Construction Waste Reduction through Application of Different Structural Systems for the Slab in a Commercial Building: A South Korean Case

Seunguk Na, Seok-Jae Heo * and Sehee Han

Department of Architectural Engineering, College of Engineering, Dankook University, 152 Jukjeon-ro, Suji-gu, Yongin-si 16890, Korea; drseunguk@dankook.ac.kr (S.N.); edu.hansh@gmail.com (S.H.)
* Correspondence: mill@dankook.ac.kr; Tel.: +82-31-8005-3727

Abstract: Construction waste generation along with the extensive consumption of natural resources has propelled researchers to investigate effective measures for minimising the waste. While several studies have shown that the structural design would be an influencing factor on the carbon dioxide emissions of a building, there is a lack of studies to corroborate the effect of different structural systems to generate waste during the construction stage. This article seeks to bridge some of the knowledge gaps regarding the waste generation from different structural systems during the construction phase in a building project in South Korea and demonstrate its potential for waste reduction. In this study, the amount of waste generation during the construction phase was calculated based on the quantities and the material loss rate of each building material to estimate the quantity of construction waste by the changes in the application of different structural systems for the slab of the studied model. The total waste generation during the construction phase of the different slab systems shows that the solid slab system produces the largest amount of construction waste, which is 101,361.385 kg. On the other hand, the void slab system generates 87,603.958 kg of the construction waste, which is the lowest amount among the four variables of this study. The additional purchasing costs due to the loss of construction materials indicate that the solid slab system would require 80,709.76 USD, which is the highest value of the four variables in this study. The void slab system would cost USD 50,054.12 for additional materials purchasing costs, which is approximately 38% lower than the solid slab system.

Keywords: construction waste; waste management; waste reduction; material loss rate; construction industry; structural system

1. Introduction

Construction activities consume a large volume of natural resources such as oil, gas, and coal, leading to a lot of greenhouse gases emissions including carbon dioxide, methane, nitrous oxide, and so forth. The Intergovernmental Panel on Climate Change (IPCC)’s Fifth Assessment report indicated that the construction industry consumes about 40% of global energy and emits roughly 30% of total global greenhouse gas emissions [1]. At the same time, the construction industry accumulates a vast amount of construction waste which would cause serious environmental pollution such as air pollution, land loss for waste landfilling, rainwater leaching, scouring, and infiltration of surface water [2–4]. In particular, flammable building materials, corrosive substances, and chemicals would cause critical damage to construction workers and the surrounding environment during and after construction projects. According to European Official Statistics [5], construction activities during the last few decades have generated approximately 8.2 million tons of construction waste each year, which is responsible for about 46% of the total waste. In a similar vein, statistics in Hong Kong show that more than 3158 tons of construction waste was transported to landfills per day, accounting for about 35% of municipal solid waste [6].
The construction waste management situation in South Korea is similar to other countries by generating approximately 181,494 tons per day, accounting for about 45% of the total solid waste [7]. The construction waste generation along with the extensive consumption of natural resources has propelled researchers to investigate effective measures for minimising the waste.

Several researchers have maintained that one of the most effective measures to alleviate the generation of construction waste at site would be incentive policies which can stimulate stakeholders to participate in waste reduction initiatives [8–11]. Tam and Tam [10], for example, showed that a gradual increase of intensive policy for waste reduction would make employees join waste reduction activities more effectively. Another successful method to reduce the construction waste would be an increase in the financial burden imposed by the government, which could encourage stakeholders to take part in avoiding additional costs from their construction waste generation [3,12–14]. According to Lu and Yuan [3], the waste management regulations which stipulate detailed regulations, norms, and standards are one of the critical success factors for waste management in construction projects. While incentive policies and financial burdens would make it possible for the contractors and developers to reduce construction waste over a period of time, reducing the construction waste from a site should be considered as the most effective approach which could not only minimise waste generation and eliminate waste disposal on site but also lower the construction cost of waste sorting for recycling, transporting, and disposal to a landfill [6,10,15–17].

The estimation of waste generation from construction projects is a significant step to identify the reduction potential, as well as to compare the amount of generated waste to the baseline. Moreover, the predicted amount of construction waste can be used by project stakeholders to prepare appropriate practices for managing construction waste, as well as to assess the effectiveness of the practices and provide a benchmark for reduction [18,19]. While there have been several methods to quantify waste generation during the construction phase, it is an arduous task to estimate the amount of generated waste because of the wide variety of construction materials and longer period needed to construct a building or structure. Li et al. [20], for example, calculated the construction waste based on the amount of purchased construction materials and the waste rate (%) of each material discarded during the construction phase. While this method was a useful tool to predict the waste amount of each construction material, there was an accuracy problem depending upon the waste rate provided by the project manager. Another method is to estimate the construction waste generation based on the constructed area data (weight/m² or volume/m³). This method is applied to the waste generation rate per square meter by different types of buildings [17,21–23]. It would be useful to provide information on bulk waste generation without categorising the construction materials. On the other hand, this method could be difficult to use to compare the amount of construction waste between different construction methods or techniques that require different quantities of construction materials. Furthermore, the accuracy of the estimated waste amount in this method would be dependent upon the regional database and is difficult to apply to other regions [22]. For example, Pinto [24] carried out a study to quantify the construction waste generation from new buildings, renovations, extensions, demolition, and informal construction works in the Brazilian context. Moreover, Bakshan et al. [25] proposed a method to estimate waste streams from various construction stages which would be able to be generally applied to any regions or countries. Similarly, Saez et al. [26] determined the construction waste of new residential buildings as the waste volume (m³) in relation to a building’s total floor area (m²).

In construction projects, the main source of construction waste is the loss of construction materials due to the inappropriate use of construction materials by unskilled construction workers. In particular, the typical cast-in-place reinforced concrete is composed of various types of sub-works where the formwork, reinforcement, casting, and curing are carried out on site. When conducting the concrete construction work, the amount
of waste generated by the formwork and reinforcement would vary depending upon the skill level of each worker. In order to lower the generation of waste during the construction phase, several construction methods have been proposed. For example, prefabrication is regarded as an efficient method to reduce the construction waste at a site [3,6,15,17]. In this method, components of a building or structure are manufactured in a factory or other manufacturing site and transported to the construction site and assembled on site. According to Jailon et al. [15], the application of prefabrication would achieve construction waste reductions of up to 52% on site in the context of Hong Kong. The prefabricated construction method would not only directly affect the main construction works on site but also to reduce the subsequent waste handling activities such as sorting, recycling, transporting, and disposal [6]. In a similar vein, there are several structural design variations to lower cast-in-situ formwork and reinforcement work. A number of studies have claimed that the design of a structural system could not only reduce the amount of building materials but also mitigate greenhouse gas emissions [27–30]. For example, Baek et al. [28] assessed the carbon dioxide emissions between different structural systems applied in an apartment building in South Korea. Similarly, Nadoushani and Akbarnezhad [31] indicated that the structural design would have a significant impact on the life cycle carbon emissions of a building based on a comprehensive assessment of embodied carbon and operating carbon. Along with the studies of greenhouse gas emissions from different structural systems, Lachimpadi et al. [32] corroborated the construction waste generation of three different structural systems, namely conventional construction, mixed construction, and precast construction. In this study, they claimed that precast construction achieved the lowest waste generation rate with 0.016 tons of construction waste per square floor area in a Malaysian context.

While several studies have shown that the structural design would be an influencing factor on the carbon dioxide emissions of a building, there is a lack of studies that corroborate the effect of different structural systems to generate waste during the construction stage. The quantifying of waste generation during the construction phase would be a useful tool of a benchmark for reduction. This study investigates how the waste generation during the construction phase would be affected by different structural systems. Given the situation, this article seeks to bridge some of the knowledge gaps regarding the waste generation from different structural systems during the construction phase in a building project in South Korea and demonstrate its potential for waste reduction by applying material loss rates for building materials. The objectives of this study were to review the quantification methods of the waste generation in the construction industry; to assess the generation of construction waste from different structural systems which are the solid slab system, the flat plate slab, and the void slab system; and to evaluate the benefits in terms of waste reduction and cost efficiency during the construction phase. The rest of this study is organised as follows. The research method for quantifying the construction waste is explained in Section 2. In Section 3, the results and discussion of this study are demonstrated, and the conclusions of this study are demonstrated in Section 4.

2. Research Method

2.1. Quantifying the Construction Waste

There are many approaches to estimating the approximate amount of construction waste generated on site. According to the United States Environmental Protection Agency (USEPA) [33], the amount of construction and demolition (C&D) waste can be estimated using the waste-weight-per-construction-area method. This method would be able to determine the average waste generation per building area (kg/m²), as shown in Equation (1),

\[ w = A \times g \]

where \( w \) is the total weight of construction waste (kg), \( A \) is the area of the building constructed (in m²), and \( g \) is the average construction waste generation per building area (in kg/m²). This method has been applied to estimate the amount of C&D waste in various
countries and regions such as the US states of Florida [34] and Massachusetts [35], as well as South Korea [7]. Despite of the ease of estimating the amount of construction waste, it would be difficult to calculate and compare the amount of construction waste generation by utilising the different construction methods. New construction methods have been evolving in ways to develop new structural systems, to reduce the use of construction materials, and to minimise the amount of works on site. In particular, it might be difficult to evaluate the amount of construction waste generation based on the waste-weight-per-construction-area method from the new construction methods, where the use of building materials changes.

This current research work presents a comparison to quantify different construction waste streams arising from the different structural systems for the slab in a commercial building. Since the different structural systems can lead to different amounts of building materials being used, there would be a limitation when seeking to assess the level of waste generation for each structural system based on the waste-weight-per-construction-area method. In this study, the amount of waste generation during the construction phase was calculated based on the quantities and the material loss rate of each building material in order to estimate the quantity of construction waste by the changes in the application of different structural systems for the slab of the studied model. The profile of building materials including the name of products, unit, and material loss rate were classified by reviewing the bill of quantities for all four construction methods (see Table 1).

| Building Materials | Unit | Material Loss Rate | Density (kg/m$^3$) | References |
|--------------------|------|---------------------|---------------------|------------|
| Ready-mixed concrete | m$^3$ | 0.003 | 2400 | The Korea Institute of Construction Technology [36] |
| Rebars | Kg | 0.030 | 8050 | |
| Spacers | Kg | 0.030 | 970 | |
| Forms | m$^2$ | 0.030 | 680 | |
| Void formers | Kg | 0.080 | 1050 | |
| Steel decking | Kg | 0.050 | 7140 | |
| Anchoring metal | Kg | 0.030 | 8050 | |

In this study, the amount of waste generated during the construction phase was only considered involving the major building materials for the slab system, since the only differences among the solid slab, flat plate slab systems, and the void slab system were the structural design of the slab while other design parameters were identical except the slab systems. Once the quantities of the building materials had been determined based on the bill of quantities, the amount of the produced waste during the construction phase from each structural system was calculated as shown in Equation (2)

$$ W_{Gn} = \sum_{i=1}^{n} Q_i \times L_i $$

where $W_{Gn}$ is the total amount of the construction waste for structural system $n$ (in kg), $Q_i$ represents the amount of the building material $i$ (in kg), and $L_i$ refers to the material loss rate of the building material $n$. As stated in the previous section, the major building materials for quantifying the construction waste were ready-mixed concrete, rears, forms, spacers for solid slab, flat plate slab, and the void slab system. The void slab system required additional building materials, which were void formers, steel decking, and anchoring metal materials.
2.2. Case Description

The analysed building is a commercial building located in Seoul, South Korea and the basic information of this model is indicated in Table 2. It is a 14-storey high-rise building comprising a bespoke rigid-frame structure with a total floor area of 13,486.6 m² (see Figure 1). The design of this commercial building was completed in compliance with Structural Concrete Design Code and Commentary by the Korea Concrete Institute [37] and ACI 318-05 [38]. The slabs of the studied building were designed with the thickness of 210 mm for the solid slab, 180 mm and 210 mm for the flat plate slab, and 210 mm for the void slab system. The rebars for the reinforcement of the slabs were 12.70, 15.90, and 19.20 mm with a yield strength of 400 MPa.

Table 2. The profile of the case study building.

| Item                          | Description                                      |
|-------------------------------|--------------------------------------------------|
| Location of the building      | Seoul, South Korea                               |
| Type of the building          | Commercial building                              |
| Storeys of the building       | 14 above ground and 5 underground                |
| Structural system             | Rigid-frame reinforced concrete structure         |
| Total floor area              | 13,486.62 m²                                     |

![Figure 1. The floor plan of the case study building.](image)

The studied building was initially designed with a solid slab system, which is one of the common structural systems for high-rise buildings. During the value analysis stage before design development for the construction phase, the flat plate slab and the void slab system were suggested as alternatives. Value analysis originated in the manufacturing industry in the 1940s as a systematic approach to increase the ratio between the function of a project, product, or service and the resources needed to achieve it [39,40]. The construction industry has adopted this approach for cost reduction, time-saving, and quality improvement since the 1980s. From the perspective of value analysis, a performance improvement with low cost would be the best replacement for both clients and contractors [41].

In the design development stage, the alternative slab systems were suggested to optimise the performance of building with less costs and building materials. The replacement slab systems for this studied building were the flat plate slab and the void slab system. The flat plate slab, which does not use beams and girders, would be able to maximise the serviceability for occupants with expanded spans and flexible floor plans. Likewise, the void slab system is an improved construction method which combines light-weight void formers anchored to a steel decking (see Figure 2). While the void slab system has
a similar benefit to expand the width between columns, the insertion of light-weight void formers would make it possible to reduce the self-weight of the slab, as well as to minimise the construction time. During the value analysis stage, structural performance, cost-effectiveness, and the environmental performance were the main criteria for selection of the optimal slab systems of the studied building. While previous cases only considered the emissions of the greenhouse gas, the production of construction waste on site was also estimated due to the strengthened regulations regarding the environmental performance of the construction industry.

![Figure 2](image-url)

**Figure 2.** Schematic description of the slab systems: (a) Solid slab, (b) The flat plate slab, (c) The void slab system.

### 3. Results and Discussion

#### 3.1. Total Construction Waste Generation

The total waste generation for this case study was estimated by the method and parameters described in the previous section. Table 3 shows the results of the total waste generation of the solid slab, flat plate slabs, and the void slab system. As shown in Table 3, a total of 101,361.385 kg or 43.642 m³ of construction was estimated to be generated from the solid slab system, which is the highest among the four slab systems. The waste generation rate for the solid slab system was approximately 105.220 kg/m² of the construction floor area. On the other hand, the void slab system produced the lowest amount of construction waste, which was 87,603.958 kg or 33.648 m³ in total. For the waste generation rate of the void slab system, it showed about 90.939 kg/m² of the construction floor area. In addition, the total construction waste from the flat plate slab with the thickness of 180 and 210 mm produced about 98,657.409 kg and 99,335.161 kg, respectively.

The construction waste generated by building materials from the different slab systems is depicted in Figure 3, which shows the percentage of each type of construction waste. As indicated in Figure 3, ready-mixed concrete produced the largest proportion of construction waste, at about 65% by weight in all cases. Although the material loss rate of ready-mixed concrete is relatively lower than other building materials, it was found that the amount of waste generated from this material was higher than for other building materials. In addition, the material loss rate of rebars was relatively higher than other materials because the reinforcement work at the construction site would be dependent upon the skill level of the construction workers. Moreover, the forms for concrete moulds of this case study building used plywood forms, which would make it possible to easily create various forms of concrete structures. However, the plywood forms would be difficult to recycle or reuse, since they are cut into many different sizes for creating building structures.
Table 3. The total waste generation of the case study building.

| Building Materials | Total Waste Generation (kg) | Waste Generation per Unit Floor (kg/m²) |
|--------------------|-----------------------------|----------------------------------------|
|                    | SS  | FPS180 | FPS210 | VSS | SS  | FPS180 | FPS210 | VSS |
| Ready-mixed concrete | 65,350.766 | 64,527.346 | 65,519.371 | 56,902.747 | 67.838 | 66.984 | 68.013 | 59.069 |
| Rebars              | 26,667.094 | 25,402.723 | 24,902.235 | 23,767.740 | 27.682 | 26.370 | 25.850 | 24.672 |
| Spacers             | 1456.555  | 1294.716  | 1375.635  | 687.818   | 1.512  | 1.344  | 1.428  | 0.714  |
| Forms               | 7886.970  | 7432.624  | 7537.920  | 2832.190  | 8.187  | 7.716  | 7.825  | 2.940  |
| Void formers        | 0      | 0      | 0      | 2014.901  | 0      | 0      | 0      | 2.092  |
| Steel decking       | 0      | 0      | 0      | 1216.493  | 0      | 0      | 0      | 1.263  |
| Anchoring metal     | 0      | 0      | 0      | 182.069   | 0      | 0      | 0      | 0.189  |
| Total               | 101,361.385 | 98,657.409 | 99,335.161 | 87,603.958 | 105.220 | 102.413 | 103.116 | 90.939 |

Note: SS is the solid slab, FPS 180 and FPS 210 are the flat plate slab with the thickness of 180 mm and 210 mm, and the VSS is the void slab system.

Figure 3. Construction waste generation by materials: (a) Solid slab system, (b) Flat plate slab (180 mm), (c) Flat plate slab (210 mm), (d) The void slab system.

In this study, the void slab system required additional building materials to build the slab system of the building. While void formers, steel decking, and anchoring metals were applied to the void slab system, the total amount of the construction waste showed the
lowest results among all four slab systems. For the void slab system, the steel decking played dual roles during the concrete curing process as well as acting as an additional structural material integrated with the slab itself. This made it possible to enhance the structural performance of the slab system as well as to reduce the generation of construction waste during the construction phase. In addition, the void formers produced approximately 2015 kg of the construction waste, which accounts for about 2.3% of the total waste generated during the void slab system construction. In particular, it was indicated that the amount of construction waste generated from the void slab system was small because the steel decking and the void formers were processed according to the specifications shown in the design drawings at the factory and brought to the construction site. The building materials processed at the factory would seem to show similar characteristics to the prefabrication method, which is suggested as one of the potential construction methods to mitigate on-site construction waste [3,6,17].

3.2. Potential Waste Reduction by Using Different Structural Systems

Table 4 summarises the reduced amount of construction waste and the reduction ratio of the flat plate slab systems and the void slab system compared to the solid slab. Columns 5, 6, and 7 in Table 4 show the reduction ratio of each waste source to the reduction of the total construction waste generation by applying the flat plate slab and the void slab system. The test results showed that the application of alternative structural systems would achieve a total waste reduction of 13,757.426, 2703.976, and 2026.224 kg for the void slab system, the flat plate slab systems, and the solid slab system, respectively. It was indicated that approximately 8448.019 kg of construction waste was reduced from the ready-mixed concrete by the void slab system. In this study, the results also showed that applying to the void slab system would make it possible to decrease about 5054.780 kg of construction waste from plywood forms compared to the solid slab system.

Table 4. Waste reduction of the different structural systems.

| Building Materials      | Reduction of Construction Waste (kg) | Reduction Ratio (%) |
|-------------------------|--------------------------------------|---------------------|
|                         | VS–SS  | FPS 180–SS  | FPS 210–SS | VS–SS  | FPS 180–SS  | FPS 210–SS |
| Ready-mixed concrete    | −8448.019 | −823.420   | 168.605   | −12.93 | −1.26   | 0.26       |
| Rebars                  | −2899.354 | −1264.371  | −1764.859 | −10.87 | −4.74   | −6.62      |
| Spacer                  | −768.737  | −161.839   | −80.920   | −55.88 | −11.11  | −5.56      |
| Forms                   | 5054.780  | −454.346   | −349.050  | −64.09 | −5.76   | −4.43      |
| Void formers            | 2014.901  | 0          | 0         | 59.03  | 0       | 0          |
| Steel decking           | 1216.493  | 0          | 0         | 35.63  | 0       | 0          |
| Anchoring metals        | 182.069   | 0          | 0         | 5.34   | 0       | 0          |
| Total                   | −13,757.426 | −2703.976  | −2026.224 | −13.57 | −2.67   | −2.00      |

Furthermore, the estimation results of the flat plate slab indicate the reduced amount of construction waste over the solid slab system. While the reduction value of both flat plate slab systems was relatively smaller than the void slab system, the flat plate slabs with 180 and 210 mm of thickness showed about 2.7% and 2% reduction of total waste generation during the construction phase. For the flat plate slab system, the major reduction source of construction waste was reinforcing bars, which showed about 1264.371 kg and 1764.859 kg reductions for flat plate slab with 180 mm and 210 mm of thickness, respectively. The flat plate slab system is one of the more commonly used alternative systems for solid slab systems in recent years because of its simple formworks and longer spans for occupants. However, from the perspective of waste generation, the difference between the solid slab and the flat plate slab is relatively smaller due to the additional works.
needed for enhancement around columns such as drop panels and an increased amount of reinforcement works.

From the perspective of the waste reduction in each building material when replacing the solid slab with alternative structural systems, the void slab system would be the most beneficial method to reduce waste generation during the construction phase. In the case of waste generation from the void slab system, a reduction of 12.93% of the waste from the ready-mixed concrete, 64.09% of waste from forms, and 10.87% of waste from rebars could be seen. In a similar vein, 12.93%, 10.87%, and 64.09% of reductions for the ready-mixed concrete, rebars, and forms, respectively occurred through the application of a flat plate slab system with 180 mm of thickness. Likewise, a reduction of 6.62% and 4.43% of the ready-mixed concrete and rebars occurred from the flat plate slab with 210 mm of thickness. For the flat plate slab with 210 mm of thickness, the amount of waste generated from the ready-mixed concrete slightly increased by 0.26% compared to the solid slab. The slight increase of waste generation in the ready-mixed concrete from the flat plate slab seemed to be due to the added amount of ready-mixed concrete in the drop panels to prevent punching shear. In this study, the void slab system could reduce the construction waste of plywood formwork by decreasing the amount of cast-in-place concrete used because the steel decking is applied to mould the concrete as well as fix the void formers. Based on the results of the case study, the most effective approach to mitigate the construction waste generation from the different slab systems would be the void slab system.

### 3.3. Cost Reduction of Construction Waste Disposal

The additional costs arising from the generation of construction waste for different structural systems are demonstrated in this section. The estimated additional cost referred to in this research means the added material purchasing costs due to the loss of building materials rather than the disposal costs of construction waste on site. In this study, the major building materials were considered to assess the cost reduction during the construction of slab systems for the studied building. The major building materials were ready-mixed concrete, rebars, spacers, and forms for the solid slab and the flat plate slab. The building materials for the void slab system applied three additional items, which were void formers, steel decking, and anchoring metals.

Calculation of the additional cost for purchasing the building materials was applied to the Korea Price Information Database [42] to establish the unit price of each building materials in this study. Table 5 indicates the lists of the unit price of the building materials of this study. The unit price of the building materials was converted from South Korean Won (KRW) to US dollars (USD), which would make it possible to easily comprehend and compare to foreign countries. The conversion of USD to KRW was calculated at the rate of KRW 1178 to USD 1. Moreover, the additional building materials purchasing cost was applied to Equation (3) as below:

\[
C_{m_i} = q_i \times P_i
\]

where \(C_{m_i}\) refers to the additional materials purchasing cost of building material \(i\), \(q_i\) represents the quantity of building materials \(i\) from the bill of quantities, and \(P_i\) indicates the unit cost of the building material \(i\).
Table 5. The list of unit price of the building materials [39].

| Building Materials       | Unit | Unit Price |
|--------------------------|------|------------|
|                          |      | Korean Won (KRW) | US Dollars (USD) |
| Ready-mixed concrete     | m³   | 70,580     | 59.92          |
| Rebar                    | kg   | 780        | 0.66           |
| Forms                    | m²   | 6900       | 5.85           |
| Void formers             | m³   | 10,000     | 8.49           |
| Steel decking            | kg   | 2500       | 2.12           |
| Anchoring metals         | kg   | 500        | 0.42           |

Table 6 summarises the additional costs of purchasing building materials from three different structural systems of this study. The additional construction costs generated from the additional building materials were USD 50,054.12, 76,941.50, 77,507.83, and 80,709.76 for the void slab system, the flat plate slab 180, the flat plate slab 210, and the solid slab, respectively. In this study, the plywood forms would determine the additional building material costs, which accounted for about 33.09%, 56.49%, 56.87%, and 57.14% of the void slab system, the flat plate slab 180, the flat plate slab 210, and the solid slab, respectively. Even though the plywood forms were reused approximately 3 times on site, the plywood forms would be difficult to reuse for other purposes or recycle because they were made to various forms to mould the concrete during the construction phase. In addition, regarding the cost of purchasing additional building materials, it was found that the cost of rebars accounts for a relatively high proportion of the additional costs, although the amount of construction waste generation was less than the waste of the ready-mixed concrete.

Table 6. Additional costs from the purchase of the building materials.

| Building Materials       | Total Cost (USD) | Proportion (%) |
|--------------------------|------------------|----------------|
|                          | VSS FSS180 FSS210 SS | VSS FSS180 FSS210 SS |
| Ready-mixed concrete     | 14,205.56 16,109.01 16,356.67 16,314.58 | 28.38 20.94 21.10 20.21 |
| Rebars                   | 14,767.55 16,820.14 16,488.75 17,657.33 | 31.44 21.86 21.27 21.88 |
| Spacers                  | 291.94 549.54 583.89 618.23 | 0.58 0.71 0.75 0.77 |
| Forms                    | 16,561.44 43,462.81 44,078.53 46,119.63 | 33.09 56.49 56.87 57.14 |
| Void formers             | 598.65 0 0 0 | 1.20 0 0 0 |
| Steel decking            | 2581.69 0 0 0 | 5.16 0 0 0 |
| Anchoring metals         | 77.28 0 0 0 | 0.15 0 0 0 |
| Total                    | 50,054.12 76,941.50 77,507.83 80,709.76 | 100 100 100 100 |

Meanwhile, the additional purchasing costs from the building materials were found to be decreased by approximately USD 30,655.65 when the void slab system was applied as an alternative method to the solid slab system. Furthermore, the flat plate slab systems would be beneficial to reduce the construction costs arising by the purchasing of the building materials during the construction phase, even though its reduction ratio was smaller than for the void slab system (see Table 7). Based on the results shown in this study, the additional purchase of plywood forms were the dominant factors to increase the additional material costs, which would produce construction waste. In particular, it was difficult to reduce the amount of building materials and waste, since the beams and girders require a number of plywood forms to create the structural members. However, the void slab system minimises the beams and girders due to its reduction of self-weight, and it would be the optimal slab system to mitigate the generation of waste during the construction phase.
Table 7. Cost reduction from the different structural systems.

| Building Materials       | VSS-SS | FPS180-SS | FPS210-SS | VSS-SS | FPS180-SS | FPS210-SS |
|--------------------------|--------|-----------|-----------|--------|-----------|-----------|
| Ready-mixed concrete     | −2109.02 | −205.56  | 42.09     | −12.93 | −1.26     | 0.26      |
| Rebars                   | −1919.78 | −837.19  | −1168.58  | −10.87 | −4.74     | −6.62     |
| Spacers                  | −326.29  | −68.69    | −34.35    | −52.78 | −11.11    | −5.56     |
| Forms                    | −29,558.19 | −2656.82 | −2041.10  | −64.09 | −5.76     | −4.43     |
| Void formers             | 598.65  | 0         | 0         | 1.95   | 0         | 0         |
| Steel decking            | 2581.69 | 0         | 0         | 8.42   | 0         | 0         |
| Anchoring metals         | 77.28   | 0         | 0         | 0.25   | 0         | 0         |
| Total                    | −30,655.65 | −3768.27 | −3207.93  | −37.98 | −4.67     | −3.97     |

3.4. Discussion

The case study results described above show that it would be possible to reduce the construction waste generation with the application of different slab systems over the typical solid slab system. In this study, the alternative construction method, which is the void slab system, is discussed as one of the potential approaches to alleviate the waste generation during the construction phase. In particular, the construction materials precisely processed in the factories or manufacturing facilities would contribute to decreasing the generation of construction waste on site. Furthermore, it was found that less use of the forms for the formwork made at the construction site by carpenters and workers would be an important factor in reducing the waste generation during the construction phase. Even though this case study project would fill the knowledge gaps of generation of construction waste by adopting the materials loss rate-based calculation, there are several limitations associated with the results as well as their application in generalisation.

Firstly, estimating the construction waste generation of this case study did not include the other building materials used in the different stages of the construction works. Construction a building consists of a number of sub-tasks, and it is necessary for a comprehensive comparison of the amount of construction waste generation to consider all the tasks in a construction project.

Secondly, only one case study was carried out to evaluate the amount of construction waste during the application of different slab systems. In the further research, all the construction works related to the structural systems with variety of cases applied to the void slab system and flat plate slab system should be conducted not only to enhance the accuracy but also to apply to the results shown in this study.

Thirdly, most studies [7,31,32] estimate the amount of construction and demolition waste based on the waste-weight-per-construction-area method. While this method is useful to estimate the approximate amount of waste generation during the construction phase, it would be difficult to compare the amount of waste generation from different construction methods for the same floor area. In order to overcome such a situation, the material loss rate was adopted to calculate the generation of waste during the construction phase for a different structural system.

Lastly, the quantification method of waste generation in this study would be beneficial to use for estimating the various scenarios in the same building. One of the most significant factors to guarantee the results from the material loss rate-based quantification method is to increase the accuracy of the loss rate of various building materials. In the further research, an accurate material loss rate of building materials based on the site observation and field interviews from project managers should be obtained to maximise accuracy for the general application of the method utilised in this research.

4. Conclusions

With the growing concerns towards the adverse environmental impacts brought about by various forms of waste, the construction industry will have to alleviate its generation of construction waste. In this study, the application of alternative construction methods was
assessed as one of the potential approaches to minimise the generation of waste during the construction phase. However, there is a lack of studies and methods to quantify and compare the amount of construction waste generation from different construction methods. This study, therefore, also assessed construction waste generation and its impacts on waste reduction involving the three different slab systems, namely, the solid slab system, the flat plate slab, and the void slab system. The results of the study show that:

1. The total waste generation during the construction phase of the different slab systems shows that the solid slab system produces the largest amount of construction waste, which is 101,361.39 kg. On the other hand, the void slab system generates 87,603.96 kg of construction waste, which is the lowest amount among the four variables of this study. In addition, 98,657.41 kg and 99,335.16 kg of construction waste was generated for the flat plate slab with a thickness of 180 and 210 mm, respectively.

2. In this study, the building materials processed or manufactured in a factory would be one of the potential construction waste reduction factors. In particular, the conventional cast-in-place reinforce concrete requires formwork and reinforcement, which might be dependent upon the skill level of the workers. Since the different level of skill would be one of the factors for producing different amounts of construction waste on site, the application of manufactured products on site would be helpful to reduce the amount of construction waste.

3. Among the three different slab systems assessed in this study, the void slab system would be the most beneficial method to reduce the waste generation during the construction phase. The reduction of construction waste compared to the solid slab system was by 13,757.43 kg, 2703.98 kg, and 2026.22 kg for the void slab system and the flat plate slab system with 180 mm and 210 mm, respectively. The results indicate that the void slab system reduces total waste generation by about 13%, while the flat plate slab with a thickness of 180 mm and 210 mm reduces waste by approximately 2.7% and 2.0%, respectively. In particular, the waste reduction from plywood forms and ready-mixed concrete is about 64% and 13%, which are the highest reduction ratios amongst the building materials.

4. The additional purchasing costs due to the loss of construction materials were also investigated in this study. The results indicate that the solid slab system would require additional material purchasing costs of USD 80,709.76, which is the highest value out of the four variables in this study. On the other hand, the void slab system would cost USD 50,054.12 for additional materials purchasing costs, which is approximately 38% lower than the solid slab system.

This article demonstrates the potential benefits of using different structural systems for potential reduction of construction waste. A limitation of this study is that more reliable and accurate data of the material loss rate would be the key determinant to quantify the amount of waste during the construction phase. Further research that accumulates more reliable data to quantify waste generation based on the material loss rate should be carried out to overcome this issue.

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