

Article

Evaluation Analysis of the CO₂ Emission and Absorption Life Cycle for Precast Concrete in Korea

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Abstract: To comply with recent international trends and initiatives, and in order to help achieve sustainable development, Korea has established a greenhouse gas (GHG) emission reduction target of 37% (851 million tons) of the business as usual (BAU) rate by 2030. Regarding environmentally-oriented standards such as the IGCC (International Green Construction Code), there are also rising demands for the assessment on CO₂ emissions during the life cycle in accordance with ISO (International Standardization Organization's Standard) 14040. At present, precast concrete (PC) engineering-related studies primarily cover structural and construction aspects, including improvement of structural performance in the joint, introduction of pre-stressed concrete and development of half PC. In the manufacture of PC, steam curing is mostly used for the early-strength development of concrete. In steam curing, a large amount of CO₂ is produced, causing an environmental problem. Therefore, this study proposes a method to assess CO₂ emissions (including absorption) throughout the PC life cycle by using a life cycle assessment (LCA) method. Using the proposed assessment method, CO₂ emissions during the life cycle of a precast concrete girder (PCG) were assessed. In addition, CO₂ absorption was assessed against a PCG using conventional carbonation and CO₂ absorption-related models. As a result, the CO₂ emissions throughout the life cycle of the PCG were 1365.6 (kg-CO₂/1 PCG). The CO₂ emissions during the production of raw materials among the CO₂ emissions throughout the life cycle of the PCG were 1390 (kg-CO₂/1 PCG), accounting for a high portion to total CO₂ emissions (nearly 90%). In contrast, the transportation and manufacture stages were 1% and 10%, respectively, having little effect on total CO₂ emissions. Among the use of the PCG, CO₂ absorption was mostly decided by the CO₂ diffusion coefficient and the amount of CO₂ absorption by cement paste. The CO₂ absorption by carbonation throughout the service life of the PC was about 11% of the total CO₂ emissions, which is about 16% of CO₂ emissions from ordinary Portland cement (OPC) concrete.

Keywords: precast concrete; life cycle assessment; carbon dioxide; CO₂ absorption; carbonation

1. Introduction

Internationally, greenhouse gases (GHGs) are arguably the most prevalent global environmental problem. In an effort to curb the release of GHGs, there has been an assortment of international movements that aspire to cap and/or reduce GHG emissions. To comply with this international trend, and to achieve sustainable development, Korea has established the GHG emission reduction target of 37% (851 million tons) of business as usual (BAU) rates by 2030 [1].

The building construction industry has played a role in impoverishing the environment; developments have occurred for the sake of improving our quality of life, but at a great cost of impact to the environment [2]. It is therefore incumbent upon the industry to endeavor to mitigate the effects from building construction projects on our environment [3,4].

The major construction materials accounting for about 65% of building greenhouse gas emissions include concrete and reinforcement steel. Among the CO₂ emissions generated by these major construction materials, concrete accounts for 40% [5,6].

Therefore, an assessment of the CO₂ emissions throughout the concrete life cycle has been conducted. Regarding environmentally-oriented standards such as the IGCC (International Green Construction Code) [7], there are also rising demands for the assessment on CO₂ emissions during the life cycle in accordance with ISO (International Standardization Organization's Standard) 14040 [8]. Recently, concrete research institutes in Northern Europe, such as the Swedish Cement and Concrete Institute (CBI) [9], insist that CO₂ emissions by concrete are overestimated if only processes of production are considered, and thus propose that CO₂ absorption by carbonation during the use of a structure should also be considered.

The system boundaries designed to assess CO₂ emissions throughout the concrete life cycle were drawn between the following stages: raw material, transportation, manufacture, use. However, it has been very hard to find a study on the assessment method and analysis of CO₂ emissions of precast concrete (PC). PC engineering is defined as a process of transporting the manufactured concrete member to a construction and civil-engineering site and assembling it properly. It is widely used in construction sites, such as in the underground spaces of apartments and stadiums due to its easy process management and great constructability. Now, PC is perceived as the future of construction engineering because of the shortening of the construction period, quality improvement, decrease in accidents, and eco-friendly concrete option that it provides to the construction industry. PC engineering was first introduced to the Republic of Korea in the early 1970s with the goal of supplying houses in large quantities. After reaching a peak in the late 1980s, it has lost its competitiveness due to poor technology and quality. Entering the new millennium, it is widely used again in various fields such as in stadium, underground parking lot, discount store, warehouse, and factory construction [10].

At present, PC engineering-related studies primarily cover structural and construction-related aspects, including the improvement of structural performance in the joints, the introduction of prestressed concrete, and the development of half PC. In the manufacture of PC, steam curing is mostly used for the early-strength development of concrete. At least 10 h of steam curing is used every day. In steam curing, a large amount of CO₂ is produced, thereby causing an environmental problem [11].

Hence, this study proposes a method to assess CO₂ emissions (including absorption) throughout the PC life cycle, using a life cycle assessment (LCA) method. Using the proposed assessment method, CO₂ emissions during the life cycle of PC girders (PCGs) were assessed. In addition, CO₂ absorption was assessed for PCGs, using conventional carbonation and CO₂ absorption-related models.

2. Literature Review

2.1. CO₂ Emission of Precast Concrete

Victor et al. described a methodology to optimize cost and CO₂ emissions when designing precast-prestressed concrete road bridges with a double U-shape cross-section: To this end, a hybrid glowworm swarm optimization algorithm (SAGSO) was used to combine the synergy effect of the local search with simulated annealing (SA) and the global search with glowworm swarm optimization (GSO) [12].

Duo et al. developed the precast concrete panel by substituting blast-furnace slag for part of the unit weight of cement in the precast concrete mix. A life cycle assessment technique was used to estimate the carbon dioxide reduction. Carbon reduction in the materials, as well as during the production phase, was considered [13].

Carlo et al. focused on the analysis of the entire main input inventory data used for assessing the environmental impacts linked to the life cycle of a precast concrete shed: great importance was given to the use of on-site collected specific data which was carefully verified in order to assure its quality and reliability [14].

Ya et al. compared the carbon emissions of precast and traditional cast-in-situ construction methods based on a case study of a private residential building in Hong Kong [15]. The objective of this study was to develop energy-efficient algorithms of the steam curing for the in situ production of PC members. The results of this study will provide basic information for subsequent efforts to implement an energy-efficient in situ PC production system [16].

Cassgnabere et al. discussed the results of a hydration study performed in order to explain the significant increase in compressive strength at one day of age observed on steam cured mortars when 25% by mass of cement was replaced with a metakaolin [17].

2.2. Carbonation and Absorption of Precast Concrete

Pade et al. [18] stated that CO₂ produced during cement sintering is mostly absorbed through concrete carbonation if the structure's life cycle (100 years) is considered. Liwu et al. established an understanding of the effectiveness of accelerating the carbonation process. Pressurized CO₂ (up to 1.0 MPa) was employed to enhance the carbonation of mortar blends consisting of Portland cement, fly ash, and reactive MgO [19].

Lee et al. described a numerical procedure to quantitatively evaluate carbon dioxide emissions and the absorption of ground granulated blast furnace slag (GGBFS) blended concrete structures. Based on building scales and drawings, the total volume and surface area of concrete were calculated [20].

Elke et al. performed accelerated carbonation tests on concrete specimens containing different amounts of blast-furnace slag (BFS) after different curing times. The tests revealed that, although BFS concrete has a lower carbonation resistance than ordinary Portland cement (OPC) concrete, the depth of carbonation at the end of the concrete's life (50 years) can still be acceptable in normal environments [21].

Gajda stated that among the service life of concrete structures, carbonation-based CO₂ retention capacity accounted for 3%–4% of the CO₂ emissions from the production of cement [22]. Lee et al. suggested that in concrete structures CO₂ retention capacity did not exceed 5% of the CO₂ emissions from the production of concrete [23]. In contrast, Pade et al. noted that if a recycling stage is considered along with the use stage, CO₂ emitted by chemical response during the sintering process designed to produce clinker can be collected through carbonation [18]. Yang et al. described a mathematical procedure which can estimate CO₂ retention capacity through the carbonation of concrete in each stage suggested for the assessment of the CO₂ emissions during the concrete life cycle in a reasonable fashion [24].

3. Assessment of CO₂ Emission in the Precast Concrete

The PC manufacturing process can be divided into three stages: raw material, transportation, and manufacture. In the raw material stage, the mixed ingredients of concrete (e.g., cement, aggregate, admixture, etc.) and reinforcing bar (rebar) used to produce PC are individually manufactured and transported to the PC manufacturer. These materials are weighed in a certain ratio and cast into a cement mold to produce PC. The PC production process is shown in Figure 1:

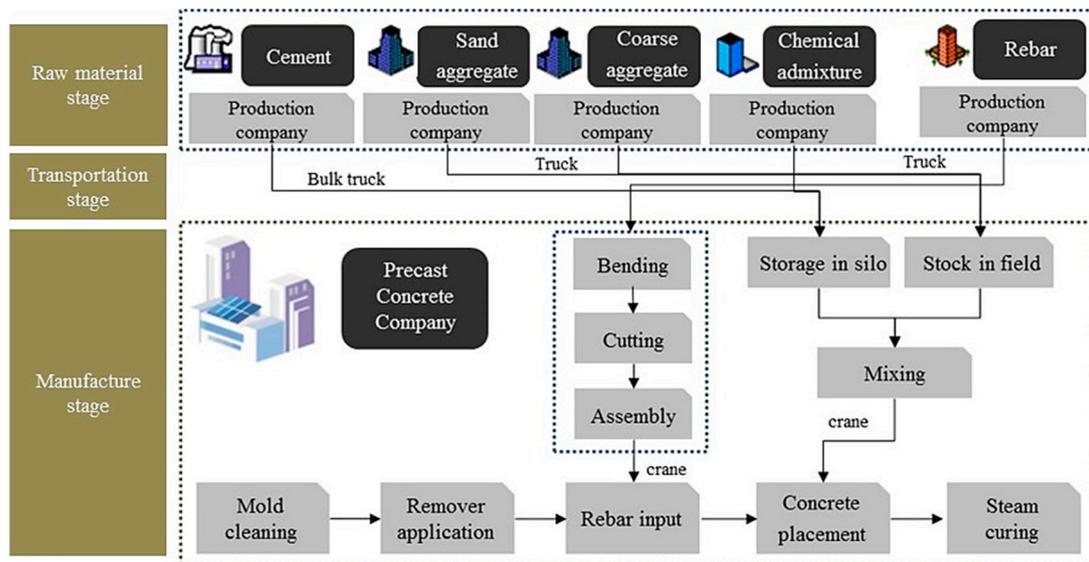


Figure 1. Production process of precast concrete.

3.1. Raw Material Stage

(1) Concrete

Using the CO₂ emission factors emitted during the production of concrete mix ingredients (m³) which are used to manufacture PC, CO₂ emission for concrete is estimated by the accumulation of multiplication between the mixing volume of each ingredient per 1 m³ and a greenhouse gas emission factor for the production of concrete (kg) [25].

For the CO₂ emission factors of concrete ingredients (ordinary Portland cement, aggregate, admixture, and water), the Korean life cycle inventory (LCI) database was adopted [26]. For the chemical admixtures without CO₂ emission factors in Korea, a foreign LCI database (Table 1) was applied [27].

Table 1. Life cycle inventory (LCI) Database (DB) reference.

Material	Unit	Reference Basis [26,27]
Ordinary Portland Cement	kg	National LCI DB (South Korea)
Coarse aggregate	kg	National LCI DB (South Korea)
Fine aggregate	kg	National LCI DB (South Korea)
Blast-furnace slag powder	kg	Overseas LCI DB (ecoinvent)
Fly ash	kg	Overseas LCI DB (ecoinvent)
Water	kg	National LCI DB (South Korea)
Chemical Admixture compound	kg	Overseas LCI DB (ecoinvent)
Reinforcing bar	kg	National LCI DB (South Korea)
Truck	km	National LCI DB (South Korea)
Train	km	National LCI DB (South Korea)
Diesel	L	National LCI DB (South Korea)
Kerosene	L	National LCI DB (South Korea)
LPG	m ³	National LCI DB (South Korea)
Electricity	kwh	National LCI DB (South Korea)

(2) Reinforcing Bar

CO₂ emission for reinforcing bar is estimated by the accumulation of multiplication between the input (kg/rebar) and CO₂ emission factor for the production of PC.

$$\text{CO}_2\text{M} = \sum (\text{M}(i) \times \text{CO}_2 \text{ emission factor } M) \quad (1)$$

(i = 1: cement, 2: aggregate, 3: admixture, 4: water, 5: reinforcing bar)

Here, CO_2M is the CO_2 emission quantity at the raw material stage of the production of a unit of concrete ($\text{kg-CO}_2/\text{m}^3$); $\text{M}(i)$ is the amount of material used (kg/m^3) in the concrete; and the CO_2 emission factor M is the CO_2 emission factor for each material ($\text{kg-CO}_2/\text{kg}$).

3.2. Transportation Stage

Among the concrete mix ingredients, ordinary Portland cement (OPC) concrete is transported from the production plant to a transit point through a bulk train. The cement at the transit point is then delivered to a ready-mix concrete manufacturing plant through a bulk cement truck (BCT). If the plant was situated in a coastal area, railroad transport accounted for about 25% of total cement transportation. When it was located in an inland region, railroad transport was as high as 60%–70%. For the assessment of CO_2 emissions during the transportation stage, the number of transportation-related vehicles/pieces of equipment is estimated with the input of concrete ingredients and reinforcing bars and the load of transportation-related vehicles/pieces of equipment. Considering distance and fuel efficiency in addition to the number of the estimated transportation-related vehicles/pieces of equipment, the consumption of diesel oil and CO_2 emissions are assessed. The calculation formula for CO_2 emissions during the transportation stage is shown in Equation (2):

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

(i = 1: cement, 2: aggregate, 3: admixture 4: reinforcing bar)

Here, CO_2T is the quantity of CO_2 emitted during the transportation of a unit of produced concrete ($\text{kg-CO}_2/\text{m}^3$); $\text{M}(i)$ is the amount of material used (kg/m^3) in the concrete; Lt is the transportation load (tons); d is the transportation distance (km); e is the fuel efficiency (km/L); and CO_2 emission factor T is the CO_2 emission factor of the energy resource ($\text{kg-CO}_2/\text{kg}$).

3.3. Manufacturing Stage

The CO_2 emissions during the manufacturing stage are estimated after measuring the amount of energy consumed during the unloading of raw materials and the manufacturing of reinforcing bars (Figure 2). For this, the amount of energy consumption should be estimated first. After investigating the type and specification of the facilities which consume electricity, diesel oil, LNG (Liquefied Natural Gas), and water, annual energy consumption and output are analyzed. Then, energy consumption and CO_2 emissions can be estimated for the manufacture of the PC product 1. The calculation formula for CO_2 emissions during the manufacturing stage is shown in Equation (3):

$$\text{CO}_2\text{F} = \sum [(E(i)/R) \times \text{CO}_2 \text{ emission factor } F] \quad (3)$$

(i = 1: electricity usage, 2: oil usage, 3: water usage)

Here, CO_2F is the amount of CO_2 emitted during the concrete manufacturing stage for producing a unit of concrete ($\text{kg-CO}_2/\text{m}^3$); R denotes the annual RMC (Ready-mixed Concrete) production (m^3/year); $E(i)$ denotes the annual energy usage (unit/year), and CO_2 emission factor F is the CO_2 emission factor of an energy resource ($\text{kg-CO}_2/\text{kg}$).

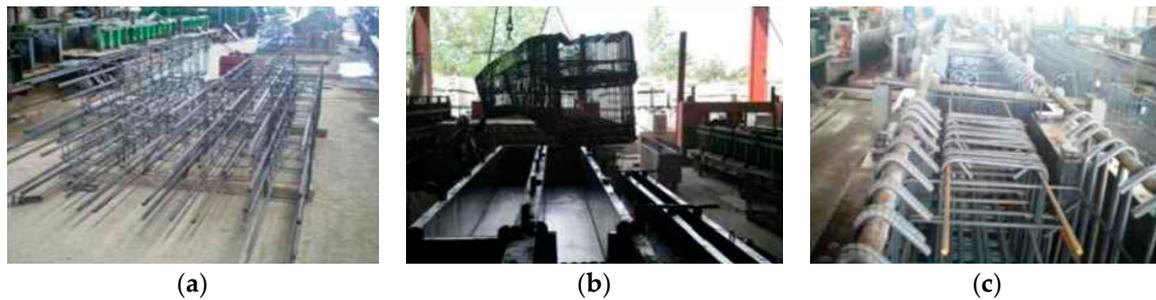


Figure 2. Assembly (a); insertion of steel (b); embedment installation (c) of reinforcing bars for precast concrete.

4. Assessment of CO₂ Absorption in Precast Concrete

The CO₂ absorption by concrete carbonation during the use of PC only was considered. In terms of a service life, 40 years are set according to the standard useful life of buildings under the Enforcement Rules of Corporate Tax Act [28]. The CO₂ absorption during the use of PC is determined by the depth of carbonation. To assess CO₂ absorption by concrete carbonation, it is required to predict the exact depth of carbonation by age. Since CO₂ absorption is assessed during the use of a building, environmental factors and concrete exposure conditions should also be considered with significance in predicting the depth of carbonation.

The CO₂ absorption (CO₂ U(t)) by carbonation for t(days) is stated below:

$$\text{CO}_2 \text{ U}(t) = A_{\text{CO}_2}(t) \times W_a \times K_c(t) \text{ (g)} \quad (4)$$

Here, $A_{\text{CO}_2}(t)$ refers to the amount of absorbable CO₂ (g/cm³) by carbonation at age t days while W_a represents the surface area (cm²) of the concrete member exposed to CO₂. In addition, $K_c(t)$ denotes the depth of carbonation at age t days.

4.1. Absorbable CO₂

Among the minerals which constitute cement paste and hydrates, $A_{\text{CO}_2}(t)$ which is decided by the water concentration of carbonation-enabled factors can be estimated as follows [29]:

$$A_{\text{CO}_2}(t) = a_h(t) \times M_d(t) \times M_{\text{CO}_2} \times 10^{-6} \text{ (g/cm}^3\text{)} \quad (5)$$

Here, $a_h(t)$ refers to the degree of hydration of cement paste at age t days while $M_d(t)$ represents the water concentration (mol/cm³) of carbonation-enabled factors in cement paste per concrete unit volume at age t days. In addition, M_{CO_2} (=44 g/mol) means molar mass of CO₂.

Papadakis et al. [29] suggested a mathematical model to set $M_d(t)$ in a fully hydrated state based on the chemical response of hydrates. Because the molar concentration of carbonation-enabled elements are estimated based on the molar mass of major cement ingredients, $M_d(t)$ is greatly influenced by the amount of unit cement. $M_d(t)$ gradually decreases over time. After one year, it converged to an almost constant value.

Therefore, $M_d(t)$ can be estimated in a simple fashion:

$$M_d(t) = 8.06 C (\times 10^{-6} \text{ mol/cm}^3\text{)} \quad (6)$$

The cement with general fineness is not fully hydrated even for 100 years. The degree of cement hydration by age reveals a parabola which converges to the extreme degree of hydration (∞). The pores of cement paste decline over time due to the progress of hydration and carbonation. After 100 days, however, the slope of decrease is close to zero. Yang et al. [24] modeled $a_h(t)$ with a water-cement ratio (W/C) based on experimental results [30].

$$Ah(t) = t/(2.0 + t) \times A(\infty) \quad (7)$$

$$A(\infty) = 1.03(W/C)/(0.19 + W/C) \quad (8)$$

In the service life (four decades) of the concrete structure from Equations (7) and (8) above, the difference between $Ah(t)$ and $A(\infty)$ is small enough to be ignored.

4.2. Carbonation Depth and CO₂ Diffusion Coefficient

In general, the carbonation depth of concrete ($K_c(t)$) is generalized as a carbonation velocity-time function as follows:

$$K_c(t) = \sqrt{\frac{2D_{CO_2}(t)}{A_{CO_2}(t)}} \times S_{CO_2} \quad (9)$$

Here, D_{CO_2} refers to the diffusion coefficient (cm²/day) at age t days while S_{CO_2} represents CO₂ mass concentration (g/cm³) on the concrete surface. The volume concentration of CO₂ (ppm) is converted into mass concentration using the ideal gas theory. In concrete, the diffusion velocity of CO₂ is influenced by its exposure conditions (relative humidity, temperature, concrete surface conditions) as well as by material properties (water-cement ratio, degree of hydration, pore size distribution, degree of saturation). As Pommer et al. [31] pointed out, in addition, supplementary cementing materials (SCMs) also have a significant effect on the diffusion velocity of CO₂. The concrete surface's finish blocks the penetration of carbonic acid gas and slows down carbonation [32]. Table 2 reveals calibration coefficients for the admixture replacement [31] while Table 3 represents calibration coefficients [32] for the finished material.

Table 2. Correction factor for the substitution of supplementary cementitious materials (SCMs).

Type	Substitution Level of SCMs (%)					
	0–10	10–20	20–30	30–40	40–50	60–80
FA	1.05	1.05	1.10	1.10	-	-
GGBS	1.05	1.10	1.15	1.20	1.25	1.30
SF	1.05	1.10	-	-	-	-

FA: fly ash; GGBS: ground granulated blast-furnace slag, SF: silica fume.

Table 3. Correction factor for the finishing materials on concrete surface.

Finishing Condition	Indoor Area							Outdoor Area			
	No Finishing	Plaster	Mortar + Plaster	Mortar	Mortar + Paint	Tile	Paint	No Finishing	Mortar	Paint	Tile
Value	1.0	0.79	0.41	0.29	0.15	0.21	0.57	1.0	0.28	0.8	0.7

5. Case Study: CO₂ Emission Assessment of Precast Concrete Girders

The CO₂ emissions and CO₂ absorption capacity by carbonation were assessed for precast concrete girders (PCGs) manufactured by a PC concrete manufacturer (Figure 3) in the Republic of Korea [33–35].

The environmental conditions (average temperature: 15 °C, average relative humidity: 66%, CO₂ concentration) were estimated based on Korean data from the year 2012 [36]. The system boundary on the CO₂ emissions at the concrete production stage is drawn after the pre-construction stage (Figure 4). The production stage thus includes all of the following: (1) purchase of precast concrete materials from the cradle to gate; (2) transport of components to the precast concrete factory; (3) manufacturing at the precast concrete factory; (4) transport of the concrete to the construction site.

In terms of CO₂ concentration, 380 ppm and 2000 ppm were assumed for outdoor and indoor environments, respectively [37]. In terms of the expected life of concrete structure, 40 years were set.



Figure 3. Production process of precast concrete girders (PCGs): (a) Spreading form oil; (b) rebar insert; (c) pouring concrete; (d) curing; (e) removal; (f) precast concrete girder.

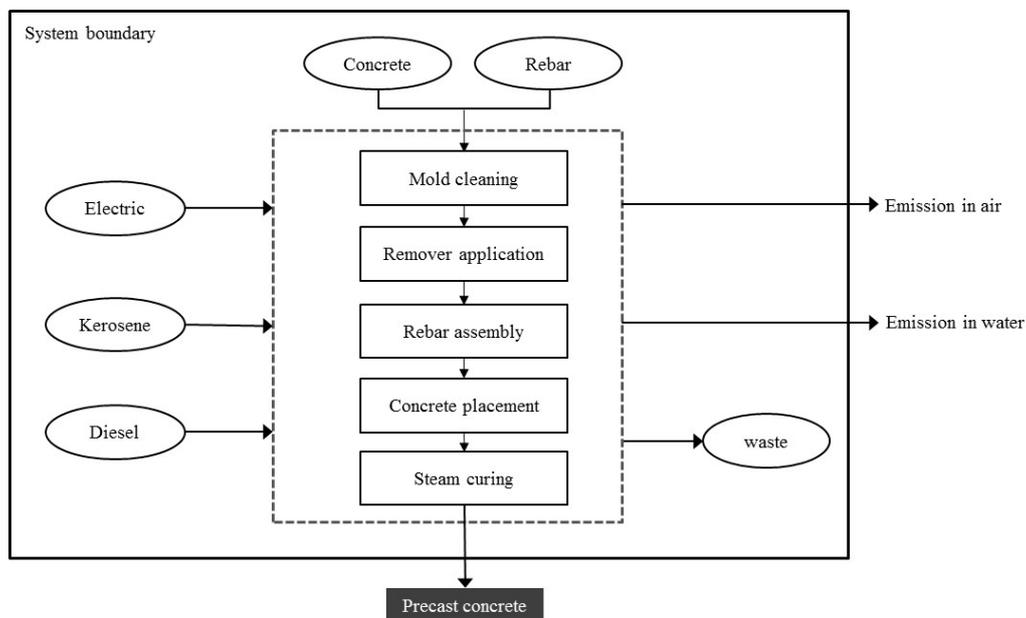


Figure 4. System boundaries for the life cycle assessment (LCA) of precast concrete.

5.1. CO₂ Emissions throughout the PC Life Cycle

The CO₂ emissions throughout the life cycle of PCGs were 1365.6 (kg-CO₂/1 PCG), as shown Table 4.

In particular, the CO₂ emissions during the raw material stage were 1390 (kg-CO₂/1 PCG), accounting for the highest portion in total CO₂ emissions. As the concrete used to produce one PCG is about 2.2 m³, concrete mixing ingredients were considered as follows: ordinary Portland cement 1100 (kg/1 PCG), coarse aggregates 2030 (kg/1 PCG), fine (sand) aggregates 1751 (kg/1 PCG), admixtures 11 (kg/1 PCG), and mixed water 352 (kg/1 PCG). The percentage of the CO₂ emissions from the ordinary Portland cement in the raw material stage was about 67%.

Deformed reinforcing bars were factored into the production of PCG. The amount of deformed bars consumed for the production of each PCG was 425 (kg/1 PCG). The CO₂ emissions from the

production of reinforcing bars were 163.6 (kg-CO₂/rebar), accounting for 11% of the CO₂ emissions from the raw material stage.

Table 4. Life cycle CO₂ emission and absorption of precast concrete girders (PCGs).

Raw Material Stage				Transportation Stage (from Gate to Ready-Mixed Concrete Plant)		
Unit: 1 PCG (Concrete 2.2 m ³)						
Unit Item	Concrete Component			D	E	F = A × D × E
	A	B	C = A × B			
	kg/unit	kg-CO/kg	Kg-CO ₂ /unit	Distance (km)	kg-CO ₂ /kg·km	kg-CO ₂ /kg
Ordinary Portland cement (OPC)	1100	9.48×10^{-1}	1.04×10^3	106	6.06×10^{-5}	7.07
Water	352	1.31×10^{-4}	4.61×10^{-1}	-	-	-
Sand aggregate	1751	1.52×10^{-4}	2.66	32	1.16×10^{-5}	6.50×10^{-1}
Coarse aggregate	2300	7.74×10^{-3}	1.78×10^2	32	1.16×10^{-5}	8.54×10^{-1}
Chemical admixture	11	2.05×10^{-3}	7.22×10^{-1}	77	1.16×10^{-5}	3.14×10^{-1}
Reinforcing rebar	425	3.85×10^{-1}	1.64×10^2	161	4.29×10^{-5}	2.94
Sum			1.39×10^3	Sum		1.18×10^1
Manufacturing Stage				Transportation Stage (from Batch Plant to Construction Site)		
Unit Item	A	B	C = A × B	D	E	F = D × E
	Input/unit	kg-CO ₂ /input	kg-CO ₂ /input			
				Distance (km)	kg-CO ₂ /kg·km	kg-CO ₂ /kg
Electric (kwh)	57.4	4.88×10^{-1}	2.80×10^1			
Kerosene (L)	29.3	3.17	9.29×10^1			
Diesel (L)	4.7	3.19	1.50×10^1	50	2.81×10^{-2}	1.41
Remover (L)	1.3	1.45×10^{-3}	1.89×10^{-3}			
Sum			1.36×10^2			
Use stage of structure						
A	B	C	D	E	F	G = D × E × F
Service life	Type	Finishing material	Exposed surface area (m ²)	aCO ₂ (g/cm ³)	xc (cm)	CO ₂ absorption (kg/m ³)
40 years	Outdoor area	Paint	9.27	0.32	5.79	-171.8
Total = 1365.6 kg-CO ₂ /1 PCG (=1537.4 (CO ₂ emission due to concrete) – 171.8 (absorption due to carbonation))						

In addition, the CO₂ emissions from the transport of the concrete mixing materials and reinforcing bars to the PCG factory were about 12 (kg-CO₂/1 PCG). The departure distances for the transport of ordinary Portland cement, fine and coarse aggregates, and admixtures to the PCG factory (Chungbuk) were 106 km (Gangwon-do), 32 km (Chungcheongbuk-do), and 77 km (Gyeonggi-do), respectively. Among the mixing ingredients, however, mixing water was excluded from the assessment because it was supplied through the waterworks of the PCG factory. Among the concrete mixing ingredients, the CO₂ emissions of ordinary Portland cement which was transported from the most distant region were about 7.11 (kg-CO₂/1 PCG), accounting for about 60% of CO₂ emissions from the transportation stage. Furthermore, in the case of reinforcing bars, the distance from the deformed bar factory in Incheon to the PCG manufacturing plant is 161 km, and the CO₂ emissions were 2.9 (kg-CO₂/1 PCG), accounting for 25% of those from the transportation stage.

The CO₂ emissions from the consumption of electricity and diesel oil during the manufacturing stage were 136.2 (kg-CO₂/1 PCG). To manufacture PCG, the following were used: 57.4 kwh (electricity), 29.3 L (kerosene), 4.7 L (diesel oil), and 1.3 L (remover). For the assessment of CO₂ emissions from oil, direct and indirect (production and combustion) emissions were considered.

Regarding wastewater, it is relevant that it is discharged after being filtered in the factory. Therefore, the influence of wastewater was not applied. The CO₂ emissions from the consumption of kerosene among the CO₂ emissions from the manufacture stage were 92.9 (kg-CO₂/1 PCG), accounting for the highest portion in the manufacturing stage. The CO₂ emissions (including production and combustion) from electricity and diesel oil were 28.2 (kg-CO₂/1 PCG) and 15.1 (kg-CO₂/1 PCG), respectively (Figure 5).

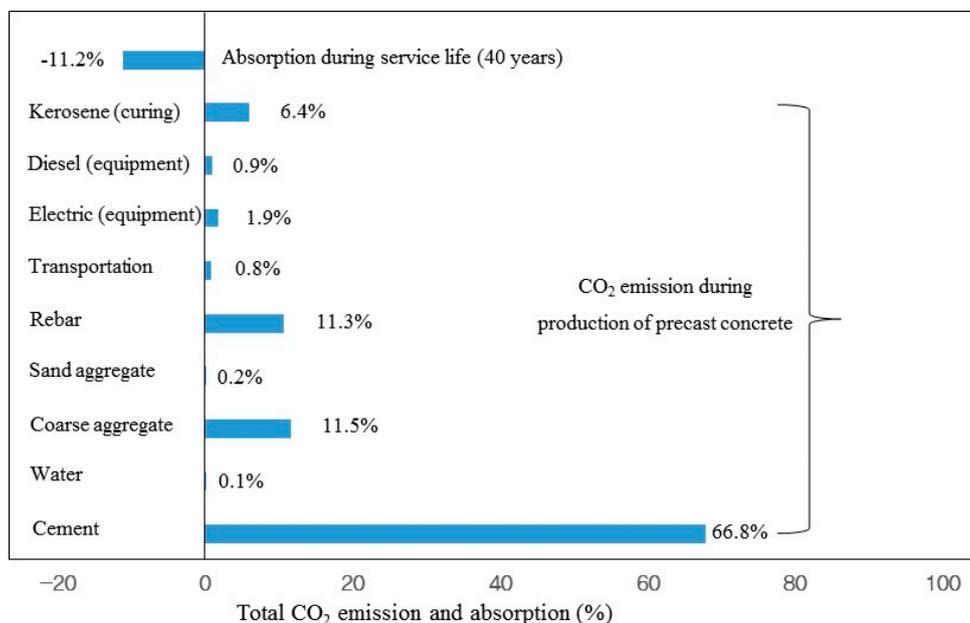


Figure 5. Detailed result of the total CO₂ emission-absorption for PCGs.

5.2. CO₂ Absorption during Service Life (Four Decades)

This study assessed CO₂ absorption assuming that the PCG was exposed to the external environment for four decades. It was also presumed that the external surface of the PCG was painted and that the external surface area was 9.27 m². A_{CO₂}(t) and x_c(t) of the PC concrete from having a 40-year age were 0.32 g/cm³ and 5.79 cm in an outdoor surface (Table 4).

Therefore, it was concluded that the CO₂ absorption throughout the service life of the PC was 172 (kg-CO₂/1 PCG), which is about 11.2% (16.5% of the CO₂ emissions by cement) of the CO₂ emissions from the production stage, as shown in Figure 6.

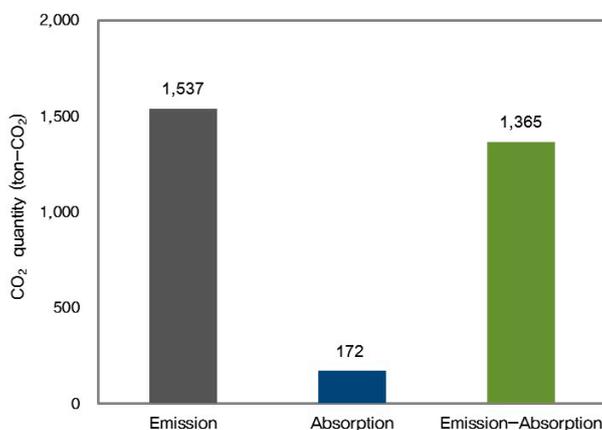


Figure 6. Total CO₂ emission-absorption of a precast concrete girder (PCG).

6. Conclusions

This study proposed the assessment of CO₂ emissions throughout the life cycle of PC and assessed CO₂ absorption by carbonation during its service life (40 years). For the assessment of CO₂ emissions during the life cycle of the PC, this study covered raw material, transportation, manufacturing, and use stages in accordance with the ISO 14044 (LCA). In case study of CO₂ emissions and absorption throughout the life cycle of a PCG, this study found that CO₂ emissions throughout the life cycle of the PCG were 1365.6 (kg-CO₂/1 PCG).

The CO₂ emissions during the production of raw materials were 1390 (kg-CO₂/1 PCG), thus accounting for a high portion to total CO₂ emissions with approximately 90% of the total. In contrast, the transportation and manufacturing stages accounted for 1% and 10%, respectively, having little effect on total CO₂ emissions.

Among the use of the PCGs, CO₂ absorption was mostly decided by the CO₂ diffusion coefficient and the amount of CO₂ absorption by cement paste. The CO₂ absorption by carbonation throughout the service life of the PC was about 11% of the total CO₂ emissions, which is about 16% of CO₂ emissions from the ordinary Portland cement.

However, this study has the following limitations: First, it has poor reliability for the assessment of CO₂ emissions from the proposed PC because it handled only one case. Therefore, there should be further verifications through diverse case studies. Second, the results for the case study on the PC were obtained from the firms in the Republic of Korea only. Therefore, they would not necessarily be applicable to the PC abroad. Hence, this study needs to improve reliability through assessment of CO₂ emissions throughout the life cycle of the PC in foreign countries as well.

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