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Life cycle Assessment of CO_2 Emission of Concrete Considering Carbonation and Structural Element Types

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ABSTRACT

Concrete industry is the main contributor of CO_2 emission, and abundant studies were done for evaluating life cycle CO_2 during production stage, construction stage, and use stage. The uptake of CO_2 due to carbonation in service life is not detailed considered. Furthermore, the uptake of CO_2 in demolition stage and the influences of structural element types on CO_2 uptake performance are also not detailed considered. To overcome the weak points of current study, this paper proposed a numerical procedure about life cycle assessment of CO_2 emission of concrete considering carbonation and structural element types. The CO_2 emission and uptake in production stage, construction stage, use stage, and demolition stage are calculated; the influences of structural element types, shapes, and sizes on CO_2 uptake performance are clarified. For concrete structures with different structural types, such as frame structures and shear-wall structures, the relative ratios for different structural element are different, hence the CO_2 uptake ability are also different.

1. INTRODUCTION

With the growing global warming, carbon dioxide emissions become more and more people's attention (Streimikiene et al., 2009). Concrete industry is the main contributor of CO_2 emission, cement as the most important consistent material, and the amount emission of CO_2 from the worldwide production of OPC occupies as many as 7% of the total global CO_2 emissions (Benhelal et al., 2013). The life cycle of concrete structure refers to the cradle to grave for total life of concrete, which involves production stage, construction stage, use stage and demolition stage (Frank, 2010). Figure 1 illustrates the four stages during the life cycle of concrete structure. People concerned the CO_2 emissions of concrete, while often ignored the CO_2 absorption based on concrete carbonation. Meanwhile, due to the exposed surface area of concrete is deferent; lead to deferent structural element types will capture unequal CO_2. The present study aims to evaluate the influences of CO_2 absorption in life-cycle of concrete

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structure on CO_2 emission and the influences of structural element types on CO_2 uptake performance.

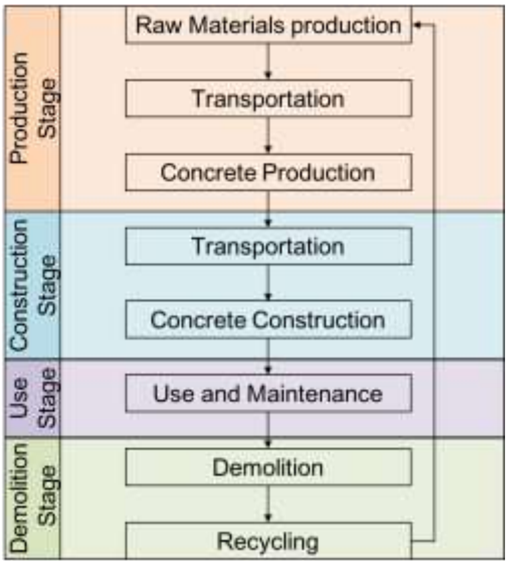

Fig.1 Life cycle of the concrete construction system

2 Development of concrete structure life-cycle CO_2 emission evaluation method

To quantitatively assess the CO_2 emission is a difficult task, due to the situation is complex for concrete industry and the basic unit of CO_2 emission for deferent Countries or regions is not uniform. In this study, we adopt the Ministry of the Environment provides the National Life Cycle Inventory database and Inter-industry (LCI DB) Analysis (2016), sometimes use the database from Japan Society of Civil Engineers (JSCE) (2016*)and Institute for Diversification and Energy Saving. Because the life-cycle of concrete is classified four stages, therefore, evaluation the CO_2 emission correspondingly should be divided four sections. The detailed calculation procedure will be introduced as following.

2.1 Production stage

Different from the Carbon Emission Coefficient Method (CECM) to calculate the CO_2 emission, in this study, the method for evaluate the CO_2 emission by stage according to concrete production was be developed (Tatiana et al., 2014). According to the concrete production procession, a total CO_2 emission equal to the sum of CO_2-emitting from constituent material of concrete during production stage, transportation stage and concrete production stage. The calculation can be expressed by the following equation:

$$C_E = CO_{2\text{-}M} + CO_{2\text{-}T} + CO_{2\text{-}P} \quad (1)$$

Where C_E indicates the total CO_2 emission of concrete, and the $CO_{2\text{-}M}$, $CO_{2\text{-}T}$, $CO_{2\text{-}P}$ indicate the CO_2 emission in the materials production, transportation and production stages, respectively.

2.1.1 CO_2-emitting during constituent material production stage

For the constituent material production stage, the CO_2 emission associated with the production of materials required for concrete production (cement, coarse, sand, water, mineral admixture and chemical admixture) are calculated based on the CO_2 basic unit of each material (Tae et al., 2011). $CO_{2\text{-}M}$ can be calculated as follow:

$$CO_{2\text{-}M} = \sum_{i=1}^{n} (M_{(i)} \times BU_{CO_{2(M,i)}}) \quad (2)$$

Where *i* represents one kind of constituent material of concrete, n is the total number of constituents for concrete, $M_{(i)}$ is the unit volume weight for each material added in concrete(kg/m^3), and $BU_{CO2(M,i)}$ is the basic unit of CO_2 emission for each material(CO_2-kg/kg). For the basic unit of CO_2 emission, as there is not the uniform data for different Country, the database from Japan Society of Civil Engineering(JSCE), the National LCI database of Korea and Inter-industry Analysis database were adopted as references(Table1).

Table 1. The basic unit of CO_2 emitted by each material during raw material production stage

Item	Unit	CO_2-kg/kg	Reference
OPC	kg	0.944	S. Korea LCI DB
Sand	kg	0.0026	
Coarse	kg	0.0075	Inter-industry Analysis
Water	kg	1.96×10^{-4}	
GGBFS	kg	0.0208	JSCE
chemical admixture	kg	0.25	

2.1.2 CO_2-emitting during material transportation stage

For the constituent material transportation process, according to the amount of oil consumed by the freight vehicle for transporting materials from the material producer to the ready-mixed concrete plant, the CO_2 emission can be calculated by summing the amount CO_2 emitted by oil consumed during transportation of each raw material. In this calculation, the transportation distance for each material, the load and standard fuel efficiency of the freight vehicle should be considered. $CO_{2\text{-}T}$ can be calculated as follow:

$$CO_{2\text{-}t} = \sum_{i=1}^{n} (M_{(i)} \times D_i \times BU_{CO_{2(T,i)}}) \quad (3)$$

Where *i*, n and $M_{(i)}$ express the same meaning as above, D_i represents the transportation distance for each raw material *i* from its material producer to the ready-mixed concrete plant, $BU_{CO2(T,i)}$ is the basic unit of CO_2 emitted by unit raw material per 1km for transportation distance (CO_2-kg/(kg km)). Generally, the cementations materials are transported by diverse-ton capacity bulk trailer, and aggregates are transported by diverse-ton capacity diesel truck. Table2 gives the reference data of CO_2 emission in the transportation stage (Yang et al., 2015).

Table 2. The basic unit of CO_2 emission during the transportation stage

Item	Unit	CO_2-kg/(kg km)	Reference
23-ton capacity bulk trailer	kg	5.18×10^{-5}	Inter-industry Analysis
15-ton capacity diesel truck	kg	6.3×10^{-5}	
1.5-ton capacity diesel truck	kg	2.2×10^{-5}	
$6m^3$ capacity in-transit mixing truck	m^3	0.674 CO_2-kg/(m^3 km)	

2.1.3 CO_2-emitting during production stage

In regard to production stage of concrete structure, except concrete production, steel production of bars should be included. There are many methods to calculate the CO_2 emission during the concrete production. Such as the standard energy computation method proposed by Junghoon Park (2012), which was established based on the process flow of the ready-mix concrete and the capacity data from each facility. That means utilizing the daily energy consumption of the batcher plant during production fresh concrete to compute the CO_2 emission. The production process of fresh concrete was classified into storage, transportation, measurement, and mixing process. Analyzing the ratio of the capacity of the classified facilities and CO_2 emission by corresponding facility, the CO_2 emission for total energy used to produce fresh concrete can be calculated. $CO_{2\text{-}P}$ can be calculated as follow:

$$\mathrm{CO}_{2\text{-P}} = \sum_{j=1}^{m} \left[E_{\mathrm{e,j}} \times \mathrm{BU}_{\mathrm{CO_{2(P,i)}}} \right] \quad (4)$$

Where *j* represent different facility during produce fresh concrete, m is the total number of facilities, $E_{e,j}$ represent the consumption of electricity by production facility per $1m^3$ concrete(kwh/m^3), $BU_{CO2(P,i)}$ is the basic unit of CO_2 emission for each energy source(CO_2-kg/kwh).Generally, considering the storage, transportation, measurement, and mixing process during concrete production to one item, the CO_2 emission for production $1m^3$ fresh concrete in plant can be computed as the Table3.

Table 3. The basic unit of CO_2 emission during the concrete production stage

Item	Unit	CO_2-kg/kg	Reference
Fresh concrete	Kg*	0.00768	S. Korea LCI DB

*indicate the total mass of each constituent material for production $1m^3$ of concrete.

2.2 Construction stage

It relates to transport the produced steel bars and fresh concrete to the construction site and cast concrete using pump and vibrator, in which the evaluation of CO_2 emission during transportation process adopts the same method as above. The method of calculating CO_2 emitted by casting concrete is similar to the production of fresh concrete. Utilizing the energy consumption of the pump and vibrator during casting fresh concrete computes the CO_2 emission. During construction stage, the CO_2 emitted by using pump and vibrator to cast concrete can be referenced as the following Table4.

Table 4. The basic unit of CO_2 emission during construction stage

Item	Unit	CO_2-kg/m^3	Reference
Pump	m^3	0.074	Institute for Diversification and Energy Saving
Vibrator	m^3*	0.04	

2.3 Use stage

In the use stage, due to CO_2 or other aggressive substances penetrate into concrete and react with $Ca(OH)_2$, which is the main hydration production of cement, cause the steel embedded corrosion and concrete structure destroy. Therefore, CO_2 will be emitted during replace some damaged concrete elements. In this study, comparing the CO_2 capture, the problem of concrete elements destroys can be ignored. Thus, in the life cycle of concrete elements, the CO_2 absorption will be considered during the use stage, not the CO_2 emission.

2.4 Demolition stage

When concrete structure gets to the using life, concrete structure and elements need to be demolished. The prophase of demolition stage, CO_2 emission stems from using the dissolution equipment; the late demolition stage, CO_2 emission involves the waste transportation, recycled using as an aggregate in the production new concrete and so on. The CO_2 emitted by waste transportation can adopt the same method as the raw materials transportation stage, the calculation during demolition and crushing process can be referenced as the following Table5.

Table 5. The basic unit of CO_2 emission during demolition stage

Item	Unit	CO_2-kg/m^3	Reference
Demolition	m^3	3.81	Institute for Diversification and Energy Saving
Crushing	m^3*	0.59	

3 Development of concrete structure life-cycle CO_2 absorption evaluation method

Because CO_2, due to react with $Ca(OH)_2$ existing in cement hydration productions, can be captured during the use stage and demolition stage, CO_2 absorption should be considered as evaluate the CO_2 emission. About the evaluation method of CO_2 absorption, many scholars present some different methods, in which the common using method is utilize the carbonation depth multiply the exposed surface areas of concrete. Pade and Guimaraes (2007) and Dodoo et al. (2009) used the following equation to calculate CO_2 absorption based on the predictive models of Fick's first law of diffusion and the life of concrete structure.

$$\begin{aligned} C_A &= x \times M_c \times f_{CaO} \times r_{CaO} \times A \times m \\ x &= k\sqrt{t} \end{aligned} \tag{5}$$

Where C_A indicates the total CO_2 absorption of concrete, x expresses the carbonation depth, M_c is the quantity of OPC per cubic meter of concrete, f_{CaO} is the amount of CaO content in Portland cement CaO (assumed to be 0.65), r_{CaO} is the proportion of CaO can be carbonated (assumed to be 0.75, Lagerblad 2005), A is the exposed surface area of concrete, m is the chemical molar fraction (CO_2/CaO equate to 0.79), k is the carbonation rate coefficient and t indicates the years of service life. According to the EHE code (Fomento 2008), the service life can be calculated by classifying two sections as following equation (6).

$$t = \left(\frac{c_d}{k}\right)^2 + \frac{80 \times c_d}{d_s \times v_c} \tag{6}$$

Where c_d is the protective layer thickness of concrete (mm), d_s is the diameter of steel bar (mm), v_c is the corrosion speed (um/year).

4. Study on the case of CO_2 emission–absorption of concrete structure

4.1 Overview

In this study, one RC plate, beam, column and shear-wall were taken to research during the lifetime of concrete structure, respectively. The compressive strength value is same (25MPa) for the four elements, as well as the concrete mix, dimension and steel reinforcement of three kinds of elements were provided in Table6 and Table7. To obtain the CO_2 emission during life-cycle of three elements, assuming the distance and type of freight vehicle indicates in Table8, in which Fresh Concrete denotes the distance from the ready-mixed concrete plant to the construction site, Demolition Concrete denotes the distance from the construction site to Waste disposal Center and others indicate from its material producer to the ready-mixed concrete plant.

Table 6 Concrete mix (C25)

	Cement	Water	Sand	Coarse	GGBFS	Plasticizer
Kg/m^3	220	170	850	1050	110	2.5

Table 7 Dimension and reinforcement

Item	a(m)	b(m)	h(m)	c_d(m)	SR*
Plate	2	1	0.1	0.02	10Φ12
Beam	0.25	0.45	1	0.03	4Φ16
Column	0.4	0.4	1	0.03	4Φ20
shear-wall	1	1	0.16	0.02	16Φ12

*In this study, CO_2 emission of the steel reinforcement did not be considered.

Table 8 Dimension and reinforcement

Item	Transportation	
	Distance(km)	Type of freight vehicle
OPC	200	23-ton capacity bulk trailer
GGBFS	200	1.5-ton capacity diesel truck
Admixture	200	
Sand	150	15-ton capacity diesel truck
Coarse	150	
Fresh Concrete	50	$6m^3$ capacity in-transit mixing truck
Demolition Concrete	100	23-ton capacity bulk trailer

4.2 Evaluation CO_2 emission of concrete structure

Using the method in section2 introduction, CO_2 emission of concrete structure can be evaluated. The detailed calculation process indicates Table9, and the final result was given in the Table10.

Table 9 Examples for evaluation CO_2 emission of deferent stages (kg/element)

Item(unit: Element)	Material Production Stage								Transportation Stage			
	A			B	A.B			D	E	A.D.E	A.D.E	A.D.E
	kg/unit			CO_2-kg/kg	CO_2-kg/unit			km	CO_2-kg/(kg km)	CO_2-kg/unit		
	P	B	C/S		P	B	C/S	Distance		P	B	C/S
OPC	44	24.75	35.2	0.944	41.536	23.364	33.229	200	5.18×10^{-5}	0.456	0.256	0.365
Sand	170	95.625	136	0.0026	0.442	0.442	0.354	150	6.3×10^{-5}	1.607	0.904	1.285
Coarse	210	118.125	168	0.0075	1.575	1.575	1.26	150	6.3×10^{-5}	1.984	1.116	1.588
Water	34	19.125	27.2	1.96×10^{-4}	6.664×10^{-3}	3.749×10^{-3}	5.331×10^{-3}	-	-	-	-	-
GGBFS	22	12.375	17.60	0.0208	0.458	0.257	0.366	200	5.18×10^{-5}	0.228	0.128	0.182
Admixture	0.5	0.281	0.4	0.25	0.125	0.07	0.1	200	2.21×10^{-4}	0.022	0.012	0.018

	Sum				44.142	24.830	35.304	Sum		4.298	2.416	3.438
Production Concrete	480.5	270.281	384.4	0.00768	3.69	2.076	3.438	50	0.674 -kg/(m^3 km)	6.74	3.79	5.392

Table 10 Examples for evaluation CO_2 emission of deferent concrete elements (kg/element)

Item		Plate	Beam	Column	Shear-wall
Production stage	Material	44.142	24.830	35.304	35.304
	Transportation	4.298	2.416	3.438	3.438
	Production	3.69	2.076	2.91	2.91
Construction stage	Transportation	6.74	3.79	5.392	5.392
	Construction	0.023	0.013	0.018	0.018
Demolition stage	Demolition	0.762	0.429	0.608	0.608
	Transportation	2.58	1.457	2.130	2.130
	Recycling	0.118	0.066	0.092	0.092
Sum		62.353	35.077	49.892	49.892

4.3 Evaluation CO_2 absorption of concrete structure

During the process of calculation CO_2 absorption of life-cycle concrete, combined with the actual situation, two surface area of plate, three surface area of beam and four surface area of column are considered to uptake CO_2 existing in ambient air. According to the EHE code, assuming the carbonation rate coefficient k equal to 4.72mm/year$^{0.5}$, and the corrosion speed rate equal to 2um/year. The years of service life, using the equation (6), for plate, beam, column and shear-wall is 84.62 year, 115.40year, 100.40year and 84.62 year, respectively. Obviously, because the protective layer thickness of plate is thinner than beam and column, the service life for plate is shorter than that beam and column. CO_2 capture depends on the service life and exposed surface area, according to the above introduction and just computed service life, the CO_2 absorption can be calculated by using equation (5), and the results present in the Table11.

Table11 Examples for evaluation CO_2 absorption of deferent concrete elements (kg)

Item	Plate	Beam	Column	Shear-wall
use stage	14.72	4.94	6.41	7.36
Demolition stage	16.42	5.51	7.15	8.21
Sum	31.14	10.45	13.56	15.57

4.4 Assessment results and analysis

Drawing the CO_2 emissions during every stage of concrete life in a picture, as shown in Fgure2, we will find the max emission appears in the production stage, especially in the material production stage, above 70% emission happens in this stage. Additional, because the dimension of four concrete elements is different, in order to make the results comparable, changing the CO_2 absorption and emission of these four elements into the same volume, as illustrated in Table12. Simultaneously considering CO_2 emission and absorption, the result of four concrete elements was drawn in a same picture as the Figure3 shown. Observing the results, we can get the total emission of CO_2 per unit volume is same for different concrete elements; however, the total absorption of CO_2 per unit volume is totally different. The reason for this result is that the exposed surface area of concrete plate is the larger, and the capture of CO_2 is the most in the three elements. Therefore, when we assess the emission CO_2 of life-cycle concrete, concrete carbonation and structural element types must be considered. Using this regular to concrete structures with different structural types, such as frame structures and shear-wall structures, we can deduce that one frame structure, in the case of the same building area, will emit more CO_2 than that of one shear-wall structure.

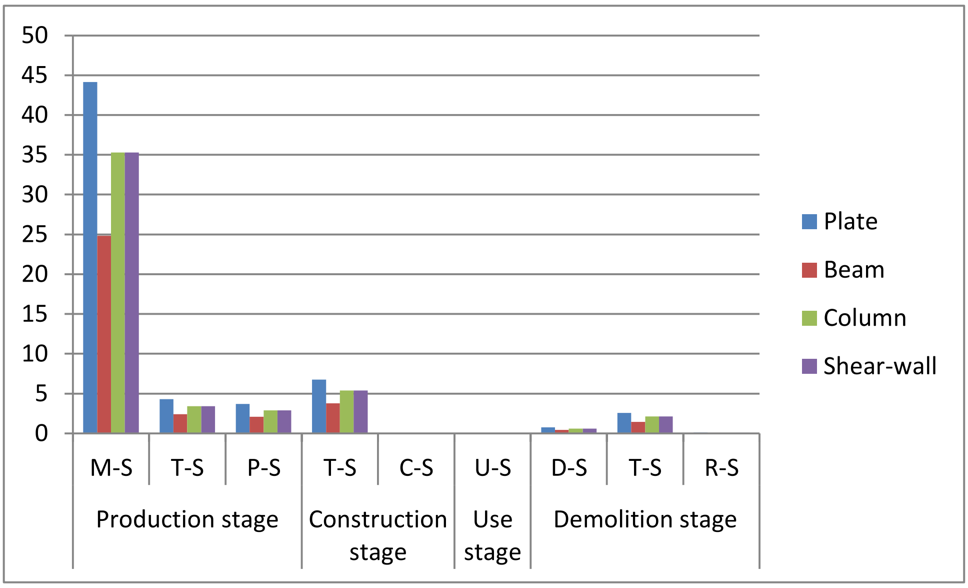

Fig. 2 CO_2 emissions during every stage of concrete life

Table 12 CO_2 emission and absorption per unit volume of each concrete element (kg/m^3)

Item	Plate	Beam	Column	Shear-wall
Emission	311.78	311.80	311.83	311.83
Absorption	155.7	92.89	84.75	97.31
Total	156.08	218.91	227.08	214.52

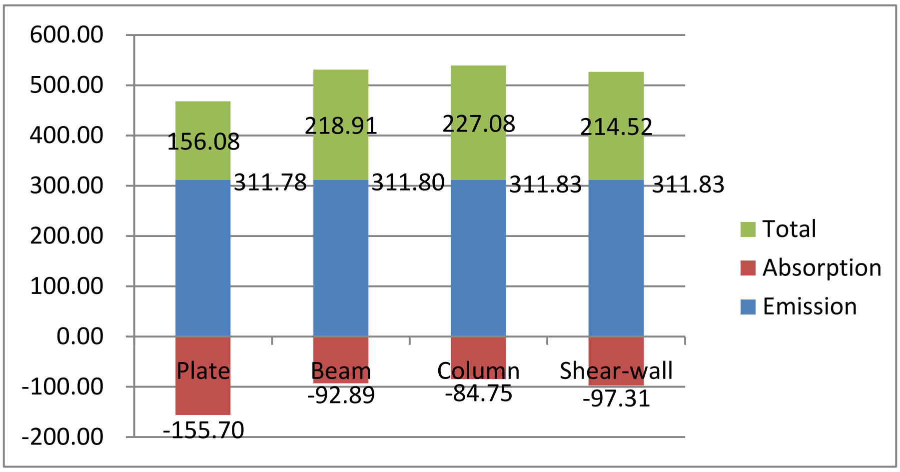

Fig. 3 CO_2 emission- absorption of four concrete elements

5. Conclusions

In this study, the CO_2 emission and uptake in production stage, construction stage, use stage, and demolition stage are calculated; meanwhile, the influences of structural element types, shapes, and sizes on CO_2 uptake performance are clarified. Under the specific cases adopted in this study, the following conclusions can be drawn:

- In the life-cycle of concrete structure, the CO_2 emission and absorption will happen, regardless the production stage, construction stage, use stage, and demolition stage. Generally, the emission main happen in the production stage, construction stage and demolition stage, especially the production stage, and the absorption main happen in the use stage and demolition stage.
- When the reinforced steel bars did not be considered, the total emission of CO_2 per unit volume is same for different concrete elements; however, if concrete carbonation was considered, the result is totally different. The larger exposed surface area of concrete, the more CO_2 emission of concrete.
- For concrete structures with different structural types, because the relative ratios for different structural element are different, the CO_2 uptake ability is also different. The more areas of plate or shear wall, the less CO_2 emission of concrete structure.

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