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Research Article

Evaluation of the Flexural Performance and CO_2 Emissions of the Voided Slab

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Reinforced concrete is regarded as one of the ideal structural materials which comprises concrete with high compressive strength and reinforcing bars with high tensile strength. However, concrete has been pointed out that it consumes a large volume of energy and emits a lot of carbon dioxide during its manufacturing. In order to lower such environmental burdens of concrete structures, a number of studies and approaches have been carried out. The voided slab is also suggested as a new method to reduce the environmental burden since voided section of the slab would use less concrete compared with the normal reinforced concrete slab. However, no studies have evaluated the CO_2 emissions and environmental performance of voided slabs. The purpose of this study was to evaluate the structural performance of voided slabs and empirically corroborate their environmental influence. The flexural performance test was carried out based on the variables of the depth of slab, types of the void former materials, and the hollowness ratio. In addition, comparison of the emission of CO_2 was also performed by considering the hollowness ratio and types of void former materials over the normal reinforced concrete slab. The structural performance of the voided slab was similar or slightly higher than the normal reinforced concrete slab. The yield strength of specimens was increased approximately 10~30% over the anticipated yield strength. Based on this result, it is considered that the voided slab would be sufficient to structural performance and beneficial to plane planning in buildings. In general, it is considered that the voided slab would be beneficial to both structural and environmental aspects. However, the test results in this research showed that the voided slab would emit more carbon dioxide emissions compared to the normal reinforced concrete slab. The main source of more CO_2 emissions in the voided slab was the anchoring materials. In this research, wires were used to fix the void former materials to the reinforcing bars. In order for the voided slab to become a more eco-friendly and sustainable material, new anchoring methods such as use of recycled materials, new void former materials without anchoring, or other eco-friendly materials should be applied to reduce the emission of CO_2.

1. Introduction

Reinforced concrete is regarded as one of the ideal structural materials and is commonly used in the architectural, engineering, and construction (AEC) industry [1, 2]. Reinforced concrete is a composite structure which comprises concrete with high compressive strength and reinforcing bars with high tensile strength. Reinforced concrete is highly useful not only because it can be structured in any form that the architect intends but also as it ensures a highly durable structure. Moreover, concrete is relatively inexpensive compared to steel and other construction materials, although there are various advantages such as a low corrosion rate, high fire resistance, and high water resistance. For these reasons, reinforced concrete has been chosen as a suitable material and used for a long time in the AEC industry.

However, studies have shown that concrete consumes a large volume of energy and emits large quantities of carbon dioxide [3–6]. In order to reduce the environmental burdens from concrete structures, a number of studies have been carried out and approaches tested. Kim et al. [7] suggested the I-slab system, which incorporates polystyrene forms in precast concrete panels to reduce the amount of concrete.

Various other researchers have also proposed new methods to reduce the amount of concrete, such as replacing normal-strength materials with high-strength materials, using by-products and recycled materials, and designing optimal structural systems to minimise construction materials [8–14]. For example, using high-strength concrete with added by-products such as silica fume or other by-products is one of frequently suggested approaches to enhance environmental performance of concrete. In addition, design and selection of optimal structural system would be one of the frequently suggested approaches to reduce the emission of CO_2 in the AEC industry [8, 15–18]. Baek et al. [15] propose that changing the block-type bearing wall system which is common to building apartment housing in South Korea to a column and beam system would reduce a significant amount of CO_2 emission during the construction stage. In a similar vein, Han and Kim [8] researched the emission of carbon dioxide from reinforced concrete structure and steel structure building. In this study, they showed that a steel structure building would emit relatively less CO_2 over the reinforced concrete building. Penadés-Plà et al. [16] indicate that optimal design of structural system would make it possible to lower the environmental impact even though the manufacturing stage of concrete box-girder would emit a large volume of carbon dioxide. Moreover, Molina-Moreno et al. [17] highlight the significance of low-carbon design for three aspects, which are structural performance, economic costs, and environmental impacts. Like other methods to minimise the amount of material used in the AEC industry, the voided slab is also suggested as a new method to reduce the environmental burden since voided section of the slab would use less concrete compared to the normal reinforced concrete slab [19–23]. Despite a number of studies regarding the voided slabs systems describing that the environmental friendliness of the voided slabs, it is sparse to corroborate the carbon dioxide emission of the voided slab by an empirical manner. The voided slab has also been suggested as a new method to reduce the environmental burden, since the voided section of the slab would use less concrete than a normal reinforced concrete slab [8, 15–18]. However, it is sparse that studies have evaluated the CO_2 emissions and environmental performance of voided slabs. The purpose of this study was to evaluate the structural performance of the voided slab by testing the flexural experiment and empirically corroborate their environmental influence.

2. Literature Review

The AEC industry is regarded as one of the main actors emitting large volumes of carbon dioxide and consuming a significant amount of energy [24]. The life cycle of a building can be divided into four distinctive phases: design, construction, operation and maintenance, and demolition or decomposition. Throughout the life cycle, the CO_2 emissions of a building are divided into embodied carbon and operating carbon. As a lot of new technologies have been developed and applied to newly constructed and existing buildings, the emissions of carbon dioxide from operating carbon have gradually shown a decreasing tendency [25, 26]. As a result of this, the proportion of embodied carbon in buildings is experiencing a relatively incremental trend. In order to reduce embodied carbon during building construction, various approaches have been suggested and researched, such as the using high-performance materials, material replacement, implementation of optimal design, and the application of structural system alternatives [5, 25–28].

A number of academics have proposed that an effective approach to reduce CO_2 emissions in the AEC industry is to replace conventional materials with low-carbon ones [11, 12, 28]. Enhancing the strength of materials, applying recycled substances or by-products, and planning the optimal design are popular methods for replacing materials to reduce CO_2. Cho and Chae [11] suggested application of recycled materials or industrial by-products and shortening the manufacturing process of materials to lower CO_2 emissions during construction. According to Kim et al. [28], using 60 MPa high-strength concrete would incur 1.5 times less CO_2 emissions compared with 24 MPa normal-strength concrete. In this research, when buildings with same area were constructed, the total amount of CO_2 emissions was reduced when using high-strength concrete since the amount of materials required decreased. The authors suggested three ways to reduce CO_2 emissions from construction: firstly, using high-strength concrete, which would lower the required quantity of concrete and rebars; secondly, an optimal mixture design, using admixtures such as blast-furnace slag; and lastly, taking the location of ready-mixed concrete into consideration, as this would lower emissions from transportation. Cho and Na [12] indicated that the application of high-strength reinforcing bars would reduce carbon dioxide emissions in reinforced concrete structure buildings. Their research showed that high-strength rebars lead to a reduction in the amount of materials needed, even though there was a slight increase in splice and development in connections.

Many researchers have emphasised the effectiveness of reducing CO_2 emissions through application of high-strength concrete. Tae et al. [5] evaluated the environmental impact of high-strength concrete by comparing energy consumption and CO_2 emissions in existing apartment housing in South Korea. They concluded that the application of high-strength concrete has a significant impact on the reduction of carbon dioxide emissions compared to normal-strength concrete. According to this research, the application of high-strength concrete would lead to the lowering of rebars in concrete, as well as cross section reduction of vertical members. They assert that pursuing material strength enhancement is an effective approach to minimise emission of carbon dioxide and energy consumption.

Additionally, Park et al. [29] analysed the CO_2 emissions of concrete based on different compressive strengths and seasonal attributes, and they proposed a formula to estimate the emissions of carbon dioxide based on the compressive strength of concrete. These researchers also considered seasonal characteristics, which would have a crucial impact on the emissions of CO_2 during the construction stage.

They suggested that construction during the winter season would emit much more CO_2 compared with other seasons in South Korea. According to them, the reason for this is the reduced application of admixture, increased inputting of cement, and longer curing time.

Along with the implementation of high-strength concrete, some researchers have proposed ensuring the optimal design of concrete and material selection in the design stage. González and Navarro [9] highlighted the significance of the early design stage for crucial decision-making about construction materials. Their research shows that appropriate materials selection would reduce approximately 28% of CO_2 emissions, compared with a building that was built without considering carbon dioxide emissions. In addition, Chau et al. [10] examined ten buildings to assess the relationship between construction materials and their environmental impacts in Hong Kong. According to them, concrete and reinforcing bars are the first and second contributors to the environmental impact of buildings throughout their life cycle. Since these are two major building materials, they concluded that it would be necessary to account for the environmental effects of concrete and rebars in building construction. They asserted that designers would have a significant role in reducing carbon dioxide emissions during building construction by selecting low-emission building materials, thus improving sustainability.

There are also other approaches to reduce CO_2 such as recycling and developing optimal design programmes. Lee et al. [30] considered the life cycle of apartment housing and suggested CO_2 reduction strategies in South Korea. They proposed not only the extension of the service life of the building but also recycling the concrete as sub-base material or aggregates after demolition of the building. Similar to Lee et al. [30], Yan et al. [31] compared the emissions of carbon dioxide between residential and commercial buildings. In their research, they suggested that utilisation of recyclable, rather than nonrecyclable, materials would be ideal for reduction of CO_2 emissions.

While CO_2 reduction strategies such as selection of alternative materials and optimizing design might be considered a micro-perspective, there is also a "macro-approach," which considers the entire building system rather than its individual parts or materials. Nadoushani and Akbarnezhad [14] studied the relationships between different structural systems and CO_2 emissions. In this research, they indicated the significance of comprehensive assessment of embodied carbon and operating carbon for choosing the optimal structural materials during structural design. Moreover, Han and Kim [8] examined the total carbon dioxide emissions of different structural types for apartment and office buildings in South Korea. The test results showed that steel structure buildings emitted less carbon dioxide than reinforced concrete structures. Moreover, the authors proposed that using high-strength materials (e.g., high-strength concrete and reinforcing bars) would be an effective method to minimise CO_2 emissions in reinforced concrete structures.

Cole [32] examined [33] not only energy consumption and greenhouse gas emissions of different structural systems but also energy consumption during transportation and from construction personnel. In this study, the author showed that concrete structures consumed the highest energy as well as emitted the largest volume of CO_2 during construction. In contrast, steel structures consumed the lowest energy and emitted the lowest CO_2 among concrete, wood, and steel structures. The author inferred that "the more labour intensive a process, the greater the amount of worker transportation." Baek et al. [15] compared different structural types of apartment buildings in South Korea. According to them, structural system has a significant influence on lowering carbon dioxide emissions in the construction phase. In this research, apartment houses built with a column and beam system emitted less CO_2 than bearing wall systems. They also suggested that the application of high-strength concrete and adding blast furnace slag would be beneficial to reduce CO_2 emissions.

3. Materials and Methods

3.1. Assessment of Structural Performance of the Voided Slabs

3.1.1. Flexural Performance Test. In this study, the depth of slab, type and presence of void former materials, and hollowness ratio were used as the main variables to test the flexural strength of concrete slab specimens. The details of the dimensions and properties of the specimens are summarised in Table 1, and Figure 1 shows cross-sectional diagrams of the specimens. The tested specimens were 4230 mm in length and 700 mm in width. The depth of slabs varied between 169 and 210 mm.

To evaluate the flexural performance of the voided slab specimens, the test specimens were simply supported as shown in Figure 2, and four-point bending tests were conducted. The applied load to the specimens was monotonic loading which used an actuator with a capacity of 100 kN resisted by a steel frame with a capacity of 200 kN. The applied load was at a relatively low deflection rate of 2.0 mm/min for accurate examination of the initial flexural behavior before and immediately after the initial flexural cracklings. A load cell with a capacity of 100 kN was used to obtain the load data. In order to receive the displacement of the slabs, a linear variable differential transformer (LVDT) was installed under the specimens. The LVDT in this research was able to measure up ranges of 200 mm of the displacement. The data were gathered by a data logger (Tokyo Sokkie).

All the specimens were reinforced by 10 mm and 13 mm deformed bars, and $\phi 6$ wires were used as a means to anchor the void formers to the upper and lower reinforcing bars. Details of the void former materials and their anchoring are depicted in Figure 3.

3.1.2. Properties of Materials. The detailed characteristics of the materials used in the voided slab are shown in Table 2. The concrete had a designed compressive strength of 27 MPa and comprised 333 kg/m^3 ordinary Portland cement, 821 kg/m^3 fine aggregate, 1086 kg/m^3 coarse aggregate, and 108 kg/m^3

Table 1: Properties of specimens.

Specimens	Type of slab	Depth of slab (mm)	Specification of void former materials
S1	Normal reinforced concrete slab	210	—
S2	Voided slab	210	Sphere shape Diameter 100 mm
S3	Voided slab	210	Oblate shape Diameter 170 mm Height 110 mm
S4	Normal reinforced concrete slab	169	—

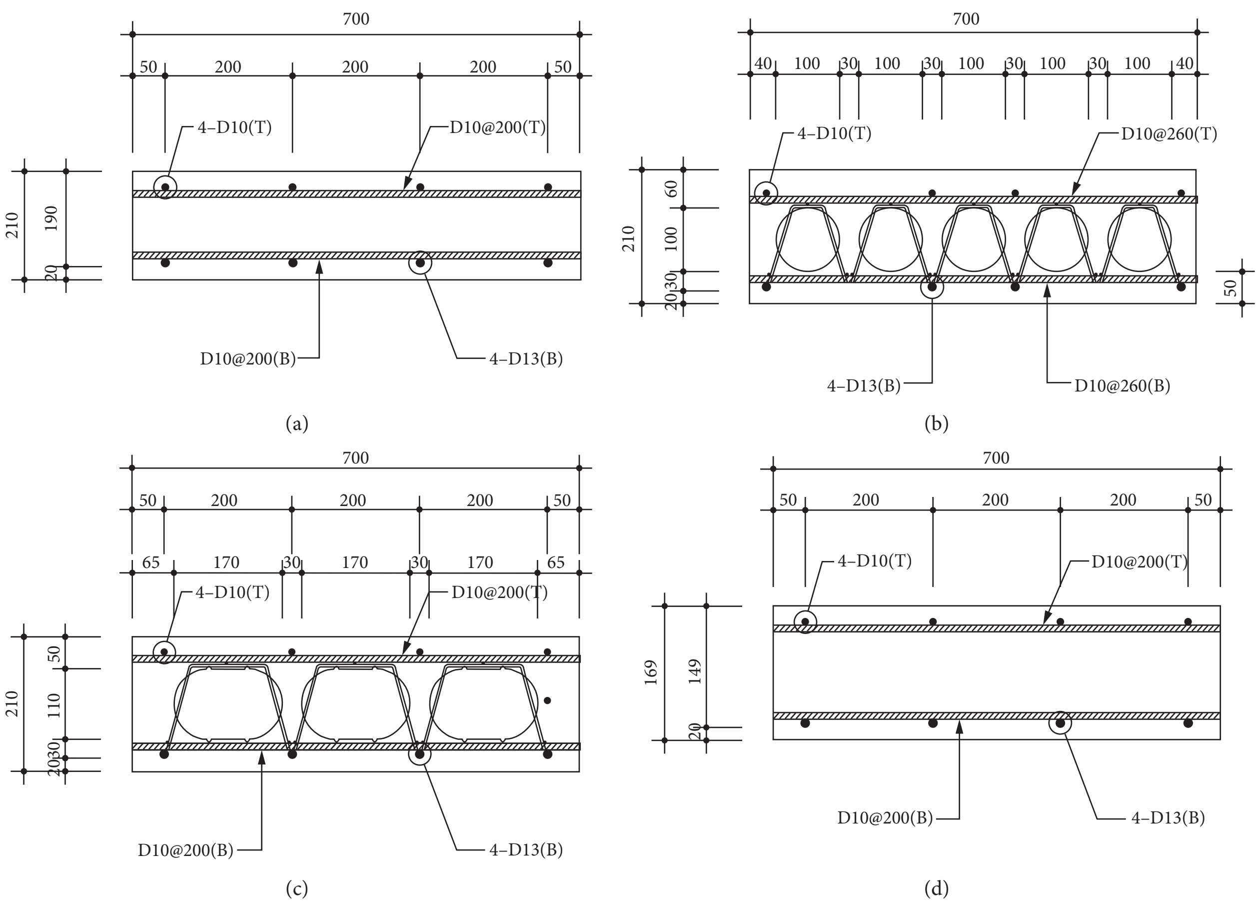


Figure 1: Details of the specimens. (a) S1. (b) S2. (c) S3. (d) S4.

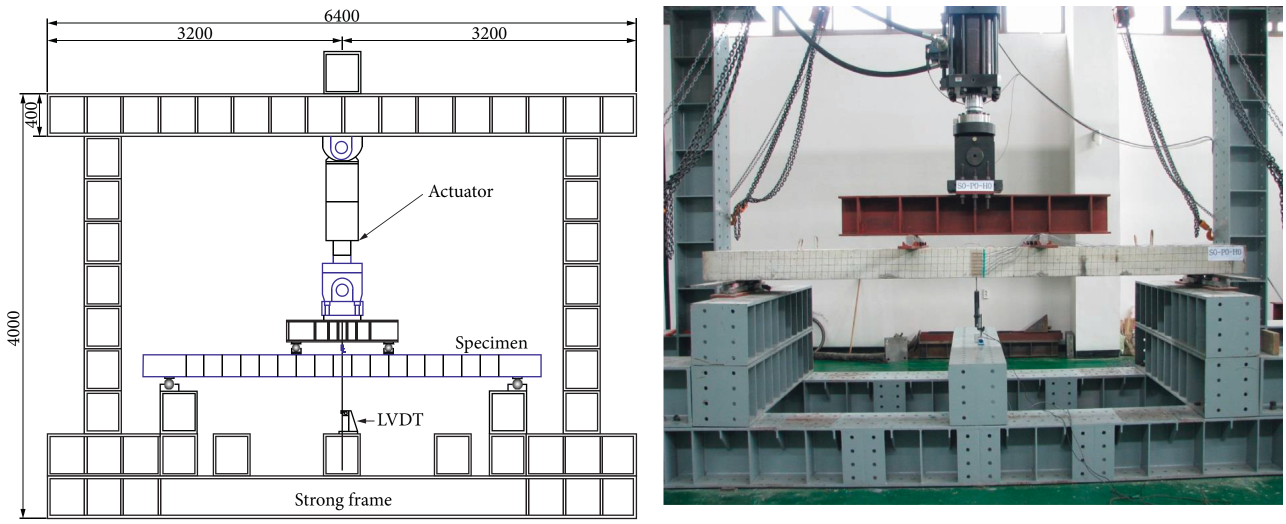
water. The tested compressive strength was 35.16 MPa after 28 days curing in a water bath. The slump and the entrapped air void were 80 mm and 2%, respectively (Table 2).

The reinforcing bars used in the specimens were named D10 and D13 based on the diameter; their nominal yield strength was $f_y = 400$ MPa. According to the direct tension test specified in KS B 0802 [29], the ultimate tensile strength of the reinforcing bars used in this research was 630–651 MPa (Table 3).

3.2. Evaluation of CO_2 Emissions in the Voided Slabs

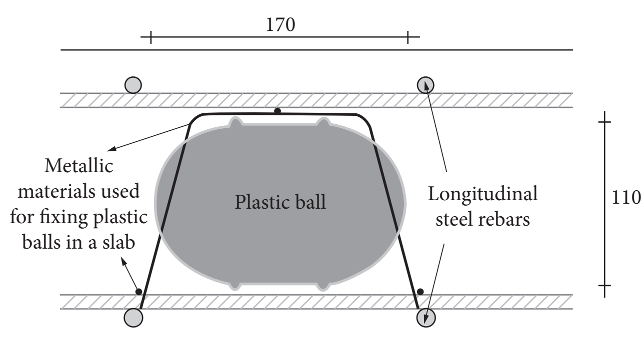
3.2.1. A System Boundary. It is necessary to calculate the life cycle of voided slabs to evaluate their CO_2 emissions. Based on ISO 14044 [34] and ISO 21930 [35], the system boundary of voided slabs was determined as the product stage of voided slabs (i.e., cradle to gate). The production stage of voided slabs is divided into three broad stages, which are the raw materials, transportation, and manufacturing stages. CO_2 assessment of the first stage requires evaluating the CO_2 of each ingredient in the voided slab. The raw materials of voided slabs are the mixed ingredients of concrete (i.e., cement, aggregates, admixture, and water), reinforcing bars, and void former materials (i.e., high-density polyethylene and expanded polystyrene). Each material was weighed in a certain ratio in compliance with the mix design of concrete and casted into cement moulds to produce voided slabs.

The transportation stage refers to CO_2 emissions during transporting the ingredients of voided slabs to the



(a) (b)

Figure 2: Test setting of the voided slab. (a) Flexural test setup diagram (unit: mm). (b) Test setting and loading configuration.



(a) (b)

Figure 3: Details of the void former materials and anchoring. (a) Details of the void former materials and anchoring. (b) Photo of the void former materials

Table 2: Design of concrete mixture.

Designed compressive strength (MPa)	w/c (%)	s/a (%)	Unite content (kg/m^3)					Air content (%)
			Water	Cement	Fine aggregate	Coarse aggregate	Admixture	
27	45.7	44.3	108	333	821	1086	3.33	2.0

Note: w/c is the water/cement ratio, and s/a is the sand/aggregate ratio.

Table 3: Specifications and test results of reinforcing bars.

Types	Diameter (mm)	Yield strength (MPa)	Ultimate strength (mm)
D10	10	519	630
D13	13	531	651

manufacturing site. These occur during the manufacturing of the voided slabs from the electricity, gas, oil, etc., used in the manufacturing plant. The system boundary of life cycle CO_2 emissions of voided slabs is depicted in Figure 4.

3.2.2. Raw Materials Stage. Carbon dioxide emissions from the raw materials of voided slabs were calculated as the sum of the quantity of individual components, which were concrete, reinforcing bars, and void formers. The CO_2 emissions of concrete were evaluated through the sum of multiplication of the quantity of each ingredient utilised for producing 1 m^3 of concrete and the CO_2 emission factor for producing concrete. The following equation was used for computation of the CO_2 emissions of a unit of concrete:

$$CO_2 M = \sum \left(M(i) \times CO_2 \text{emission factor } M \right), \quad (1)$$

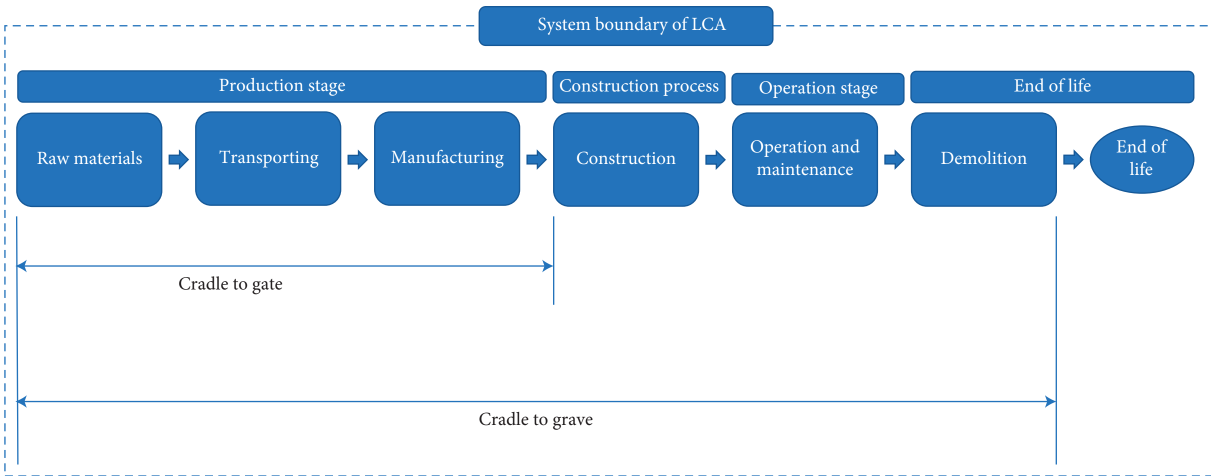


FIGURE 4: The system boundary of the voided slabs.

in which CO_2M (kg-CO_2/m^3) is the quantity of CO_2 emissions during the raw materials stage; M ($i = 1$: cement, 2: aggregate, 3: chemical admixture, 4: water, 5: reinforcing bar, 6: HDPE) is the amount of each material used to produce the concrete (kg/m^3); and CO_2 emission factor M (kg-CO_2/kg) is the CO_2 emission factor of each material used during the production of concrete.

The CO_2 emission factors of cement, aggregates, and water given in the Korea Life Cycle Database (LCI DB) [36] were applied. Since the CO_2 emission factor for chemical admixture was not listed in the Korea LCI DB, the overseas LCI DB [37] was applied to the chemical admixture. Table 4 shows the source of LCI DB for the individual ingredients of concrete.

TABLE 4: Reference of life cycle inventory database.

Material	Unit	Source
Ordinary Portland cement	kg	The Korea LCI DB (South Korea)
Coarse aggregate	kg	The Korea LCI DB (South Korea)
Fine aggregate	kg	The Korea LCI DB (South Korea)
Chemical admixture	kg	Overseas LCI DB (ecoinvent)
Water	kg	The Korea LCI DB (South Korea)
HDPE	kg	The Korea LCI DB (South Korea)
Iron wire	Kg	The Korea LCI DB (South Korea)

3.2.3. Transportation Stage. The CO_2 emissions of transportation occur as individual components of the voided slabs are delivered to the manufacturing site. The number of vehicles, distance from the origin to the manufacturing plant, and fuel efficiency of each vehicle were considered when assessing CO_2 emissions. The speed of the vehicles and the traffic situation were not considered. Equation (2) was used to calculate the CO_2 emissions from the transportation stage of the voided slabs:

$$CO_2T = \sum\left[\left(\frac{M(i)}{L_t}\right) \times \left(\frac{d}{e}\right) \times CO_2 \text{ emission factor } T\right]. \tag{2}$$

Here, the quantity of CO_2 emitted from transporting a unit of manufactured voided slab is CO_2T (kg-CO_2/m^3); the quantity of material applied in the voided slab is M ($i = 1$: cement, 2: aggregate, 3: chemical admixture, 4: water, 5: reinforcing bar, 6: HDPE) (kg/m^3); the transported load is L_t (tons); the transportation distance is d (km); e is the fuel efficiency of the transportation method (km/L); and CO_2 emission factor T (kg-CO_2/kg) is the CO_2 emission factor of the energy resource consumed by the transportation method.

3.2.4. Manufacturing Stage. The CO_2 emission of voided slabs from the manufacturing process is the sum of consumed energy and unloading of raw materials and manufacturing of reinforcing bars and HDPE. The energy consumption of the manufacturing process was estimated based on the process of manufacturing which was divided into loading, storage, transportation, and mixing. The types of energy sources used in the voided slabs manufacturing process were electricity, diesel, liquefied natural gas (LNG), and water. The calculation of CO_2 emissions during the manufacturing is shown in the following equation:

$$CO_2F = \sum\left[\left(\frac{E(i)}{R}\right) \times CO_2 \text{ emission factor } F\right], \tag{3}$$

here, CO_2F is the amount of CO_2 occurring from a unit of voided slab manufacturing stage (kg-CO_2/m^3); $E(i)$ represents the annual energy usage (unit/year); R (m^3/year) denotes the annual production of concrete; and CO_2 emission factor F is the CO_2 emission factor of each energy resource (kg-CO_2/kg).

4. Results

4.1. Structural Analysis of the Voided Slabs. The flexural test results of the voided slab specimens are summarised in Table 5 and Figure 5. The overall trend of cracking in the

Table 5: Test results of flexural performance.

Specimens	Initial cracking		Yield load		Ultimate load	
	Load (kN)	Displacement (mm)	Load (kN)	Displacement (mm)	Load (kN)	Displacement (mm)
S1	14.4	1.5	53.9	24.3	73.3	216.4
S2	9.2	1.0	60.7	34.0	70.3	141.8
S3	5.6	0.7	46.0	29.2	54.5	175.1
S4	5.4	0.7	38.1	40.4	45.6	213.2

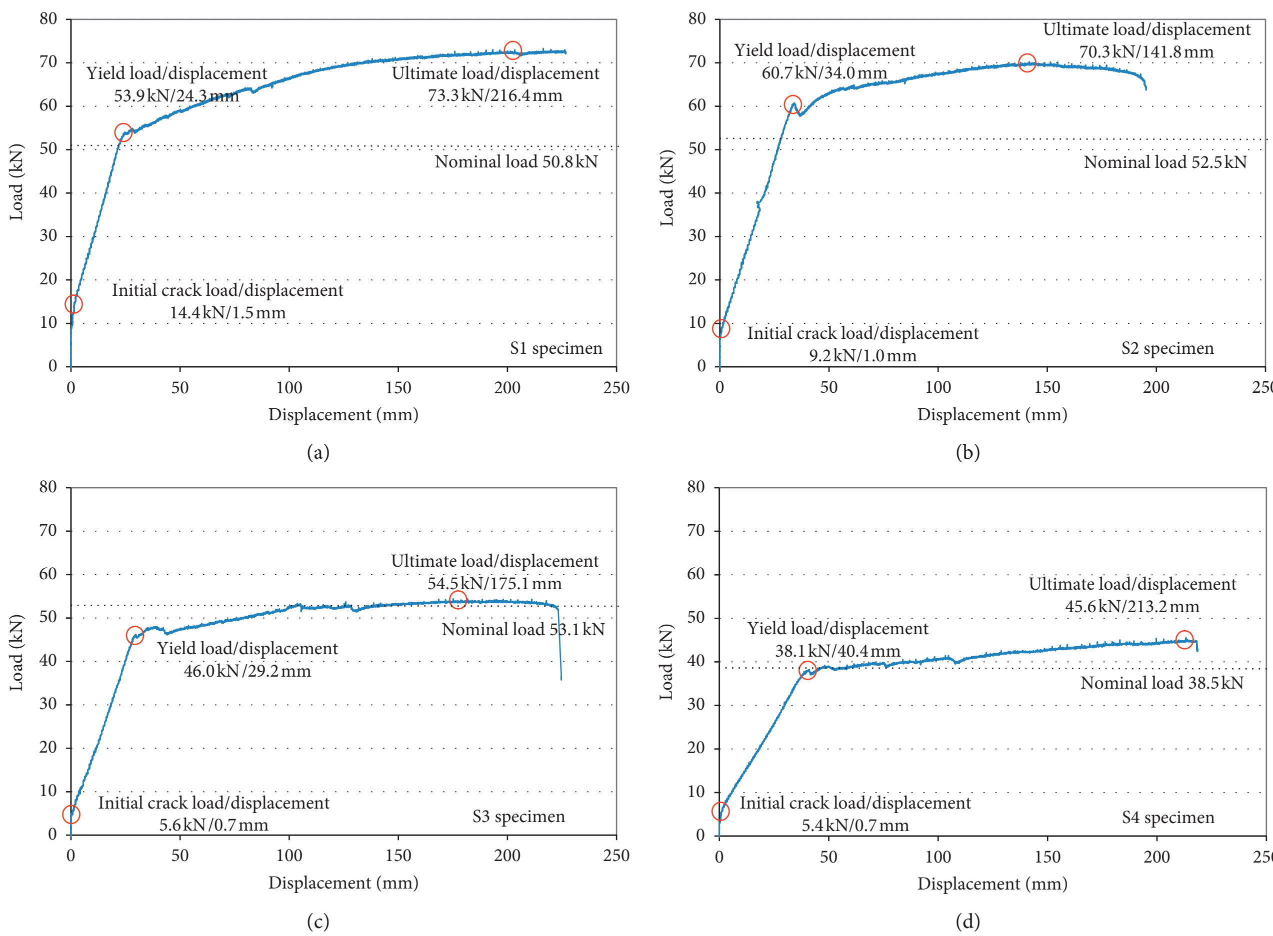


Figure 5: Load-displacement curves of specimens. (a) S1 specimen. (b) S2 specimen. (c) S3 specimen. (d) S4 specimen.

specimens indicated that, after initial flexural cracking occurred in all specimens, cracking gradually expanded to both ends as the loads increased. When flexural yielding occurred, the strength of specimens increased approximately 10–30% compared to the reference specimen S1, followed by flexural fracture in all specimens.

The comparison between the expected value of cracking strength and yield strength, calculated in accordance with the Structural Concrete Design Code and Commentary in South Korea [38], and the actual experimental values of the voided slabs are summarised in Table 6. According to the test results, the experimental value of each specimen was higher than the anticipated load. The experimental ultimate strength was about 115–139% of the yield strength of the specimens. A likely reason that the ultimate strength observed in the experiment exceeded the expected strength is that the wires that anchored the void formers influenced the strength of the voided slab.

4.2. Analysis of CO_2 Emission of the Voided Slabs. The CO_2 emissions of each component of the voided slab were 334.0749 kg-CO_2/m^3 for concrete, 2.5266 kg-CO_2/kg for D10 reinforcing bars, 2.4858 kg-CO_2/kg for D13 reinforcing bars, 2.034 kg-CO_2/kg for wires, and 2.06 8kg-CO_2/kg for HDPE (Tables 7 and 8). The CO_2 emissions of reinforcing bars were calculated using input-output analysis.

Table 6: Comparison between anticipated and actual values.

Specimen	A Anticipated strength (kN)	B Anticipated strength with anchoring (kN)	C Ultimate strength (kN)	C/A	C/B
S1	50.8	—	73.3	1.443	—
S2	52.5	59.6	70.3	1.339	1.180
S3	53.1	57.5	54.5	1.026	0.948
S4	38.5	—	45.6	1.184	—

Table 7: CO_2 emission of concrete in product stage.

Items	Raw materials			Transportation			
	A kg/unit	B kg-CO_2/kg	C = A ∗ B kg-CO_2/unit	D Location	E km	F kg-CO_2/kg-km	G kg-CO_2/kg
Concrete							
Ordinary Portland cement	333.000	0.948000	315.6840	Damyang	277.00	$6.06 * 10^{-5}$	5.590
Fine aggregate	821.000	0.000152	0.124792	Hadong	322.00	$1.16 * 10^{-5}$	3.067
Coarse aggregate	1086.00	0.007740	8.405640	Gyeonggi, Gwangju	37.60	$1.16 * 10^{-5}$	0.474
Chemical admixture	3.330	0.002050	0.006826	Gyeonggi, Anseong	66.000	$1.16 * 10^{-5}$	0.003
Sub sum			324.232274				9.133
Manufacturing	1 m^3	0.71 kg-CO_2/FU	0.710000				
Total			334.078975				

Table 8: CO_2 emission of voided slabs components in product stage.

Items	CO_2 emission	Transportation			D = A ∗ B ∗ C
		A Location	B Distance	C Factor	
HDPE	1.875	Shihwa	70.40	$2.735 * 10^{-3}$	0.193
		CO_2 emission + D			2.068
Wire	1.732	Dangjin	110.54	$2.735 * 10^{-3}$	0.302
		CO_2 emission + D			2.034
Rebar D10	2.5266	Dangjin	110.54	$2.735 * 10^{-3}$	0.302
		CO_2 emission + D			2.8286
Rebar D13	2.4858	Dangjin	110.54	$2.735 * 10^{-3}$	0.302
		CO_2 emission + D			2.788

4.2.1. CO_2 Emissions of the Voided Slabs with Consideration of Anchoring

(1) Overview of CO_2 Emissions. The CO_2 emissions of all specimens are summarised in Table 9. The total amount of concrete used in specimen S1 was 0.21 m^3, and the amounts of reinforcing bars used in S1 were 8.38 kg of D10 and 4.97 kg of D13. Based on the materials used in the specimen S1, the total emissions of carbon dioxide from S1 were 107.15 kg-CO_2/FU. In the case of S1, concrete accounted for the highest proportion of the volume. The amount of CO_2 emissions from concrete was 69.59 kg-CO_2, which accounted for 69.94% of the total CO_2 emissions (Figure 6).

The specimen S2 was made of voided slab of approximately 16% hollowness ratio. In this specimen, 64 spherical void formers of 100 mm diameter were used to fill the hollow sections of the slab. The volume of concrete used was 0.17 m^3, approximately 0.04 m^3 less than that used in the reference model S1. Reinforcing bars applied in the S2

Table 9: The CO_2 emissions of specimens (unit: kg-CO_2/FU).

Ingredients of the voided slab	S1	S2	S3	S4
Concrete				
Volume (m^3)	0.21	0.17	0.16	0.17
CO_2 emissions (kg-CO_2)	69.59	57.66	53.36	55.89
Rebars				
D10				
Weight (kg)	8.38	6.71	8.38	8.38
CO_2 emissions (kg-CO_2)	23.72	18.97	23.72	23.72
D13				
Weight (kg)	4.97	3.97	4.97	4.97
CO_2 emissions (kg-CO_2)	13.85	11.08	13.85	13.85
Wires				
Weight (kg)	—	19.86	7.76	—
CO_2 emissions (kg-CO_2)	—	34.42	13.44	—
HDPE				
Weight (kg)	—	3.90	3.98	—
CO_2 emissions (kg-CO_2)	—	7.31	7.45	—
Total emissions (kg-CO_2/FU)	107.15	129.44	111.82	93.45

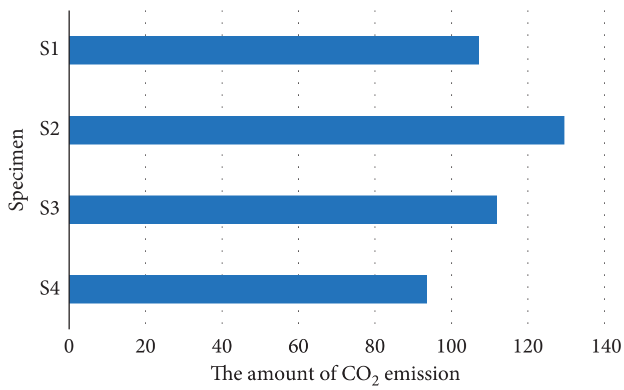


Figure 6: Total CO_2 emissions with anchoring.

specimen were 6.71 kg of D10 and 3.97 kg of D13. In addition, 19.86 kg of wires (ϕ6) were also used to address buoyancy of the void formers in the specimens. The CO_2 emissions of the specimen S2 were 129.44 kg-CO_2/FU. In this specimen, quite a large amount of wires was applied to anchor the void formers, which is the reason that the CO_2 emissions were higher than the ordinary reinforced concrete slab specimen S1.

The specimen S3 was voided slab model with about a 22% hollowness ratio, including 25 oblate shape void formers. The oblate shape void formers were 170 mm in length and 110 mm in height, and each component had a volume of 1,903,594 mm^3. The concrete applied in the S3 specimen was 0.16 m^3, and the quantity of CO_2 emitted from this concrete was 53.36 kg-CO_2. The rebars used in the S3 specimen were 8.38 kg for D10 and 4.97 kg for D13. The CO_2 emissions of each type of reinforcing bars in specimen S3 were 23.72 kg-CO_2 for D10 and 13.85 kg-CO_2 for D13. The total CO_2 emissions from deformed bars were 37.57 kg-CO_2. Furthermore, 7.76 kg of wires (ϕ6) was used to anchor the void formers in the section of the slab, from which the amount of carbon dioxide emissions was 13.44 kg-CO_2. Based on these data, the total amount of carbon dioxide emissions from the S3 specimen was 111.82 kg-CO_2/FU.

The S4 specimen was made of 0.17 m^3 of concrete which was comparable with the amount of concrete used in the S2 and S3 specimens. It was designed to compare the structural performance with the voided slabs. The mass of the reinforcing bars applied to the S4 specimen was 8.38 kg for D10 and 4.97 kg for D13. The carbon dioxide emitted by the S4 specimen was 93.45 kg-CO_2/FU.

(2) Comparisons of the CO_2 Emissions with Anchoring. The hollowness ratio is one of the most significant characteristics regarding the voided slab. In this study, the hollowness ratio of the specimens was established 0, 15.96, and 22.66% for the S1, S2, and S3 specimens, respectively. The CO_2 emissions from each sample showed distinctive features dependent upon the ratio of hollowness. Figure 7 shows the overall tendency of CO_2 emissions of the specimens based on the hollowness ratio of the slabs.

The first specimen, S1, was an ordinary slab which is normally applied to reinforced concrete buildings in South Korea. The depth of this slab was 210 mm, which is the minimum depth of slab for prevention of noise complaints between floors of apartment housing in South Korea. The emitted carbon dioxide from the S1 specimen was 107.15 kg-CO_2/FU. Concrete was the highest carbon dioxide emitter among all of the components of this reinforced concrete slab. Reinforcing bars were the second largest source of CO_2 emissions in this specimen.

The S2 and S3 models were voided slab specimens that showed 129.44 kg-CO_2/FU and 111.82 kg kg-CO_2/FU, respectively. The S2 specimen had a 15.96% ratio of hollowness to the total volume of concrete. The hollow section of the slab was filled with void formers made from HDPE. The void formers were spherical, with 100 mm diameter, and 64 balls were inserted in the specimen. Twenty-five oblate shape void formers were buried in the S3 slab to create a ratio of 22.66% hollowness to concrete. The size of each component was 170 mm in length and 110 mm in height. All the void formers in both specimens were anchored by wires to prevent buoyancy or separation between reinforcing bars during the placing and curing of concrete. The amount of concrete used in the specimens was 0.17 m^3 for S2 0.16 m^3 for S3, respectively. Based on the reduction of concrete use in the slab, approximately 12 and 16 kg-CO_2/FU less CO_2 were emitted from the S2 and S3 specimens, respectively. As the CO_2 emissions from concrete decreased as the concrete use was reduced, the emissions from concrete also decreased in response to this tendency. However, the total CO_2 emissions from specimen S2 and S3 were higher than those in the S1 specimen. The S2 specimen showed about 21% increase of carbon dioxide emissions compared to the S1 specimen.

In addition, the S3 voided slab indicated approximately a 4% rise of CO_2 emissions over the S1 specimen. The reason for the increase of CO_2 emissions in the voided slabs might be the application of wires for anchoring the void formers. It is unavoidable for voided slabs to utilise anchoring materials such as wires, deck-plate, and wire mesh; for example, in this research, wires were utilised for the anchoring component of the voided slab. The amount of wires applied in both voided slab specimens was quite large: 19.86 kg for S2 and 7.76 kg for S2. Based on these data, the emitted carbon dioxide from the S2 and S3 specimens was 34.42 kg-CO_2 and 13.44 kg-CO_2, respectively. These results show that about 27 and 12% more carbon dioxide was emitted from anchoring wires, and anchoring wires accounted for a significant proportion of CO_2 emissions in the voided slab (Figure 8). In other words, wires for anchoring void formers to reinforcing bars were a source of large volumes of CO_2 emissions in the voided slab specimens.

Furthermore, the CO_2 emissions of the voided slab exhibited different features depending upon the shape of the void formers. Two different shapes of materials were applied to fill the hollow section of the concrete slab in this research. The S2 specimen, into which spherical void formers were inserted, showed higher CO_2 emissions than the S3 specimen, into which oblate shape ones were inserted. Oblate shape materials emitted approximately 18 kg-CO_2/FU less carbon dioxide than spherical ones. The reason for higher emissions of CO_2 from spherical materials might be that the

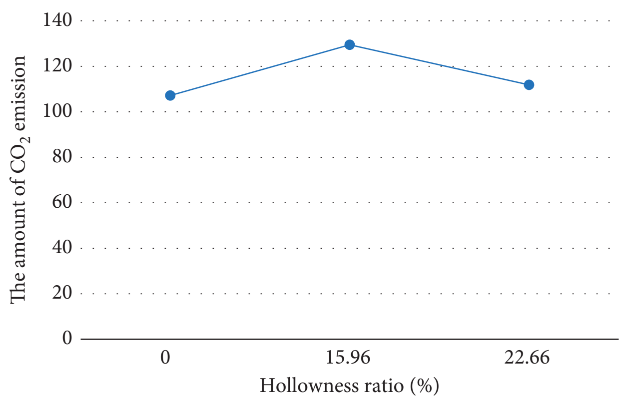


FIGURE 7: CO_2 emission variation based on hollowness ratio.

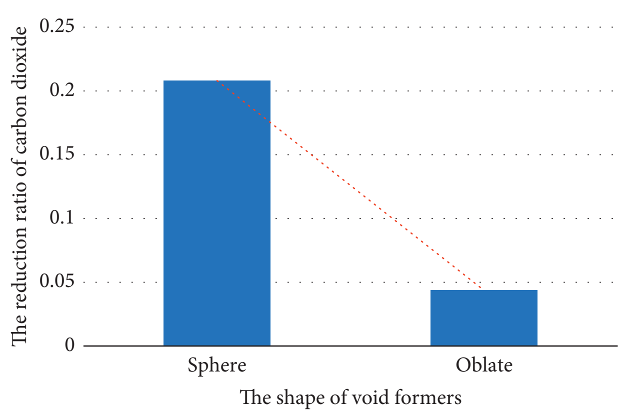


FIGURE 8: CO_2 emissions reduction ratio by the shape of void former materials.

individual spherical void formers were smaller than the oblate shape ones. As the size of each former was smaller, more anchoring wires may have been required to harness the formers in the voided slabs overall. As shown in Table 9, about 19.86 kg of wires were used in the S2 specimen, which was about 13 kg more than that in the S3 specimen. Moreover, the carbon dioxide emission of reinforcing bars and wires is different depending on their size. The CO_2 emissions of steel materials in construction works such as reinforcing bars, wires, wire mesh, and so forth might increase as the diameter of rebars or wires decreases [12, 39]. In this research, quite a large amount of smaller size wires was applied to anchor, and this might be a significant reason for the observed increase in carbon dioxide emissions.

(3) Comparisons of the CO_2 Emissions without Anchoring. Considering the CO_2 emissions in terms of the pure hollowness, which refers to the void slab without considering the utilisation of anchoring materials, the amount and characteristics of carbon dioxide emissions were considerably different than when anchoring materials were considered. Figure 9 shows total carbon dioxide emissions of the specimens without consideration of anchoring wires.

The CO_2 emissions of S2, S3, and S4 specimens were 95.0241, 98.3753, and 93.4536 kg-CO_2/FU, respectively. The

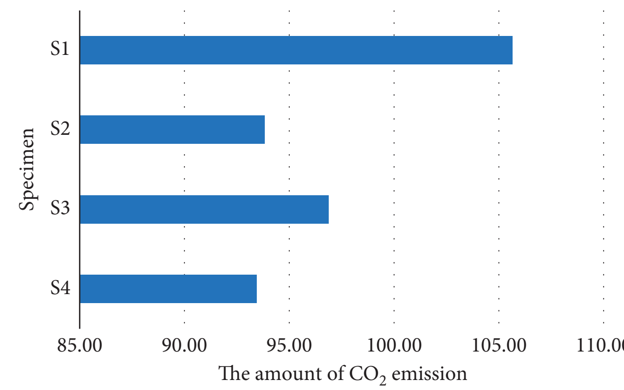


FIGURE 9: Total CO_2 emissions without anchoring.

reduced amount of CO_2 compared to the reference model S1 was 12.1265 kg-CO_2/FU for S2, 8.7754 kg-CO_2/FU for S3, and 13.6971 kg-CO_2/FU for S4 (Figure 9). When the CO_2 reduction ratio was considered, S2 and S3 showed 11.32 and 8.19% reduced amounts of CO_2 versus the reference model, S1 (Figure 10). Since concrete was one of the main sources of CO_2 emission in reinforced concrete structures, removal of concrete would seem to have a significant impact on the reduction of carbon dioxide emissions. While the void formers accounted for quite a large volume in the voided slab, the CO_2 emissions from the void formers was of smaller proportion because the thickness of each material was only 20 mm.

In summary, the CO_2 emissions of higher void ratios were lower in this research. The reason for this tendency is the application of more anchoring materials, since the size of the individual components in the higher hollowness ratio was smaller than in the lower hollowness ratio. Thus, more utilisation of materials led to the occurrence of more carbon dioxide emissions in this research.

5. Discussion and Limitations

It is generally known that voided slabs are environmentally friendly and beneficial for a sustainable environment. In addition, utilisation of less concrete would lead to lower energy consumption and carbon dioxide emissions from voided slabs. However, the carbon dioxide emissions of voided slabs showed higher CO_2 emissions compared to normal reinforced concrete slabs in this research.

The structural performance of the voided slab proved to be comparable to a normal reinforced concrete slab. In this study, the flexural performance of the voided slab was similar or slightly higher than the normal reinforced concrete slab. From a structural perspective, the voided slab would be appropriate to apply to long span structures due to its light weight, as well as to prevent noise complaints between floors in apartment housing in South Korea. Moreover, the application of the voided slab would make it possible to remove beams in reinforced concrete structure. The voided slab is thus an alternative to lightweight materials.

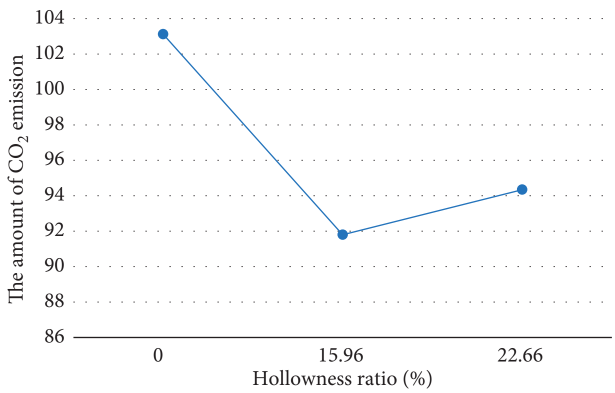


Figure 10: CO_2 variation by void ratio without anchoring.

When comparing the carbon dioxide emissions of normal reinforced concrete slab and voided slab, the CO_2 emissions of the voided slab were higher than those of the normal reinforced concrete slab, considering all the materials used in the voided slab such as concrete, void former materials, reinforcing bars, and wires for anchoring. In particular, the amount of anchoring wires to manage buoyancy occupied a considerable proportion of the total amount of carbon dioxide emissions, approximately 25% in each specimen. Based on these results, replacing or reducing current anchoring materials to more environmentally friendly ones should be considered to lower the amount of CO_2 emissions in the voided slab.

Additionally, the variation of carbon dioxide emissions by the application of different types of void formers (i.e., spherical and oblate shape) was studied. In this study, oblate shape void formers emitted 4.35% in S2 and 20.80% in S3 additional carbon dioxide. Since the overall size of the spherical type was smaller than the oblate one, more wires were used to anchor the void formers to the reinforcing bars. The anchoring wires were one of the main sources of CO_2 emissions in the voided slab.

It is normally considered that plastics or other petrochemical products might be less effective than other materials for environmental performance. The CO_2 emission per unit weight of petrochemical material (i.e., HDPE in this study, which was used for void materials) was higher than other components of voided slab. However, the amount of HDPE applied in the specimens was smaller than other materials such as concrete, reinforcing bars, and wires. Thus, the influence of carbon dioxide emissions of HDPE in the voided slab was not significant compared to other materials.

In order for the voided slab to meet both environmental and structural performance requirements, current anchoring methods using wires, deck-plate, cable ties, and so forth should be replaced with more eco-friendly or recycled materials. Additionally, other methods to connect void former materials directly to reinforcing bars should be developed, in order to reduce the application of anchoring materials in the voided slab. Based on such research approaches, further studies should consider the optimal design of the voided slab with using optimal materials which would meet both structural and environmental performance.

This research was limited to the slab component of a building, but further studies should be carried out to confirm the reduction of construction materials and variation of carbon dioxide emissions in the entire building through application of the voided slab. Although this study only focused on the case of South Korean construction industry, this study would also provide a useful reference for assessing the emission of CO_2 from the voided slab to other countries. It is considered that further studies should be also carried out to validate the cases of voided slab in other countries.

Moreover, this study only dealt with the emission of carbon dioxide for the voided slab during the manufacturing phase. However, it is recently considered that the significant impact of operational carbon of a building's life cycle. As for this reason, further research should be conducted to assess the influence of operational carbon for the voided slab system compared to the normal reinforced concrete structure. Along with the consideration of operational carbon for the voided slab system, other factors such as geographical aspect which would impact the transportation distance and energy consumptions.

6. Conclusions

The purpose of this research was to confirm the flexural performance as well as the variation of carbon dioxide emissions from voided slabs. The flexural performance was assessed based on the variables of the depth of slab, types of the void former materials, and hollowness ratio. In addition, CO_2 emission comparisons were also conducted considering the hollowness ratio and types of void formers compared to the normal reinforced concrete slab. The system boundary of the voided slab was limited to the production stage, known as cradle to gate, in accordance with ISO 14044 [30].

The structural performance of the voided slab was similar or slightly better than the normal reinforced concrete slab. The yield strength of specimens increased approximately 10–30% over the anticipated yield strength. Based on this result, it is considered that the voided slab has sufficiently good structural performance and would be beneficial to planning in buildings.

The results of assessment of the CO_2 emissions showed that the voided slabs emitted more carbon dioxide compared to the normal reinforced concrete slab, regardless of the hollowness ratio and the types of void formers. In this research, the slab with a higher hollowness ratio emitted less carbon dioxide emissions than that with a lower hollowness ratio. Additionally, the voided slab would require additional materials to anchor the void formers to the reinforcing bars in order to prevent buoyancy of the formers during the placing and curing of concrete.

In general, a number of studies have shown that voided slabs are beneficial both structurally and environmentally. However, the results of this study showed that voided slabs emitted more carbon dioxide compared to normal reinforced concrete slabs. The main source of this additional CO_2 from the voided slab might be the materials anchoring the void formers to the reinforcing bars. In this research, wires were used to fix the void formers, and they were a reasonably large source of CO_2 emissions. In order for the voided slab to become a more eco-friendly and sustainable material in buildings, new anchoring methods such as use of recycled materials, new void formers without anchoring, or other eco-friendly materials should be developed to reduce the emission of CO_2.

Data Availability

The data used to support the findings of this study are included within the article. In addition, some of the data used in this study are supported by the references mentioned in the article. If you have any questions regarding the data, the data to support of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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