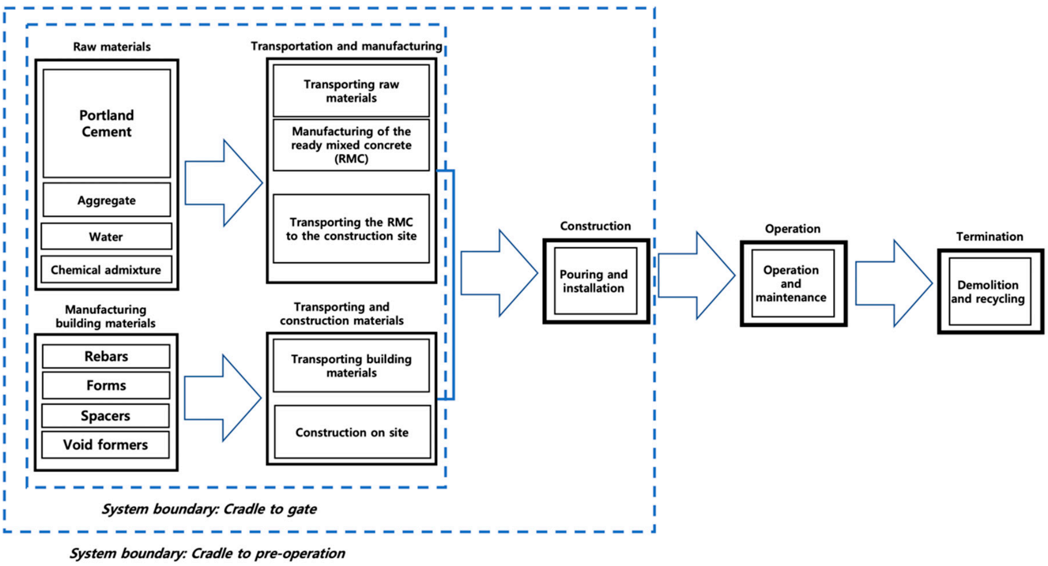


Figure 2. System boundary for the construction process.

The manufacturing of building materials (E_1) refers to the carbon dioxide emissions during the production of major building materials for slabs. In this study, building materials were divided into temporary and permanent materials for the construction of slab systems. The energy consumption of building materials to the construction site (E_2) is the CO_2 emissions from the fuel combustion of transportation for building materials, which was either from the manufacturing site, or from the distribution centres. The energy consumption of construction equipment (E_3) is the carbon dioxide emissions of consumption from the operation of construction equipment and machinery on site.

2.3. Quantification Method of the Carbon Dioxide Emissions

Based on the sources of carbon dioxide emissions during the construction of slab systems in a building, Equation (1) describes the total emissions:

$$E_{Total} = \sum_{i=1}^{3} E_i \quad (1)$$

where, E_{Total} is the total carbon dioxide emissions during the construction stage in kg CO_2 eq., E_i is the carbon dioxide emissions from the ith stage during the process of construction, and in this study, i is from 1 to 3. Equations (2)–(4) describe the quantification method for calculating the carbon dioxide emissions during the construction phase of the three slab systems:

$$E_1 = \sum M_j \times f_j \quad (2)$$

where E_1 is the carbon dioxide emissions of all building materials (in kg CO_2 eq.), M_j is the amount of building materials j (in m^3 for ready-mixed concrete, kg for rebars and expanded polystyrene for void formers, and m^2 for forms and steel decking), and f_j the carbon dioxide emissions factor of building material j (in kg CO_2/unit). The value of the carbon dioxide emissions factors may vary dependent upon the country. In this study, data on the carbon dioxide emissions factors of building materials are limited to South Korean data. The carbon dioxide emissions factors in this study were adopted from the South Korean National Life Cycle Inventory Database [48]. Table 1 presents the related carbon dioxide emissions factors (f_j) of five dominant materials for the construction of slab systems for the current study.

$$E_2 = \sum_{i=1}^{3} \sum_{j=1}^{j} L_c \times N_t \times f_{trans} \quad (3)$$

where E_2 is the total carbon dioxide emissions from the transportation of building materials to the construction site (in kg CO_2 eq.), L_c is the amount of fuel consumed in the transportation stage (in litres), N_t is the number of vehicles used to transport the building materials, and f_{trans} is the carbon dioxide emissions factors of each type of vehicle to transport the building materials. The consumed amount of fuel was computed by the distance between the supplier's location and the construction site (km), and the fuel efficiency of the transportation method (km/L). In addition, the number of vehicles required to transport the building materials was calculated by the amount of construction materials, and the capacity of the transportation methods. Table 2 summarises the distance and the type of transportation of this study:

Table 1. Carbon dioxide emissions factors of building materials.

Material	Unit	CO_2 Emission Factors (kg CO_2 eq./unit)	Source
Ready-mixed concrete	m^3	4.29×10^2	National Life Cycle Inventory Database [48]
Rebars	kg	3.48×10^1	
Forms	m^2	1.49×10^2	
Void formers (Expanded polystyrene)	kg	1.91×10^1	
Steel decking	m^2	3.90×10^1	

Table 2. Distance of suppliers and transportation methods.

Materials	Distance (unit: km)	Type of Transportation
Ready mixed concrete	25	Concrete mixer
Reinforcing bars	220	11.5-ton lorry
Steel decking	252	11.5-ton lorry
Forms	90	4.5-ton lorry
Void formers	170	1.5-ton lorry

The carbon dioxide emissions from the construction equipment usage on site was determined by the fuel consumed by the equipment and machinery. The equation below was used to calculate the carbon dioxide emissions from the construction equipment on site:

$$E_3 = \sum F_j \times f_j \tag{4}$$

where E_3 is the total carbon dioxide emissions from the energy consumption of construction equipment (in kg CO_2 eq.), F_j represents the amount of fuel j consumed by construction equipment (in L, and f_j is the carbon dioxide emissions factors for fuel j consumed by construction equipment (kg CO_2 eq./L). The construction equipment in this study consumed only diesel to operate the construction equipment on site. The amount of fuel consumption for the construction equipment was determined from the construction daily report. The carbon dioxide emissions factor for diesel is 6.82×10^{-2}, which was adopted from the South Korean National Life Cycle Inventory Database [48].

2.4. Description of the Case Study

The case study in this study demonstrated the aforementioned process-based quantification method for the carbon dioxide emissions, and a comparative study amongst the three different types of slab systems in a building. Table 3 summarises the profile of the studied building. The floor area of the typical storey is 963 m^2, and the total floor area is 13,487 m^2.

Table 3. Profile of the studied building.

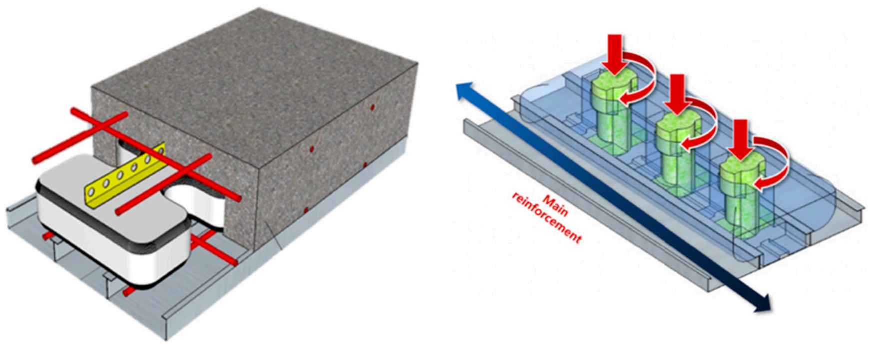
Number of Storeys (Ground/Basement)	Type of Structure	Type of Footings	Concrete Compressive Strength (MPa)	Rebars Tensile Strength (MPa)	Permanent Load (kN/m^2)	Servicing Load (kN/m^2)
10/4	Rigid frame	Bearing capacity of soil (Mat footing)	f_{ck} = 24 (All storeys)	f_y = 400 f_y = 500	7.52	3.00

The evaluated case of this study is a commercial building located in Yeosu-si, South Korea, whose construction period was from 2017 to 2019. The building is a rigid-frame structure that has 10 storeys above ground, and four storeys underground for parking. The model was designed in compliance with Structural Concrete Design Code and Commentary by the Korea Concrete Institute [49] and ACI 318-05 [50]. Table 4 summarises the factors of seismic and wind loads that were applied to this building project:

Table 4. Load factors of the building.

Type	Seismic Load				Wind Load		
	Site Coefficient	Importance Factor	Ground	Response Modification Coefficient	Terrain Category	Design Wind Speed (m/s)	Gust Influence Factor
Office building	A	1.5	Sc	5.0	B	30	2.2

The slabs of the studied building were designed according to three different slab systems, which were the ordinary reinforced concrete slab (i.e., slab-column fames), flat plate slab, and voided slab systems. The slab thickness of 300 mm was selected for the three slab systems in this study. The slab reinforcement consisted of 12.70, 15.90, and 19.10 mm diameter deformed bars with a yield stress of 400 MPa. The 12.70 and 15.90 mm diameter reinforcing bars were placed for upper reinforcement, while the 15.90 and 19.10 mm diameter rebars were placed for lower reinforcement of the slabs. Various types of slab systems would be applied for different types of building, such as residential, office, and apartment. The selection of an adequate and economic slab system might depend upon the type of building, architectural layout, and the span length between columns. During the value analysis process in this project, both the flat plate slab and voided slab systems were suggested as alternative methods for the ordinary reinforced concrete slab. When the value analysis was carried out in this project, the cost-effectiveness and the serviceability for future occupants were the most significant factors. The voided slab system is a newly developed voided slab system that combines lightweight void formers and bottom steel decking for anchoring void formers inside the slab. For the voided slab system, anchoring the void formers firmly in the slab is one of the significant compositional elements. Various methods have been suggested to overcome such difficulties during the construction of the voided slab. In this study, the voided slab system proposed a new method to fix the void formers, as shown in Figure 3:



(**a**) (**b**)

Figure 3. Description of the voided slab system: (**a**) Schematic of the voided slab system, (**b**) Anchoring mechanism of the voided slab system.

3. Results and Discussion

3.1. Total Carbon Dioxide Emissions of Each Slab System

Table 5 summarises the estimated carbon dioxide emissions of alternative slab systems over the ordinary reinforced concrete slab during the construction phase, as well as the share of each life cycle (i.e., the manufacturing of building materials, transportation of building materials, and carbon dioxide emissions of construction equipment) in the total carbon dioxide emissions. The total carbon dioxide emissions during the construction phase of the ordinary reinforced concrete slab, flat plate slab, and the voided slab systems are 3275, 3157, and 2943 tons CO_2 eq. (equivalent to 242, 234, and 218 kg CO_2 eq./m^2), respectively. A reduction of 0.8 tons per 100 m^2 was achieved in the building with flat plate slab, which is approximately 3.6% less than the ordinary reinforced concrete slab. Likewise, 2.4 tons per 100 m^2 of carbon dioxide was reduced in the voided slab system, about 10.1% less CO_2 compared with the ordinary reinforced concrete slab.

Table 5. Total carbon dioxide emissions of each slab system.

Source	Emissions (kg CO_2 eq.)			Ratio (%)		
	Ordinary Reinforced Concrete Slab (ORC)	Flat Plate Slab (FPS)	Voided Slab System (VDS)	Ordinary Reinforced Concrete Slab (ORC)	Flat Plate Slab (FPS)	Voided Slab System (VDS)
E_1	3,230,945	3,117,203	2,905,564	98.63	98.73	98.70
E_2	24,381	23,428	22,657	0.74	0.74	0.77
E_3	20,386	16,628	15,474	0.62	0.53	0.53
Total	3,275,712	3,157,260	2,943,695	100	100	100

The reduction of carbon dioxide emissions from the voided slab system indicated the highest reduction ratio amongst all three cases. The high reduction potential from the voided slab system might be attributed to the reduction of building materials, even though steel decking and void formers were additionally utilised in the voided slab system. In particular, high reduction of concrete and reinforcing bars would make it possible for the voided slab system to emit less carbon dioxide compared with the two alternatives of this study. In addition, the flat plate slab is frequently suggested as an alternative structural system for residential or commercial building in South Korea, since it would enhance the workability for construction workers and serviceability for occupants. In South Korea, it has been tabooed to apply a flat plate slab to buildings since the collapse of a department store building in 1995 [51,52]. However, flat plate slabs have been increasingly applied to commercial and residential buildings in recent years, because of the system's advantages, such as simple formworks during the construction phase, and extended span for enhanced serviceability. As indicated in Table 6, the carbon dioxide emissions of flat plate slab were reduced by about 3.5% over the ordinary reinforced concrete slab. Based on these results, when the environmental impact is considered to select the structural system in buildings, both flat plate slab and the voided slab system would be an alternative method to the ordinary reinforced concrete slab.

Table 6. Reduction of the total carbon dioxide emissions.

Source	Emissions (kg CO_2 eq.)		Reduction Ratio (%)	
	FPS	VDS	FPS	VDS
E_1	−113,741	−325,381	−3.52	−10.07
E_2	−955	−1724	−3.91	−7.07
E_3	−3758	−4913	−18.43	−24.10
Total reduction	−118,452	−213,565	−3.62	−10.14

Table 6 summarises the reduced amount of carbon dioxide emissions and the reduction ratio of the flat plate slab and voided slab system over the ordinary reinforced concrete slab. Columns 4 and 5 in Table 5 present the reduction ratio of each emissions source to the total carbon dioxide emissions reduction brought by the application of flat plate slab and the voided slab system. A total of 3.52% and 10.07% of the carbon dioxide emissions reduction are due to the manufacturing of building materials (E_1); 3.91% and 7.07% of reduction are due to the transporting of building materials to the construction site (E_2); and 3.62% and 10.14% of carbon dioxide emissions were reduced in the construction equipment usage on site (E_3). Amongst the three cases, the manufacturing of building materials contributed the largest proportion of carbon dioxide emissions reduction (see Figure 4):

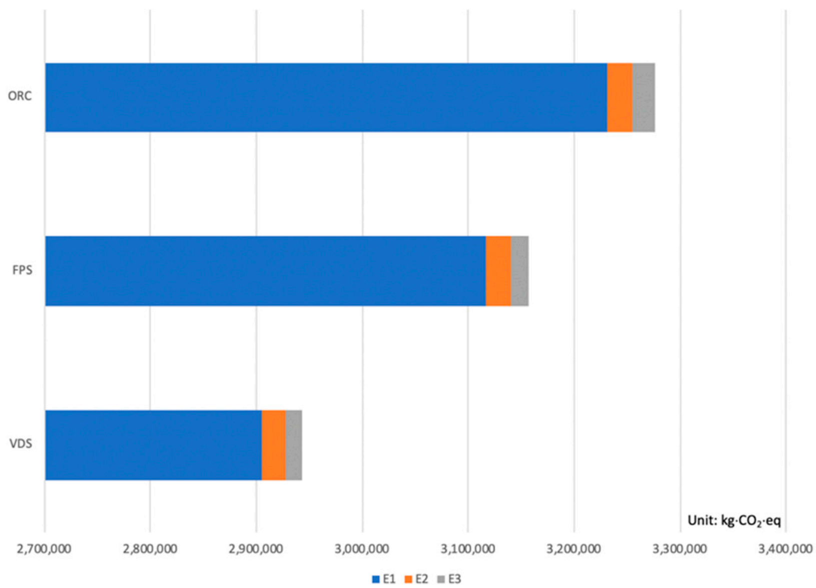


Figure 4. Total carbon dioxide emissions (unit: kg CO_2 eq.).

In the current study, the reductions of carbon dioxide emissions from the transporting of building materials to the construction site were 3.91% and 7.07% for the flat plate slab and the voided slab systems, respectively. Moreover, 18.43% and 24.10% reduction of the carbon dioxide emissions for flat plate slab and the voided slab systems, respectively, were achieved by the utilisation of construction equipment on site. Table 6 shows that the major contributor of reduction of the total carbon dioxide emissions was manufacturing of the building materials in all cases. On the other hand, the largest reduction ratio was shown in the utilisation of construction equipment on site for the flat plate slab and the voided slab systems.

From the perspective of the reduction in each emissions source when replacing the ordinary reinforced concrete slab by alternative methods, columns 4 and 5 in Table 6 indicate that the voided slab system would be the most beneficial approach to the reduction of CO_2, compared to the ordinary reinforced concrete slab method. In the case of the voided slab system, a reduction of 10.07% of the emissions from the manufacturing of building materials, 7.07% of the emissions from the transporting of building materials, and 24.10% of the utilisation of construction equipment were indicated when replacing the ordinary reinforced concrete slab by the voided slab system. Similarly, 3.52%, 3.91%, and 18.43% of reduction for the manufacturing of building materials, transporting of building materials to the construction site, and utilisation of construction equipment, respectively, were noted from the adoption of the flat plate slab system. Based on these results, the most effective method to mitigate the impact of the carbon dioxide emissions from the slab system of buildings would be the voided slab system as indicated in Figure 5.

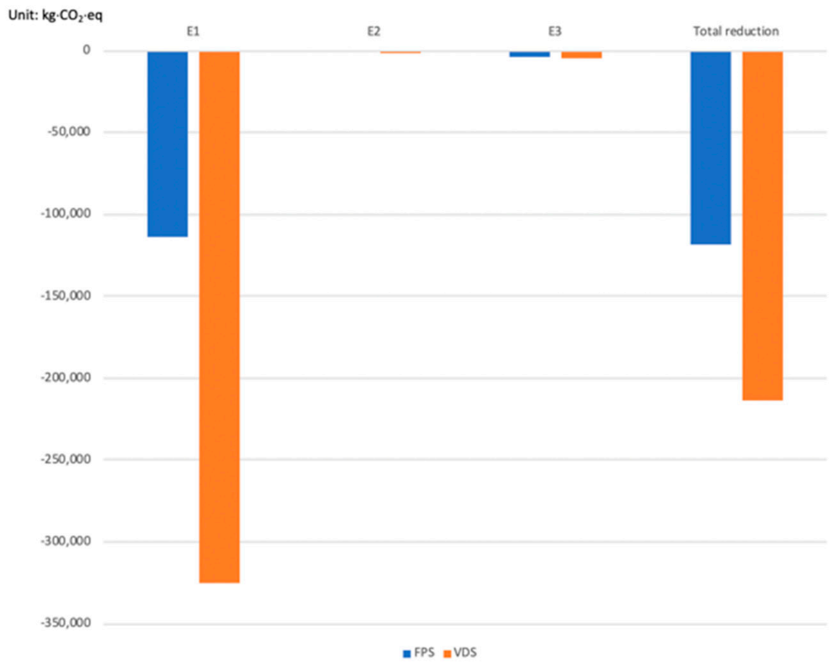


Figure 5. Reduction of CO_2 emissions of the flat plate slab and the voided slab systems.

3.2. Carbon Dioxide Emissions from the Manufacturing of Building Materials

As the largest source of total carbon dioxide emissions amongst the three different types of slab system, the CO_2 emissions from each building material varied from its input amount. Tables 7 and 8 show the carbon dioxide emissions per square meter of each building material. The building materials used in the three cases were divided into permanent and temporary materials. Concrete, reinforcement rebars, steel decking, and void formers were categorised into permanent materials that were integrated with the slab. Temporary materials were auxiliary materials that were removed when the construction work was finished. In this study, forms were the only temporary materials, and were reused 7 times for concreting and moulding work.

Table 7. Material quantity and carbon dioxide emissions per square meter.

Materials	Material Quantity (unit/m^2)			Emissions of CO_2 (unit: kg CO_2 eq./m^2)					
	ORC	FPS	VDS	ORC		FPS		VDS	
				Amount	%	Amount	%	Amount	%
Ready-mixed concrete	0.28	0.29	0.24	120.9	50.7	124.5	53.9	102.5	47.6
Rebars	32.95	30.35	26.69	112.0	46.9	103.2	44.7	90.7	42.1
Forms	2.00	1.05	0.65	6.5	2.4	3.4	1.4	2.1	1.0
Steel decking	N.A.	N.A.	0.61	N.A.	N.A.	N.A.	N.A.	19.9	9.2
Void formers	N.A.	N.A.	0.02	N.A.	N.A.	N.A.	N.A.	0.1	0.1
Total	35.32	34.29	28.21	238.4	100	231.1	100	215.3	100

Table 8. Total carbon dioxide emissions and reduction of building materials.

Materials	CO_2 Emissions (kg CO_2 eq.)			Reduction			
	ORC	FPS	VDS	ORC-FPS		ORC-VDS	
				Amount	%	Amount	%
Ready-mixed concrete	1,631,735	1,679,253	1,382,080	47,518	2.91	−249,656	−15.3
Rebars	1,510,906	1,391,616	1,223,834	−119,290	−7.9	−280,072	−19.0
Forms	88,303	46,335	28,709	−41,969	−47.5	−59,594	−67.5
Steel decking	N.A.	N.A.	269,554	N.A.	N.A.	269,554	N.A.
Void formers	N.A.	N.A.	1387	N.A.	N.A.	1387	N.A.
Total emissions	3,230,944	3,117,204	2,905,564	−113,741	−3.5	−325,381	−10.1

The carbon dioxide emissions of building materials generated approximately 238, 231, and 215 kg CO_2 eq./m^2 for the ordinary reinforced concrete slab, flat plate slab, and voided slab systems, respectively. In all cases, ready-mixed concrete is the largest contributor of carbon dioxide emissions during the manufacturing of building material stage. Specifically, the contribution percentage of each material in the ordinary reinforced concrete slab system is 50.7% for ready-mixed concrete, 46.9% for reinforcing bars, and 2.4% for forms. The flat plate slab system indicated similar proportions to the ordinary reinforced concrete slab system, and accounts for 53.9% of ready-mixed concrete, 44.7% of rebars, and 1.4% of forms, respectively. Additionally, the proportions of materials for the voided slab system are 47.6% for ready-mixed concrete, 42.1% for rebars, 1.0% for forms, 9.2% for steel decking, and 0.1% for void formers. In the voided slab system, the steel decking was the third largest carbon dioxide emissions source.

Table 8 shows that the carbon dioxide reduction in the voided slab system was the largest amount of carbon dioxide reduction amongst all the three slab systems. A total of 113,741 and 325,381 kg CO_2 eq. in reduction of carbon dioxide emissions were contributed by the flat plate slab and the voided slab systems, compared to the ordinary reinforced concrete slab system (see Table 8). These amounts yielded approximately 3.5% and 10.1% in reduction compared to the ordinary reinforced concrete slab in this study. Comparisons of the three slab systems indicate that the reinforcing bars and forms were significant building materials to mitigate the emissions of carbon dioxide in the flat plate slab and the voided slab systems. In particular, reinforcing bars in the flat plate slab and voided slab systems were the main contributor to lowering the carbon dioxide emissions during the manufacturing of building materials stage. Totals of 119,290 and 280,072 kg CO_2 eq. for the flat plate slab and voided slab systems, respectively, were reduced in rebars amongst all the building materials. Moreover, a reduction of 249,656 kg CO_2 eq. in ready-mixed concrete was contributed by the voided slab system over the ordinary reinforced concrete slab. In the voided slab system, the hollow parts were filled with light-weight void formers, which were made by Expanded Polystyrene (EPS). Since the void formers were relatively lighter than the other materials, it would make it possible to not only reduce the carbon dioxide emissions, but also to lower the weight of the slab itself. On the other hand, a slight increase of 47,518 kg CO_2 eq. in the ready-mixed concrete was indicated in the flat plate slab system. It is considered that this might be caused by the additional structural members, such as drop panels to enhance the nominal shear strength of flat plate slab at the critical section around the columns. Consequently, the voided slab system would have the least environmental impact compared to the other slab systems, even though it has additional building material, such as steel decking and void formers (see Figure 6).

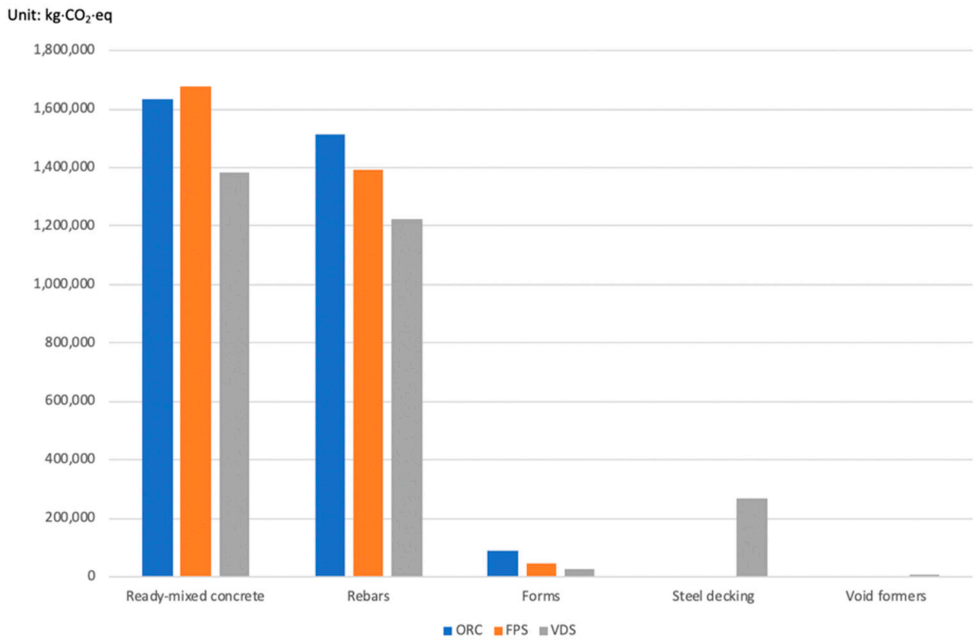


Figure 6. Carbon dioxide emissions of building materials.

3.3. Carbon Dioxide Emissions during Transporting of the Building Materials

Carbon dioxide emissions associated with transporting building materials from the manufacturer's location to the construction site were calculated based on the fuel efficiency of each vehicle, and the distance between the manufacturing place and the construction site. The total carbon dioxide emissions from the transporting building materials were 24,381, 23,428, and 22,657 kg CO_2 eq. for the ordinary reinforced concrete slab, flat plate slab, and voided slab systems, respectively. As to the lower total CO_2 emissions in the voided slab system, which involves two more types of transportation than the other slab systems, the emissions of CO_2 from transporting building materials were less than those of the ordinary reinforced concrete slab and flat plate slab systems. In this study, it was interesting that the carbon dioxide emissions for transporting the void formers were larger than for the forms, even though the unit weight of void former (i.e., approximately 1.6 kg/void former) was relatively lighter than that of the other building materials. This was attributed to the height of void formers being 0.9 m, which required more vehicles to convey them to the construction site. Due to the road traffic act in South Korea, the maximum clearance of each vehicle was 4.5 m, so the number of lorries for the void formers was larger than for the other materials.

In this study, the emissions of carbon dioxide from the transporting of building materials were calculated by two different approaches. The first method was to compute the CO_2 emissions based on the fuel efficiency of vehicle type, and the distance of location between the manufacturer and the construction site. The other approach was to determine the carbon dioxide emissions for transportation based on the operating time of vehicles by the vehicle logs of operation. Table 9 shows that the emissions of carbon dioxide had slightly different value, depending upon the calculation methods. For ready-mixed concrete, the CO_2 emissions from calculation by vehicle operation time indicate more than the former method. The distance from ready-mixed concrete supplier to the construction site was 25 km, which was relatively shorter than that of the other building materials. However, the transporting time for the ready-mixed concrete was influenced by traversing the central district area, and it would waste more time to convey the building materials, compared to the others in this study. Moreover, the transporting quantity of the ready-mixed concrete was unable to be altered, since it was delivered by the standardised size of lorries (i.e., the Ready-mixed concrete mixer capacity is 5 m^3 in standardised size). On the other hand, different sized vehicles were able to be used flexibly for other building materials, depending upon the situation at the construction site.

Table 9. Emissions of carbon dioxide for transporting building materials (unit: kg CO_2 eq.).

Materials	Method 1			Method 2		
	ORC	FPS	VDS	ORC	FPS	VDS
Ready-mixed concrete	16,683	17,166	14,137	22,982	23,648	19,475
Rebars	5362	5094	4423	3650	3467	3011
Forms	2336	1168	1168	1161	1064	581
Steel decking	N.A.	N.A.	1839	N.A.	N.A.	1129
Void formers	N.A.	N.A.	1090	N.A.	N.A.	258
Total	24,381	23,428	22,675	27,793	28,179	24,454

3.4. Carbon Dioxide Emissions from the Utilisation of Construction Equipment on Site

The construction equipment used in this study were concrete pump trucks and vibrators for ready-mixed concrete, and cranes for the lifting and loading of rebars, forms, steel decking, and void formers on site. The reductions in the amount of total carbon dioxide emissions from the utilisation of construction equipment replacing the ordinary reinforced concrete slab by the flat plate slab and the voided slab systems were 3758 and 4913 kg CO_2 eq., respectively (see Table 10). The carbon dioxide emissions from utilising construction equipment were reduced by 3.6% and 10.1% for the flat plate slab and voided slab systems, respectively. The lowering of carbon dioxide for the flat plate slab and voided slab systems is associated with the reduction in the amount of ready-mixed concrete. In high-rise buildings, the utilisation of concrete pump trucks would be inevitable to convey ready-mixed concrete to the upper floors. In addition, the use of vibrators in concrete work is indispensable during the concrete pouring and curing steps to remove internal bubbles, and to prevent material segregation.

Table 10. Emissions of carbon dioxide from the construction equipment usage.

Materials	Emissions (kg CO_2 eq.)			Reduction (kg CO_2 eq.)	
	ORC	FPS	VDS	FPS-ORC	VDS-ORC
Ready-mixed concrete	10,737	11,050	9095	−313	1642
Rebars	1300	1198	1053	102	247
Forms	8349	4381	2714	3968	5635
Steel decking	N.A.	N.A.	2,535	N.A.	−2535
Void formers	N.A.	N.A.	77	N.A.	−77
Total	20,386	16,629	15,474	3757	4914

Moreover, the use of cranes was one of the significant factors to load and lift heavy building materials from the transporting vehicles to the upper floors. In the ordinary reinforced concrete slab, the large number of beams and girders was attributed to be the main factor to the use of a large volume of forms. For this reason, the emissions of carbon dioxide from cranes were higher for this slab system than for the other two slab systems (see Table 10). Similarly, in the voided slab system, the cranes were used to lift steel decking and the void formers. However, the emissions of carbon dioxide were less than for the two other methods, since the weights of both building materials (steel decking and void formers) were lighter than that of the forms in this study. Based on the results, in the emissions of carbon dioxide from the use of construction equipment, as the height of the building increased, it was inevitable to utilise concrete pump trucks and cranes. Hence, it would be important to minimise the lead time and intervals between activities during the construction work. For example, an effective strategy to reduce time waste during the construction process would be the adopting of principles and practices of lean construction [53–55].

3.5. Discussion

In this study, the variations of carbon dioxide emissions amongst the different slab systems were dependent upon reinforcing bars. The reason for the variance of reinforcing bars in the slab systems was that the application of rebars is due to the design requirements and standards [49,50]. Reinforcing bars are the most significant element in reinforced concrete structures to reduce vulnerability by increasing tensile strength. In particular, numerous beams and girders of reinforcement bars are embedded into the ordinary reinforced concrete slab. Beams and girders would distribute service and permanent loads of the slab, as well as resist external forces in a structure. However, the flat plate slab and voided slab systems would require lesser amounts of reinforcing bars over the ordinary reinforced concrete slab, as in both cases, the number of beams and girders were reduced. In particular, the decreased number of beams and girders in the flat plate slab and voided slab systems might not only require less quantity of rebars, but also a lesser amount of forms, which during the manufacturing of building materials would make it possible to reduce the carbon dioxide emissions.

Meanwhile, approximately 270,000 and 1400 kg CO_2 eq. for steel decking and void formers, respectively, were attributed to the voided slab system. The total amount of carbon dioxide generated from steel decking and void formers was almost the same as the emissions from reinforcing bars. In the case of the voided slab system, the total amount of carbon dioxide emissions was reduced by approximately 10%, even though the CO_2 generated from steel decking was quite large. Based on these results, ready-mixed concrete was the most significant factor in determining the overall reduction of carbon dioxide emissions in the different slab systems. Therefore, further design optimisation would be able to reduce the total carbon dioxide emissions of the building materials. Moreover, the application of high-strength materials, such as high-strength concrete and rebars, as well as recycled materials and by-products, would be a useful approach to mitigate the environmental impacts from building materials.

Table 5 shows that the carbon dioxide emissions from the transport of building materials were determined by the distance between the location of manufacturers and the construction site. Consequently, a potential way to reduce the carbon dioxide emissions from transporting the building materials would be in selecting the manufacturer who was proximate to the construction site. Moreover, the utilisation of imported building materials was beneficial to the economic perspective, which would reduce the cost of construction. However, the environmental loads from such material would have more environmental impact, compared to the domestically produced one. In this regard, further research to compare the domestic and imported building materials should be carried out to verify the influences, since the spatial restrictions are disappearing.

4. Conclusions

It is recognised that construction projects emit substantial volumes of carbon dioxide emissions. Various construction methods and alternatives have been suggested to minimise the emissions of carbon dioxide during construction work. A structural system of a building is a significant factor to not only sustain the entire building from external forces, but also to determine the quantities of building materials. Previous studies regarding structural systems have mainly focused on the structural performance, such as the flexural or shear capabilities of structures, and optimal design for workability during the construction stage, rather than the evaluation of environmental impacts by different structural systems. The purpose of this study was to evaluate the carbon dioxide emissions of different slab systems as a means of mitigating the environmental impacts of a high-rise commercial building project in South Korea.

The total carbon dioxide emissions of the three slab systems during the construction phase are comprised of the manufacturing of building materials, transporting of building materials to the construction site, and carbon dioxide emissions from the energy consumption of construction equipment. The results show the total CO_2 emissions of 3275, 3157, and 2943 tons CO_2 eq., which are equivalent to 242, 234, and 218 kg CO_2 eq., for the ordinary reinforced concrete slab, flat plate slab, and voided slab systems, respectively. The manufacturing of building materials is the main contributor of CO_2 emissions, which indicate 3,230,945, 3,117,203, and 2,905,564 kg CO_2 eq., respectively. Based on the results, approximately 3.7% and 10.1% reduction of carbon dioxide emissions would be achieved by replacing the ordinary reinforced concrete slab by the flat plate slab and the voided slab systems, respectively. In this context, the voided slab system would be able to achieve the most carbon dioxide reduction amongst three different slab system of this study.

Comparing the building materials in the three slab systems, the reinforcing bars and forms were significant building materials to reduce the CO_2 emissions in the flat plate slab and voided slab systems. In this study, reinforcing bars were the main contributor to lowering the carbon dioxide emissions in the flat plate slab and voided slab systems. Moreover, the emissions of carbon dioxide from transporting building materials were relatively small, compared to the manufacturing of building materials. However, it is recommended that the selection of location of material providers would contribute to lowering the CO_2 emissions from this stage. Based on the results of this study, the reduction potential of the voided slab system is the greatest amongst all the three different slab systems. Moreover, replacing the ordinary reinforced concrete slab system by alternative methods would make it possible to reduce the carbon dioxide emissions during the construction phase in building projects.

While this study was carried out on the evaluation and comparison of the carbon dioxide emissions from an actually designed building in South Korea, there is a limitation that should be addressed in future research. In order to verify the practicability and expand the applicability of the voided slab system in building projects, more cases need to be investigated in future studies. Moreover, life cycle assessment of the flat plate slab and voided slab systems during the operation and maintenance phases should be performed from the whole life cycle perspective of a building.

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