

Research Article

Analysis of CO₂ Emission Reduction Effect of On-Site Production Precast Concrete Member according to Factory Production Environment

Youngju Na ¹, Bumjin Han ², and Seunghyun Son ³

¹Department of Architectural Engineering, U1 University, Yeongdong-gun, Chungcheongbuk-do 29131, Republic of Korea

²Department of Research and Development, Korea Construction and Transport Engineering Development Collaboratory Management Institute, Yongin-si, Gyeonggi-do 17058, Republic of Korea

³Department of Architectural Engineering, Mokpo National University, 1666 Yeongsan-Ro, Cheonggye-myeon, Muan-gun, Jeonnam 58554, Republic of Korea

Correspondence should be addressed to Seunghyun Son; seunghyun@khu.ac.kr

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Precast concrete (PC) method of construction is preferred for excellence in the reduction of construction period, lightweight, and durability and for PC member to be mostly transported to a site after its production in the in-plant production because the in situ production of the PC member is negatively perceived because of the limitation of space or production process being complex and difficult. However, if the PC member is produced on site and installed, it is possible to reduce the carbon dioxide emissions that are generated during shipping and loading and unloading, which are indirectly required for in-plant production. Carbon dioxide emission reduction effect due to the difference between the in situ production and in-plant production process of the PC member was confirmed by the existing studies, but the study of the carbon dioxide reduction effect according to various production environments of the in-plant production has not been performed. Therefore, the purpose of this study is to analyze the CO₂ emission reduction effect of the PC member produced in site according to the in-plant production environment. As a result, it was found that when PC members were produced on site, there was an effect of reducing CO₂ emissions by an average of 25.64% compared to factory production. In future, the results of this study will be used as basic data for establishing a CO₂ emission reduction plan at construction sites.

1. Introduction

1.1. Research Background and Objective. Carbon dioxide emissions are the major cause of global warming, accounting for 80% of the world's greenhouse gas emissions designated by the United Nations Environment Programme and World Meteorological Organization in 1985 [1]. The Ministry of Environment's "2019 National Greenhouse Gas Inventory Report" shows that carbon dioxide emissions in Korea rose steadily from 1990 to 2017, along with industrial development [2]. As a result, Korea ranked 11th in carbon dioxide emissions. To preserve the environment, in 2015, Korea set a goal of 37% reduction compared to emissions prospect in the year

2030 (Business As Usual (BAU)) [3]. Construction industry is one of the industries that have a significant impact on the environment due to the high consumption of energy and raw materials, which is the requirement of the industry [4].

The resources consumed by the construction industry among the entire industry fields account for 40% of energy consumption, 48% of raw material consumption, and more than 42% of carbon dioxide emissions [5]. For the preservation of the environment and prevention of global warming, efforts are needed to reduce energy consumption, raw material consumption, and carbon dioxide emissions in the construction industry that has a negative impact on environmental destruction [6, 7].

CO₂ emissions continue to increase worldwide. In particular, in the recent construction field, large-scale buildings such as logistics centers are rapidly increasing. Most of these large buildings are built using the precast concrete (PC) method. However, in general, PC methods are produced in factories and transported to the site [8]. In order to reduce CO₂ emissions generated in this process, the on-site production of PC members is essential. In other words, in terms of eco-friendliness, if the PC member is produced in the field, CO₂ emission generated during the transportation process can be reduced.

The installation of precast concrete (PC) after in situ production accounts for more than 14.3% of CO₂ reduction compared to in-plant production. At this time, Lim and Kim [8] claimed that transportation of PC members makes difference in the production of PC members because in situ production is processed in the same way as in-plant production and selected a case site to support the claim. After producing 72 PC columns in the site, the difference in CO₂ emissions compared to in-plant production was calculated, which led to the confirmation that in situ production was more advantageous in terms of CO₂ reduction. However, the study did not report the difference in CO₂ generation according to the environment of in-plant production of PC members and manpower. Therefore, it is necessary to study the CO₂ emission reduction effect analysis, including the aforementioned items.

1.2. Research Method. The purpose of this study is to prove the effect of reducing CO₂ through the on-site production of PC members. For this study, the CO₂ reduction effect is proved through the comparison of the production environment between the factory and the construction site. Also, the CO₂ emission reduction effect was confirmed through calculating the CO₂ emissions by the manpower and in-plant production environment that were not considered in the preliminary study of Lim and Kim [8]. This study was performed as shown in Figure 1.

Initially, the CO₂ unit calculation method, the examination of Life Cycle Inventory (LCI) analysis database, and the preliminary study were reviewed. Then, the CO₂ emission in the case site of Lim and Kim [8] was analyzed, and the CO₂ emission generated by the manpower was calculated. They proved the CO₂ reduction effect of on-site production on actual sites. However, they only analyzed the CO₂ reduction effect only for the manpower deployed to the field. Rather, it is correct to analyze the effect of CO₂ reduction caused by changes in the production environment of factories and sites. Therefore, in this study, the environmental factors of in-plant production were identified and the CO₂ emission was calculated. Later, the calculated CO₂ emissions of in situ production and in-plant production were compared and analyzed and the CO₂ emission reduction effect was confirmed. Finally, evaluation and conclusion of the CO₂ emission analysis results were drawn.

2. Preliminary Study

2.1. Energy Consumption and CO₂ Basic Unit Calculation Method. There are survey-based approach, input-output

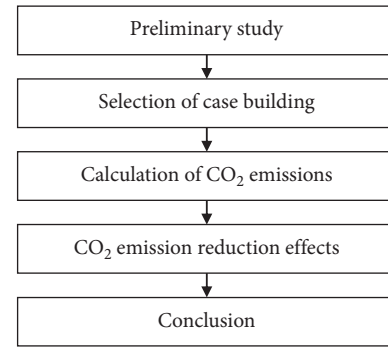


FIGURE 1: Methodology.

analysis (indirect estimator), and hybrid approach as methods for calculating energy consumption and CO₂ basic unit [9]. The method used typically is input-output analysis [10]. The comparison of these methods is as follows.

2.1.1. Survey-Based Approach. Survey-based approach is a method of surveying carbon dioxide emissions and energy consumption generated at each stage, such as the collection, transportation, and processing of natural resources using materials and energy used in the building life cycle. In the case of the survey process, the system of the analysis target is dismantled and, then, each stage is examined and evaluated comprehensively. The scope of the survey includes raw materials, energy, and materials used for the analysis target. Additionally, it is necessary to conduct a site survey of all the processes from the construction, maintenance, and dismantling stage of the building construction process [11, 12].

2.1.2. Input-Output Analysis. Input-output analysis is an analysis using an input-output table. The input-output table shows the cross-trading between the goods and service industries in the unit of one year regarding national economy. Direct and indirect correlations between industries as a unit of goods and services can be identified in the table [13]. In Korea, the Bank of Korea drafts an input-output table on a yearly basis. It is a method of quantitatively identifying the input and emission factors generated in the trading process, calculating the mutual goods and services between each industry in monetary units [14].

2.1.3. Hybrid Approach. Hybrid approach is a method of calculating a basic unit by combining the survey-based approach with input-output analysis [15]. The survey-based approach has difficulty in examining the simultaneous input of various materials. This can be supplemented using input-output analysis. Additionally, the survey-based approach is used for building materials and material and energy consumption that have a large impact on the environment load, while analyzing the detailed items of input-output analysis. A combination of the two methods is used to analyze each stage of the industry and increase the accuracy and reliability [16, 17].

2.2. Life Cycle Inventory Database. Life Cycle Inventory Database (LCI DB) is a collective data of waste and emission generated from raw materials and energy resources needed in the production of materials. LCI DB is managed and provided worldwide, including the United States, Europe, and Australia. In Korea, the Korea Institute of Environmental Industry and Technology provides LCI DB developed by the Ministry of Environment and the Ministry of Industry and Trade. The entire production stages of the product are classified into the material and component manufacturing, processing process, transportation, and disposal, listing a total of 438 data [18–20].

2.3. Carbon Dioxide Basic Unit Calculation Structure. The CO₂ basic unit construction structure by work classification is calculated with the sum of CO₂ basic units in equipment, manpower, production, and transportation. The output structure is the same as Figure 2.

The CO₂ basic unit for the comprehensive work consists of the sum of the material CO₂ unit and the construction CO₂ basic unit. The construction CO₂ basic unit here is a combined value of construction CO₂ basic unit and CO₂ basic unit for equipment operation by manpower. Material CO₂ basic unit is calculated using the sum of the CO₂ basic unit generated in the process of material production and the CO₂ basic unit generated during the transportation of the materials. In this study, the CO₂ basic unit for equipment, manpower, production, and transportation is calculated since the working CO₂ unit is calculated [21, 22].

2.4. Review on the Preliminary Study of the Existing Carbon Dioxide Emissions. Many preliminary studies have been performed to calculate CO₂ emissions during the stage of construction by analyzing the CO₂ emitted from the materials used in the construction by means of the survey-based approach, input and output analysis, and hybrid approach [23–26]. Recently, the study related to the CO₂ emissions of the buildings was conducted using PC members. Among them, the study of Lim and Kim [8] is a very important study that selected a case and proved the effect of reducing CO₂ due to the on-site production of PC members. However, only CO₂ reduction effects according to manpower input were analyzed, and changes in the production environment were not considered. We analyze in more depth the CO₂ reduction effect of changes in the production environment based on Lim and Kim's [8] research. Lim and Kim [8] selected a case site, PC columns were produced through in situ and in-plant productions, and the CO₂ emissions were comparatively analyzed. As a result of the study, 211 T-CO₂ (22.6%) of CO₂ emission reduction effect was calculated by 72 PC columns made through in situ production, 641 T-CO₂ (22.8%) by 240 PC columns, and 2,647 T-CO₂ (15.7%) by 982 PC columns. The in situ production of the PC column was confirmed to be an eco-friendly way compared to in-plant production based on the calculation. To supplement this, the study on the CO₂ reduction effect includes the CO₂ emissions caused by manpower and the environment of in situ production.

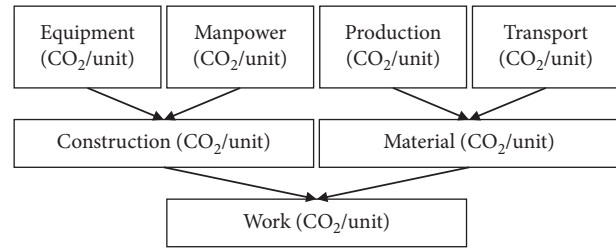


FIGURE 2: Carbon dioxide unit calculation structure [21].

3. CO₂ Emissions Based on Precast Concrete Member Production Method

3.1. CO₂ Emissions by Production, Transportation, and Equipment. According to the study results of Lim and Kim [8], only the amount of transportation equipment for transporting materials and equipment used in the construction stage was used to analyze the emission rate to compare and analyze the CO₂ emissions [27]. Data for CO₂ emission calculation were obtained from 28 constructions sites, and the proposed CO₂ unit was used [28]. The CO₂ emissions generated from the production, transportation, and equipment phases obtained from the study are shown in Table 1. It was confirmed to have the same amount of CO₂ emission in the result of calculation, production, and equipment. However, the transport phase showed different results, which is because the completed PC columns were produced immediately without the need of transportation for in situ production [29].

3.2. CO₂ Emissions by Manpower. In the site that was subjected in the study of Lim and Kim [8], manpower input volume was the same because the production process was proceeded equally to compare the PC column productivity of the plant and that of the site [30]. At this time, for the process of producing one PC column, it took 3 days (8 h of work time per day) based on the formwork assembly, reinforcement, concrete pouring, curing, and follow-up work. Additionally, the manpower involved in the production of the PC column was 30 people in total. Thus, CO₂ emissions by manpower appear differently for men and women. However, the manpower of the case site of Lim and Kim [8] was mostly male. Thus, the study also did not take into account the CO₂ emissions of women. To calculate the CO₂ emissions, the CO₂ emission of 549.4 mg/min per male person under 25°C was applied [31].

CO₂ emissions calculated by the manpower are shown in Table 2, i.e., the CO₂ generated by the manpower is 1.71 t-CO₂ in the case of producing 72 columns, 5.70 t-CO₂ in the case of producing 240 columns, and 23.31 t-CO₂ in the case of producing 982 columns.

3.3. CO₂ Emissions per Precast Concrete Column by Production Items. By adding CO₂ emissions from manpower to the preliminary study results, the results of CO₂ emissions calculated in PC column production items are the same as Table 3. The results of CO₂ emissions in the number of 72 PC, 240 PC, and 982 PC columns are 759.71 t-CO₂, 2,226.70

TABLE 1: CO₂ emissions for production, transportation, and equipment [8].

Classification	PC column of in situ			PC column of in-plant		
	72 EA	240 EA	982 EA	72 EA	240 EA	982 EA
Production	571	1,904	12,940	571	1,904	12,940
Equipment	187	317	1,530	187	317	1,530
Transport	—	—	—	178	592	2,421

*Note: unit = $t\text{-CO}_2$.

TABLE 2: CO₂ emissions for manpower.

Classification	72 EA	240 EA	982 EA
CO ₂ emission	1.71	5.70	23.31

*Note: unit = $t\text{-CO}_2$.

TABLE 3: CO₂ emissions in PC column by production stages.

Classification	PC column of in situ			PC column of in plant		
	72 EA	240 EA	982 EA	72 EA	240 EA	982 EA
Production	571.00	1,904.00	12,940.00	571.00	1,904.00	12,940.00
Equipment	187.00	317.00	1,530.00	187.00	317.00	1,530.00
Transport	—	—	—	178.00	592.00	2,421.00
Manpower	1.71	5.70	23.31	1.71	5.70	23.31
Total	759.71	2,226.70	14,493.31	937.71	2,818.70	16,914.31

*Note: unit = $t\text{-CO}_2$.

$t\text{-CO}_2$, and 14,493.31 $t\text{-CO}_2$, respectively, in the case of in situ production and 937.71 $t\text{-CO}_2$, 2,818.70 $t\text{-CO}_2$, and 16,914.31 $t\text{-CO}_2$, respectively, in the case of in-plant production. It was confirmed that the most CO₂ emissions were from the production stage using the material directly; the lowest CO₂ emissions were the manpower.

3.4. In-Plant Precast Concrete Production Environment.

In the case of in-plant PC column production and in situ production, the CO₂ emissions were the same in the stage other than transportation [32]. This is because when producing a PC column, the material and direct energy are equally consumed in the production stage. However, in the case of in-plant production, electricity and oil are consumed indirectly for the operation of the plant. Additionally, there are various factors necessary for production, such as plant maintenance and plant facility operation for plant operations [33]. Thus, CO₂ is generated according to the in-plant production environment.

In this study, based on the cost statement provided by the Korean “Daegu New Technology Platform,” the amount of CO₂ generated by the in-plant production environment was calculated. The reason why it was used as the calculation criteria was because the same PC method was used in this study, and “precast concrete beams for underground parking using a nontension lecture line-column nonseismic junction integrated method” in the same manner of the PC member production method of the study, which makes it possible to apply the original cost statement. Additionally, it was calculated based on the percentage of the amount calculated in the “2020 Construction and Industrial Environment Facilities Corporation Costing Ratio Application

Criteria” of the Korean Public Procurement Agency [34, 35]. In this study, each amount ratio was applied to the CO₂ emissions suitable for the criteria, and the contents calculated were CO₂ emissions, as discussed in Sections 3.5 and 3.6.

3.5. CO₂ Emissions from In-Plant Production Operations.

The elements required in the plant to produce a PC member are divided into three parts, namely, materials, fuel consumption, and power consumption required for production. The material elements required for production were excluded from this topic because they are the same in both in situ and in-plant productions. Fuel consumption factors include oil, natural gas, and coal, and the power consumption factor is motor, fan, dryer, and burner [36]. Therefore, the items of plant indirect expenditure related to this were classified into five categories: electricity, water, lighting, and heating, repair, supplies, and environmental conservation [37]. To obtain the expense of each item, a cost statement provided by the Korea Daegu New Technology Platform was applied.

The cost of electricity is the cost of operating the in-plant machinery to produce a PC member and electrical energy is required. Electricity is 6.47% of the direct material cost. The water, light, and heat costs refer to the sum of the costs of electricity, gas, and water used in the office of the plant. The water, light, and heat costs amount to 2.98% of the direct material cost. Repair costs are the cost of the internal structure of the plant and equipment movement, which varies depending on the absence of the in-plant production PC. The cost was ~2.47% of the direct material cost. In addition to direct materials for PC member production, the

cost of the material is not reused as a material used for the production of the product. The consumption cost required was 2.00% of the material cost directly. Finally, the environmental conservation cost is the cost of installing and operating the facility used to prevent environmental pollution in the plant [38]. The environmental conservation cost was 0.06% of the sum of direct labor costs, direct material costs, and expenses.

If we calculate the itemized CO₂ emissions proportional to each percentage of the amount, it is the same as outlined in Table 4. CO₂ emissions according to the number of PC columns 72, 240, and 982 were found to be 83.39 *t*-CO₂, 278.06 *t*-CO₂, and 1,889.70 *t*-CO₂, respectively.

3.6. CO₂ Emissions of Indirect Manpower Factors for In-Plant Production. In addition to the production manpower, it is necessary to operate the plant during the production period. There are manpower and plant maintenance and office manpower for maintenance such as regular inspections and safety checks [39, 40]. This manpower requirement is an indirect manpower element for PC member in-plant production. To calculate the CO₂ emissions accordingly, the indirect labor cost ratio of the Korean Public Procurement Agency was utilized. In the case of the site that was used for the study of Lim and Kim [8], it took ~6 months of the construction period to produce a PC member. Thus, in the case of construction sites less than 6 months and less than 5 billion won, indirect labor costs were calculated by applying 8% of the direct labor cost. Here the CO₂ caused by direct labor is a manpower CO₂ for PC member production. Therefore, the emissions were calculated using the CO₂ generated by the manpower. The calculated CO₂ emissions are shown in Table 5. CO₂ emissions according to the number of 72, 240, and 982 PC columns were found to be 0.14 *t*-CO₂, 0.46 *t*-CO₂, and 1.86 *t*-CO₂, respectively.

3.7. CO₂ Emissions by In-Plant Production Environmental Factors. When the PC member is made by in-plant production, the generated CO₂ emissions were calculated through the indirect cost ratio. The output was calculated according to the CO₂ unit calculation structure of a total of six items—electricity, water or thermal, repair, supplies, environmental conservation, and indirect labor costs—as shown in Table 6. The calculated CO₂ emissions are 83.57 *t*-CO₂, 278.56 *t*-CO₂, and 1,891.57 *t*-CO₂, and the item showing the highest emission ratio is electricity, depending on the number of PC columns 72, 240, and 982. Based on the number of 982 PC columns, the analysis of the total CO₂ emissions by the in-plant production environment itemized ratio confirmed that the power cost has the most impact on CO₂ emissions to 44.26%. Items with high CO₂ emissions after the power cost were analyzed for water, light, and heat, repair, and environmental conservation costs. However, the least affected by CO₂ emissions has been identified as the manpower, and the itemized ratio is 0.10%. CO₂ emissions were also analyzed at the lowest value of 1.86 *t*-CO₂.

TABLE 4: CO₂ emissions of in-plant operation factors.

Cost classification	72 EA	240 EA	982 EA
Electricity	36.94	123.19	837.22
Water, lighting, and heating	17.02	56.74	385.61
Repair	14.10	47.03	319.62
Supplies	11.42	38.08	258.8
Environmental conservation	3.90	13.02	88.46
Total	83.39	278.06	1,889.70

*Note: unit = *t*-CO₂.

TABLE 5: CO₂ emissions of in-plant manpower.

Classification	72 EA	240 EA	982 EA
CO ₂ emission	0.14	0.46	1.86

*Note: unit = *t*-CO₂.

4. CO₂ Emission Reduction Effect through Precast Concrete In Situ Production

In this study, CO₂ emissions of in situ production and those of in-plant production were compared to PC column production. Manpower and in-plant production environmental factors that were excluded from prestudy were included, and CO₂ emissions from in situ and in-plant productions are the same as Table 7.

Considering item by item, the item that produced the largest amount of CO₂ based on 982 PC manpower is the production stage, and the manpower is the item that produced the least CO₂ emissions. Therefore, it is confirmed that the manpower is the item that has the least CO₂ emissions, which is the same as shown in the result of in-plant production environmental factors. The reason why the in situ production of PC column shows low CO₂ emissions compared to in-plant production is because there is no need of vehicle movement required for PC column transportation and there is no indirect factor that is consumed in in-plant management. Considering the total CO₂ emissions of Table 7, it was calculated to be 759.71 *t*-CO₂, 2226.70 *t*-CO₂, and 14493.31 *t*-CO₂ in the case of in situ production on the standard of the number of 72, 240, and 982 PC columns, respectively, and in the case of in plant production, it was calculated as 1021.34 *t*-CO₂, 3109.05 *t*-CO₂, and 18,805.88 *t*-CO₂, respectively.

Through the calculated CO₂ emissions, it can be seen that PC column in situ production emits less CO₂ than in-plant production, and comparison of CO₂ reduction in in situ production and in-plant production is shown in Figure 3. In the case of 72, 240, and 982 PC columns in number, CO₂ emission reduction effects by quantity were confirmed as 261.63 *t*-CO₂ (25.62%), 882.35 *t*-CO₂ (28.38%), and 4312.57 *t*-CO₂ (22.93%), respectively.

Therefore, more than 22.93% of CO₂ emission reduction effect compared to in-plant production can be obtained in the case of in situ production of PC column. In this study, the calculation of the CO₂ emission reduction effect through the in situ production of PC members is limited to the column. However, if applied to the in situ production of other PC members beside the column, much more CO₂ reduction effects will be expected.

TABLE 6: CO₂ emissions generated by in-plant production environmental factors.

Cost classification	72 EA	240 EA	982 EA	
	CO ₂ emission	CO ₂ emission	CO ₂ emission	Ratio (%)
Electricity	36.94	123.19	837.22	44.26
Water, lighting, and heating	17.02	56.74	385.61	20.39
Repair	14.10	47.03	319.62	16.90
Supplies	11.42	38.08	258.80	13.63
Environmental conservation	3.90	13.02	88.46	4.68
Manpower	0.14	0.46	1.86	0.10
Total	83.52	278.52	1,891.57	100.00

*Note: unit = t-CO₂.

TABLE 7: CO₂ emissions of precast concrete column based on in situ production and in-plant production.

Classification	PC column of in situ			PC column of in-plant		
	72 EA	240 EA	982 EA	72 EA	240 EA	982 EA
Production	571.00	1,904.00	12,940.00	571.00	1,904.00	12,940.00
Equipment	187.00	317.00	1,530.00	187.00	317.00	1,530.00
Transport	—	—	—	178.00	592.00	2,421.00
Manpower	1.71	5.70	23.31	1.71	5.70	23.31
Plant elements	—	—	—	83.52	278.52	1,891.57
Total	759.71	2226.70	14493.31	1021.34	3109.05	18,805.88

*Note: unit = t-CO₂.

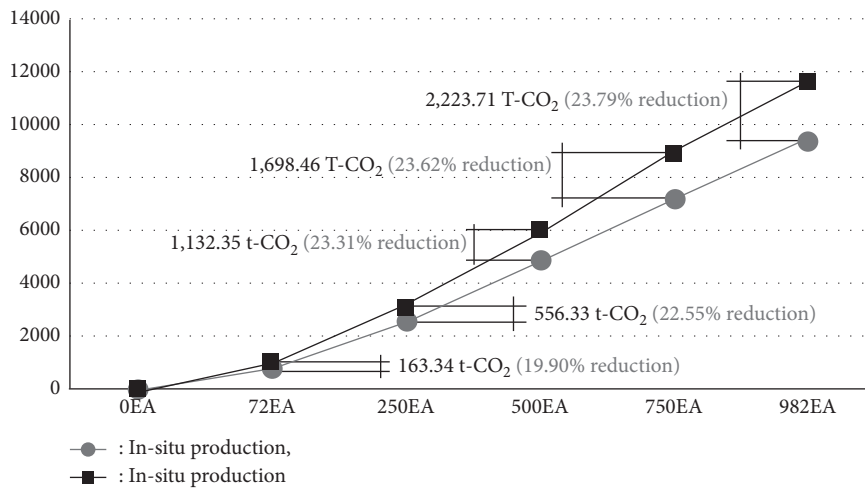


FIGURE 3: Comparing CO₂ reduction in in situ production and in-plant production.

5. Conclusion

In this study, the carbon dioxide emission generated in the environment of the in-plant production of PC members was analyzed to compare CO₂ emission of in situ production with that of in-plant production. Through the results of the analysis, the reduction effect of the CO₂ emission was also analyzed according to the types of production. For the analysis on the CO₂ reduction effect, the extra study targeting the site of prestudy was performed. The CO₂ emission and the environmental factors of in-plant production regarding the shortage of manpower in the prestudy were analyzed, on which the calculation of the CO₂ emission was based. In the case of the in situ production of PC column, it

was confirmed through the calculated results that there was a reduction in CO₂ emission compared to in-plant production.

First, the CO₂ emissions of production, transportation, and equipment as elements that are directly required for PC column production in the construction site were examined. Then, to analyze the CO₂ emissions by the manpower, the data of manpower that were put in for production and the amount of CO₂ emitted per person per minute were utilized. As a result of the calculation, the emissions of 1.71 t-CO₂, 5.70 t-CO₂, and 23.31 t-CO₂ according to columns 72, 240, and 982, respectively, were calculated. Also, regarding the environment of in-plant production, the factors that are indirectly required for PC column production were

analyzed, and they were classified into items of power, fuel, and manpower consumptions, and CO₂ emissions of the items were analyzed. The in-plant production environment CO₂ emissions were calculated through CO₂ directly emitted in the production of the PC column and the proportion of the amount required per item. As a result, the emissions of 83.52 t-CO₂, 278.52 t-CO₂, and 1,891.57 t-CO₂ were yielded according to the number of columns 72, 240, and 982, respectively. Additionally, the highest CO₂ emission ratio was the item of power cost as 44.26%, and the smallest percentage was confirmed to be the manpower as 0.10%. Finally, the total CO₂ emissions of the calculated in-plant and in situ productions were analyzed. The difference of CO₂ emission is 261.63 t-CO₂, 882.35 t-CO₂, and 4,312.57 t-CO₂ based on the number of columns 72, 240, and 982, respectively, through which the CO₂ emission reduction effect of 25.62%, 28.38%, and 22.93% was confirmed. The items for the production of PC column were classified into production, transportation, equipment, manpower, and in-plant production environment and, then, CO₂ basic unit per item was calculated. Compared to the sum of CO₂ basic unit per item estimated, the CO₂ emission reduction effect of average 25.64% was confirmed compared to in-plant production in the case of in situ production. The results will contribute to the reduction of CO₂ emissions through the in situ production of PC members and establish a CO₂ emission reduction plan for construction sites.

Data Availability

Data sharing is not applicable to this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

- [1] T. Kim and S. Tae, "A study on the development of an evaluation system of CO₂ Emission in the production of concrete," *Journal of the Korea Concrete Institute*, vol. 22, no. 6, pp. 787–796, 2010.
- [2] Ministry of Environment, "National greenhouse gas inventory report of Korea," 2019, <http://www.me.go.kr/home/web/main.do>.
- [3] S. Kim, H. Lee, H. Kim et al., "Improvement in policy and proactive interconnection procedure for renewable energy expansion in South Korea," *Renewable and Sustainable Energy Reviews*, vol. 98, pp. 150–162, 2018.
- [4] C. Hendrickson, A. Horvath, S. Joshi, and L. Lave, "Economic input-output models for environmental life-cycle assessment," *Environmental Science & Technology*, vol. 32, no. 184, p. e191, 1998.
- [5] S. Liu, R. Tao, and C. M. Tam, "Optimizing cost and CO₂ emission for construction projects using particle swarm optimization," *Habitat International*, vol. 37, pp. 155–162, 2013.
- [6] F. Meggers, H. Leibundgut, S. Kennedy et al., "Reduce CO₂ from buildings with Technology to zero emissions," *Sustainable Cities and Society*, vol. 2, no. 1, pp. 29–36, 2012.
- [7] M. J. González and J. G. Navarro, "Assessment of the decrease of CO₂ emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact," *Building and Environment*, vol. 41, no. 7, pp. 902–909, 2006.
- [8] J. Y. Lim and S. K. Kim, "Evaluation of CO₂ emission reduction effect using in-situ production of precast concrete components," *Journal of Asian Architecture and Building Engineering*, vol. 19, no. 2, pp. 176–186, 2019.
- [9] S. H. Tae, S. W. Shin, J. H. Woo, and S. G. Roh, "The development of apartment house life cycle CO₂ simple assessment system using standard apartment houses of South Korea," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1454–1467, 2011.
- [10] J. Yan, T. Zhao, and J. Kang, "Sensitivity analysis of Technology and supply change for CO₂ emission intensity of energy-intensive industries based on input-output model," *Applied Energy*, vol. 171, pp. 456–467, 2016.
- [11] K. H. Lee and J. H. Yang, "A study on the functional unit estimation of energy consumption and carbon dioxide emission in the construction materials," *Journal of the Architectural Institute of Korea Planning & design*, vol. 25, no. 6, pp. 43–50, 2009.
- [12] C. Leroy, "Provision of LCI data in the European aluminium industry methods and examples," *International Journal of Life Cycle Assessment*, vol. 14, no. 1, pp. 10–44, 2009.
- [13] B. Su, H. C. Huang, B. W. Ang, and P. Zhou, "Input-output analysis of CO₂ emissions embodied in trade: the effects of sector aggregation," *Energy Economics*, vol. 32, no. 1, pp. 166–175, 2010.
- [14] H. S. Lee, "A Comparative Study of Energy Consumption of Building Materials and Articles and Units of Carbon Dioxide Emission," Andong National University, Andong, Republic of Korea, 2010, <http://www.riss.kr/link?id=T11968554> Masters Dissertation.
- [15] Z. Zhang and H. Folmer, "Economic modelling approaches to cost estimates for the control of carbon dioxide emissions," *Energy Economics*, vol. 20, no. 1, pp. 101–120, 1998.
- [16] H. Leong, H. Leong, D. C. Foo, L. Y. Ng, and V. Andiappan, "Hybrid approach for carbon-constrained planning of bio-energy supply chain network," *Sustainable Production and Consumption*, vol. 18, no. 1, pp. 250–267, 2019.
- [17] M. L. Lahr, "A review of the literature supporting the hybrid approach to constructing regional input-output models," *Economic Systems Research*, vol. 5, no. 3, pp. 277–293, 1993.
- [18] W. S. Song, "BIM-based CO₂ Emission Measurement Program in Accordance with Building Life-Cycle," Soongsil University, Seoul, Republic of Korea, 2014, <http://www.riss.kr/link?id=T13368842> Masters Dissertation.
- [19] R. H. Kim, S. H. Tae, J. H. Kim, and J. G. Lee, "The development and application of environmental impact assessment program for apartment building element based on building materials LCI DB," *Korea Institute of Ecological Architecture and Environment*, vol. 16, no. 6, pp. 151–157, 2016.
- [20] M. O. de Eicker, R. Hischier, L. A. Kulay, and M. Lehmann, "The applicability of non-local LCI data for LCA," *Environmental Impact Assessment Review*, vol. 30, no. 3, pp. 192–199, 2010.

- [21] R. T. Pacheco, E. Jdraque, J. F. Roldán, and J. Ordóñez, "Analysis of CO₂ emissions in the construction phase of single-family detached houses," *Sustainable cities and society*, vol. 12, pp. 63–68, 2014.
- [22] S. K. Kim, S. H. Lee, Y. J. Na, and J. T. Kim, "Conceptual model for LCC-based LCCO₂ analysis of apartment buildings," *Energy and Buildings*, vol. 64, pp. 285–291, 2013.
- [23] K. H. Lee and K. H. Lee, "Journal of the architectural institute of Korea," vol. 12, pp. 197–204, 1996.
- [24] K. H. Lee and C. U. Choi, "A study on the amount of the energy consumption and CO₂ emission of public buildings using the input-output analysis," *Journal of the Architectural Institute of Korea Planning and Design*, vol. 18, no. 5, pp. 99–108, 2002, <http://www.dbpia.co.kr/journal/articleDetail?nodeId=NODE00364688>.
- [25] L. Huang, G. Krigsvoll, F. Johansen, Y. Liu, and X. Zhang, "Carbon emission of global construction sector," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1906–1916, 2018.
- [26] D. B. Lim, S. H. Son, S. K. Kim, and J. Y. Park, "Life cycle cost and CO₂ emission simulation models of apartment building projects using system dynamics," *Indoor and Built Environment*, vol. 28, no. 3, pp. 310–321, 2019.
- [27] J. Y. Lim and J. J. Kim, "Dynamic optimization model for estimating in-situ production quantity of PC members to minimize environmental loads," *Sustainability*, vol. 12, no. 19, p. 8202, 2020.
- [28] S. W. Kim, J. Y. Kim, J. S. Lee, K. H. Park, and Y. W. Hwang, "The Environmental Load Unit Composition and Program Development for LCA of Building: The Second Annual Report of the Construction Technology R&D Program," 2004, <http://www.ndsl.kr/ndsl/search/detail/report/reportSearchResultDetail.do?cn=TRKO201800015586>.
- [29] D. Y. Choi and S. K. Kim, "A study on a carbon emission and reduction plan for the construction phase of a natural gas plant," *Journal of Korean Society of Hazard Mitigation*, vol. 13, no. 4, pp. 323–331, 2013.
- [30] J. Lim, K. Park, S. Son, and S. Kim, "Cost reduction effects of in-situ PC production for heavily loaded long-span buildings," *Journal of Asian Architecture and Building Engineering*, vol. 19, no. 3, pp. 242–253, 2020.
- [31] Y. M. Cho, J. Y. Lee, S. B. Kwon, D. S. Park, J. H. Park, and K. C. Cho, "The distribution characteristics of carbon dioxide in indoor school spaces," *Journal of Korean Society for Atmospheric Environment*, vol. 27, no. 1, pp. 117–125, 2010.
- [32] J. Lim, S. Kim, and J. J. Kim, "Dynamic simulation model for estimating in-situ production quantity of PC members," *International Journal of Civil Engineering*, vol. 12, no. 19, 2020.
- [33] M. K. Kim, J. H. Choi, and D. M. Choi, "A study on the effective maintenance strategy of the fire Facilities in plant," *Journal of the Korean Society of Hazard Mitigation*, vol. 18, no. 3, pp. 173–180, 2018.
- [34] New Technology Platform of Daegu Metropolitan City, "Calculation of the Integral Court Value of Precast Concrete Beam-Column Non-earthquake Resistant Joints for Underground Parking Lots Using Non-strength Lecture Lines," 2014, <https://singisul.daegu.go.kr/>.
- [35] Public Procurement Service, "Standard for Application of the Cost Calculation Ratio of Building and Industrial Environment Facility Construction in 2020," 2020, <http://www.pps.go.kr/>.
- [36] L. Shen, T. Gao, J. Zhao et al., "Factory-level measurements on CO₂ emission factors of cement production in China," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 337–349, 2014.
- [37] W. K. Hong, S. C. Park, and M. M. Kim, "Development of structural composite hybrid systems and their application with regard to the reduction of CO₂ emissions," *Indoor and Built Environment*, vol. 19, no. 1, pp. 151–162, 2010.
- [38] Korea Institute of Civil Engineering and Building Technology, "A Study on Introduction Plan of Precast Concrete Plant Certification," 2013, <https://www.codil.or.kr/viewDtlConRpt.do?gubun=rpt&pMetaCode=OTKCRK185169>.
- [39] M. B. Sarder, S. N. Imrhan, and N. Mandahawi, "Ergonomic workplace evaluation of an Asian garment-factory," *Journal of Human Ergology*, vol. 35, no. 1-2, pp. 45–51, 2006.
- [40] G. Cho and J. Y. Kim, "An efficient technique for facility maintenance workforce scheduling in petroleum chemistry plant: a case study," *Journal of Industrial Economics and Business*, vol. 20, pp. 305–320, 2007, <https://www.dbpia.co.kr/journal/articleDetail?nodeId=NODE01658897>.