Chapter 5

$LCCO_2$ Assessment of RC Structures Considering Concrete Carbonation Degree

5.1 Outline

Concrete carbonation is a phenomenon where concrete absorbs CO_2 from the air. In this chapter, the amount of CO_2 absorption in concrete through carbonation is calculated quantitatively during service life of RC structure that is predicted in chapter 4. Also, CO_2 emission is calculated when concrete of unit volume is produced and CO_2 balance and $LCCO_2$ are defined and evaluated during service life to an apartment building.

5.2 Definition and Evaluation of CO_2 Balance of Concrete

The CO_2 balance of concrete is defined as the difference between the quantity of CO_2 emitted from the production of 1 m^3 concrete and the quantity of CO_2 absorption through carbonation during the service life of the concrete. It can be calculated by using Eq. 5.1. It is used to design and select material such concrete as an eco-friendly one.

$$CO_2 \text{ balance of concrete } (\text{kg-}CO_2/m^3) = CO_2 \text{ emission} - CO_2 \text{ absorption} \qquad \text{Eq. 5.1}$$

5.3 Calculation of CO_2 Emissions and Absorption of Concrete

5.3.1 Estimation Outline of CO_2 Emissions Arising from the Manufacture of Concrete

The CO_2 emissions of concrete can be calculated by summing the CO_2 emission of each component used in concrete based on Table 5.1.[41] Researches and data[42-46] about CO_2 emission is in Korea, but it is limited in some material in concrete so in this study data on Table 5.1 is used. The CO_2 emissions include the mining of raw materials and energy production but exclude transportation of the material. The emission of total concrete used in the process of constructing a building is calculated considering total volume of used concrete based on CO_2 emission of 1 m^3 concrete by concrete strength.

Table 5.1 *CO_2 emission of component material in concrete (unit: kg-CO_2/Kg)* [41].

	Water	Cement	Fly ash	Fine aggregates	Coarse aggregates	AE reducing water agent
kg-CO_2/kg	-	0.7466	0.0196	0.0037	0.0028	0.25

5.3.2 CO_2 Absorption Calculation by Concrete Carbonation

(A) Outline of CO_2 Absorption Calculation of Concrete

Process of concrete carbonation produces a $CaCO_3$ from combining $Ca(OH)_2$ in concrete with CO_2 absorbed in the air as in Eq. 5.2. There are other reactants such as CSH($3CaO.SiO_2.3H_2O$), C_3S($3CaO.SiO_2$), C_2S($2CaO.SiO_2$) in the concrete that can combine with CO_2 as in Eqs. 5.3 - 5.6 except for $Ca(OH)_2$.

$$\mathrm{Ca}(OH)_2 + CO_2 \xrightarrow{r_{CH}} CaCO_3 + H_2O \qquad \text{Eq. 5.2}$$

$$3\mathrm{CaO}\cdot 2\mathrm{Si}O_2 \cdot 3H_2O + 3\mathrm{C}O_2 \xrightarrow{r_{CSH}} 3CaCO_3 + H_2O \qquad \text{Eq. 5.3}$$

$$2\mathrm{CaO}\cdot \mathrm{Si}O_2 + 2\mathrm{C}O_2 + rH_2O \xrightarrow{r_{C_2S}} \mathrm{Si}O_2 \cdot rH_2O + 2CaCO_3 \qquad \text{Eq. 5.4}$$

$$3\mathrm{CaO}\cdot \mathrm{Si}O_2 + 3\mathrm{C}O_2 + rH_2O \xrightarrow{r_{C_3S}} \mathrm{Si}O_2 \cdot rH_2O + 3CaCO_3 \qquad \text{Eq. 5.5}$$

The molar concentration of $Ca(OH)_2$ that combines with CO_2 through carbonation is equal to one of CO_2 at left side in Eq. 5.1. Noting this, the molar concentration of CO_2 that concrete can absorb is assumed to be equal to total molar concentration of each reactant that can combine with CO_2 in concrete.

From this assumption, the amount of CO_2 that concrete absorbs in the air through carbonation is predicted by calculating molar concentration of substances ($Ca(OH)_2$, CSH, C_3S, C_2S) in concrete that can react with CO_2. The process for predicting molar concentration of carbonatable substances in concrete is shown in Fig. 5.1.

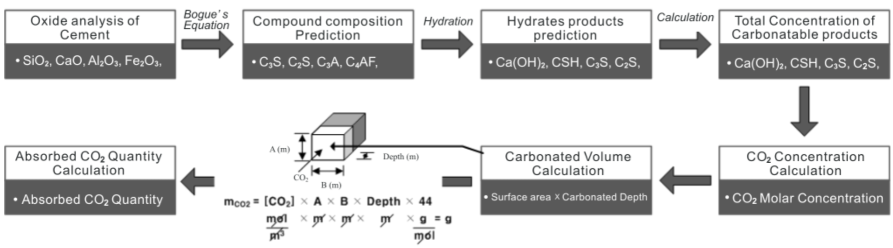


Fig. 5.1 *Absorbed CO_2 molar concentration calculation process of carbonated concrete.*

The molar concentration of carbonatable substances at an arbitrary time can be calculated by predicting hydration product of carbonatabele substances quantitatively by time after predicting cement compounds using Bogue's equation from analysis of cement oxide composition.[37] CO_2 absorption in concrete during service life can be calculated quantitatively by 1) multiplying using surface area of concrete exposed to the air, 2) carbonation depth with using time, and 3) the molar concentration of carbonatable substances in concrete under the assumption that the molar concentration of CO_2 that concrete absorbs is equal to one of carbonatable substances in concrete.

(B) Prediction of the Molar Concentration of the Cabonatable Hydration Products

Hydration model can predict the molar concentration of hydration products and this process is explained in chapter 3. Hydration products with time is shown in Fig. 5.2

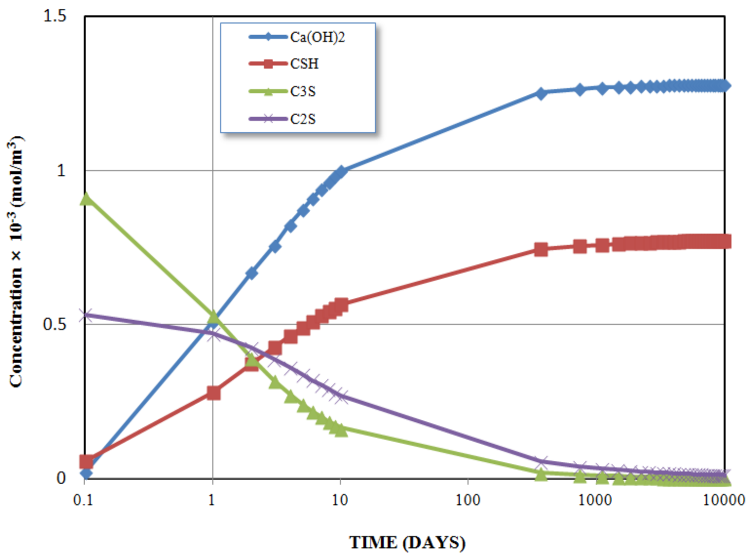


Fig. 5.2 *Hydration products process with time.*

(C) Calculation Method of CO_2 Uptake of Concrete[43)]

Fig. 5.3 shows carbonated concrete volume. CO_2 penetrate from the surface area A(m)×B(m) of concrete into the depth D in concrete. CO_2 absorption in concrete can be calculated quantitatively by multiplying the values: 1) the molar concentration of carbonatable substances in concrete, 2) the carbonated volume of concrete, 3) the molecular weight of CO_2 (44g/mol).

3-1) Calculation the molar concentration of carbonatable substances:

Under the assumption that the molar concentration of CO_2 that concrete absorbs is equal to summarized one of carbonatable substances in concrete ($[Ca(OH)_2]+3[CSH]+3[C_3S]+2[C_2S]$: $[CO_2]$), the molar concentration of CO_2 that concrete can absorb is calculated in 40, 60, 80 years and the results is shown in Table 5.2 and Fig. 5.4.

Hydration of ordinary Portland cement proceeds rapidly. Hydration degree reaches 90% in 3 months and it is almost done in one year. So, the molar concentration of carbonatable substances is almost same in 20, 40, 60 years. As a result, when 1 m^3 concrete is fully carbonated in 80 years, the amount of CO_2 absorption in concrete is approximately 3,575 mol.

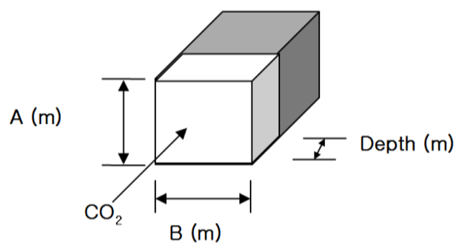


Fig. 5.3 *Concept for volume calculation of carbonated concrete.*

$$m_{co_2} = [CO_2] \times \mathrm{A} \times \mathrm{B} \times \mathrm{Depth} \times 44 = \frac{mol}{m^3} \times \mathrm{m} \times \mathrm{m} \times \mathrm{m} \times \frac{g}{mol} = g \quad \text{Eq. 5.6}$$

where:

CO_2: the concentration of materials that can react with CO_2 in the concrete,

A ×B: the surface area of the concrete exposed to air,

Depth: the carbonated depth of concrete

44: the molecular weight of CO_2 (g/mol)

3-2) In order to calculate carbonated concrete volume, carbonated depth with time and surface area exposed to the air is required. As an example, carbonated depth is predicted in 40, 60 and 80 years of service life with water to cement ratio of concrete and the results are shown in Fig. 5.5. Carbonated depth prediction with water to cement ratio uses carbonation model using FEMA in chapter 4.

Table 5.2 *Molar concentration of each carbonatable constituents and absorbable CO_2 in concrete (Unit: x 1,000 mol/m^3).*

	$Ca(OH)_2$	CSH	C_3S	C_2S	CO_2
40 years	1.261	0.763	0.002	0.009	3.576
60 years	1.262	0.764	0.001	0.007	3.575
80 years	1.262	0.765	0.001	0.007	3.575

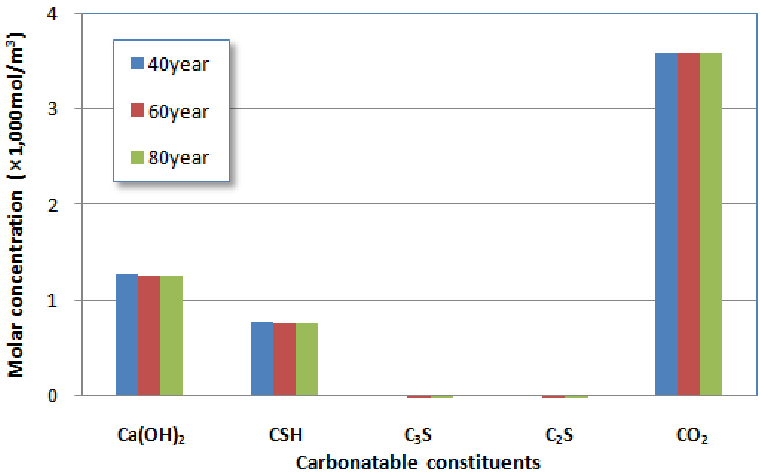


Fig. 5.4 *Molar concentration of each carbonatable constituents and absorbable CO_2 in concrete according to time.*

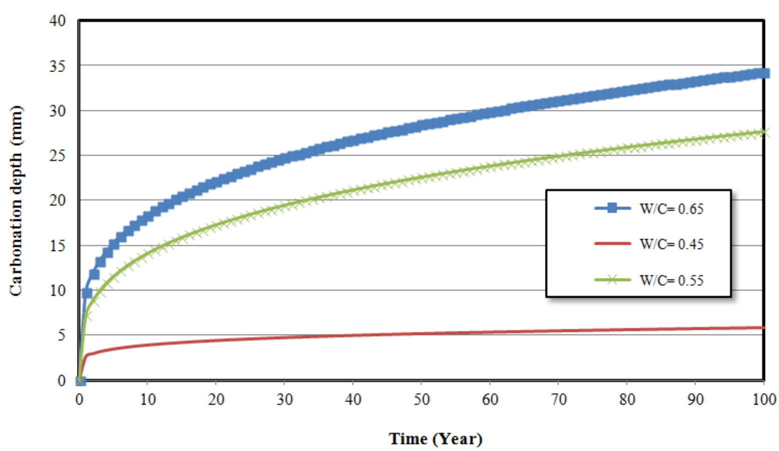


Fig. 5.5 *Carbonated depths according to w/c ratio with time.*

5.3.3 CO_2 Emissions-Absorption Evaluation Methodology Considering Concrete Production and the Use Period of Concrete

Evaluating method for CO_2 balance of concrete is the difference between the quantity of CO_2 emitted from the production of 1 m^3 concrete and the quantity of CO_2 absorption through carbonation during the service life of the concrete. CO_2 emission from concrete production can be calculated quantitatively by summarizing values that multiplied CO_2 emission of each material that are used in concrete with used quantities in concrete. CO_2 absorption in concrete in an arbitrary time during service life is calculated quantitatively using surface area of concrete exposed to the air, carbonation depth with using time, the molar concentration of carbonatable substances in concrete.

Table 5.3 shows CO_2 emission of 1 m^3 concrete production and this is a result of calculation using mix proportion as shown in Table 5.3 with water to cement ratio of 0.45, 0.55 and 0.65 and CO_2 emission of each material.

Table 5.3 *CO_2 emission of concrete and its component material (unit: kg-CO_2/kg).*

No.	Index	W/C	Mix proportion (kg/m^3)					CO_2 emission quantity
			W	C	S	G	AE reducing water agent	CO_2 emission quantity
1	C-OPC-45	0.45	216	480	751	866	0	364
2	C-OPC-55	0.55	206	375	863	866	0	286
3	C-OPC-65	0.65	202	311	944	850	0	238
CO_2 emission quantity of concrete and its component material			-	0.7466	0.0037	0.0028	0.25	kg-CO_2/m^3

Table 5.4 shows the calculation results of CO_2 absorption in 1 m^3 concrete with water to cement ratio in 30 and 60 years during service life. The molar concentration of carbonatable substances with water to cement ratio is

calculated by a hydration model in chapter 3. The molar concentration and quantity of CO_2 that concrete absorption is calculated quantitatively and the result is shown in Fig. 5.6.

Table 5.4 *Molar concentration of each carbonatable constituents and absorbable CO_2 in concrete (Unit: x 1,000 mol/m^3).*

service life	W/C	$Ca(OH)_2$	CSH	C_3S	C_2S	Fully carbonated concrete	
service life	W/C	$Ca(OH)_2$	CSH	C_3S	C_2S	absorbable CO_2	absorbed CO_2 quantity (kg/m^3)
30 year	0.45	1.281	0.774	0.002	0.01	3.634	159.90
30 year	0.55	1.008	0.609	0.002	0.008	2.859	125.82
30 year	0.65	0.841	0.508	0.001	0.007	2.385	104.98
60 year	0.45	1.282	0.776	0.001	0.007	3.632	159.82
60 year	0.55	1.008	0.611	0.001	0.006	2.858	125.76
60 year	0.65	0.841	0.509	0.001	0.005	2.384	104.93

CO_2 emission increases in a low water to cement ratio because the amount of used cement in concrete increases. Also, CO_2 absorption increases in a low water to cement ratio because carbonatable substances such as $Ca(OH)_2$, CSH in concrete increase from using more cement. As a result, the ratio of absorption over emission of CO_2 is almost same to approximately 44% regardless of water to cement ratio when concrete is fully carbonated.

But in real condition, it is difficult for concrete to be fully carbonated in the air. Therefore, CO_2 absorption capacity through carbonation in the air is proportional to carbonated depth of concrete. Carbonated concrete depth with water to cement ratio is predicted in chapter 4 and the result are shown in Fig. 5.6. Carbonated concrete depth is affected by water to cement ratio and it decreases sharply in case of water to cement ratio of 0.45. Table 5.5 shows calculation results of carbonated concrete depth and CO_2 absorption with water to cement ratio in 30 and 60 years.

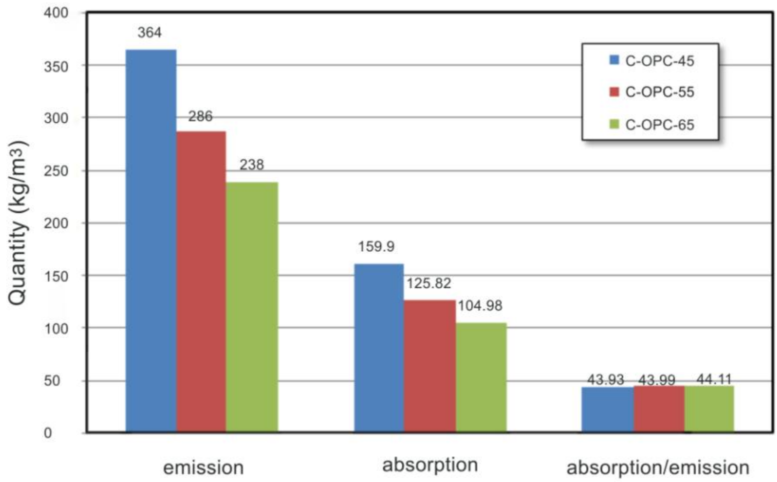


Fig. 5.6 *Calculation of emission, absorption and absorption/emission according to w/c ratio.*

Table 5.5 *Calculation amount of CO_2 absorption according to W/C in 30 and 60 years.*

		absorbable CO_2 (Unit: ×1,000 mol/m^3)	**Carbonated depth (mm)**	**absorbed CO_2 quantity (g/m^3)**
30 year	w/c=0.45	3.634	4.75	4.55
30 year	w/c=0.55	2.859	19.44	14.67
30 year	w/c=0.65	2.385	24.77	15.59
60 year	w/c=0.45	3.632	5.35	5.12
60 year	w/c=0.155	2.858	23.80	17.95
60 year	w/c=0.65	2.384	29.88	18.8

Concrete carbonation does not progress fast in a real condition of exposure to the air. As a result, CO_2 absorption of concrete through carbonation is tiny. Fig. 5.7 shows carbonated depth and CO_2 absorption of concrete with water to cement ratio according to service life. The increase of CO_2 absorption is proportional to carbonated depth of concrete. So, in case of water to cement ratio of 0.65, carbonated depth and CO_2 absorption of concrete is evaluated as the most significant.

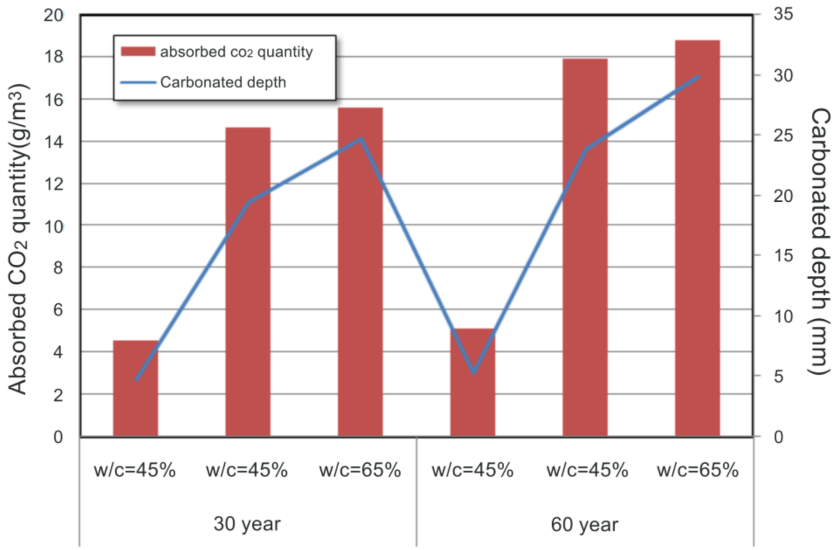


Fig. 5.7 *Calculation of the amount of CO_2 absorption and carbonated depth according to W/C in 30, 60 years.*

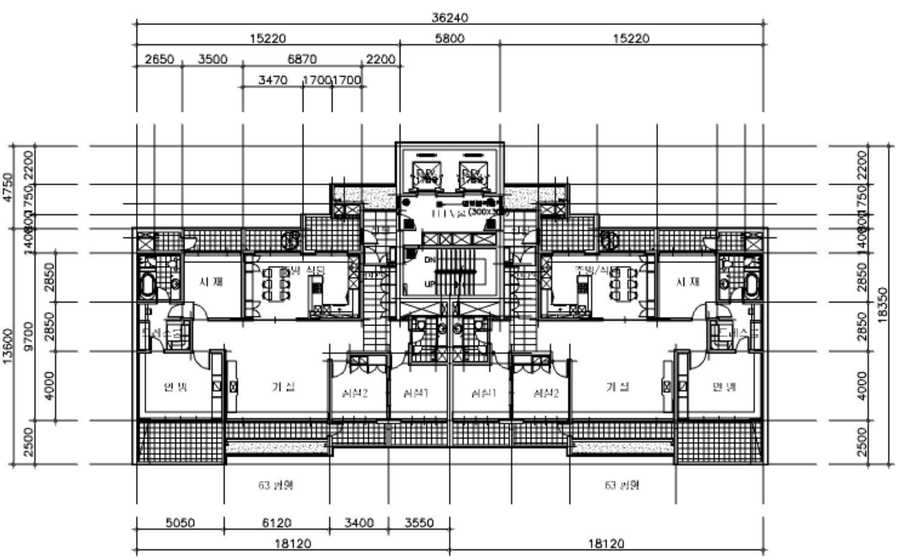
5.4 Case Study: Evaluation of the CO_2 Balance of an Apartment Building in South Korea During Its Service Life

5.4.1 Overview of the Apartment Building

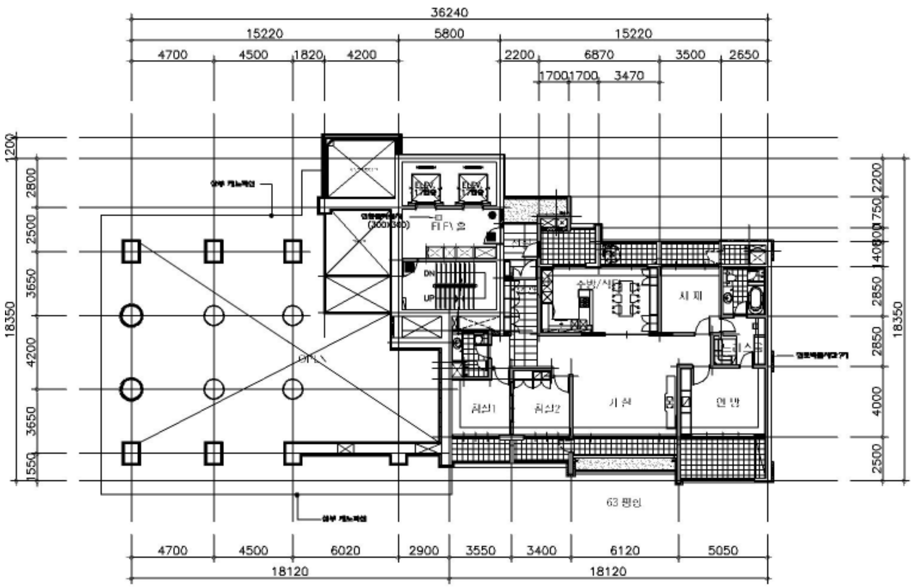
Table 5.6 outlines an apartment building with 34 floors above ground and one floor below ground. The height of each story is 2.9 m, and the total height of the building is 104.8 m. The compressive strength of concrete used for the vertical members of the building is 35 MPa from the first basement to the ninth floor, 30 MPa from the 10th floor to the 19th floor, 27 MPa from the 20th floor to the 26th floor, and 24 MPa from the 27th floor to the roof. The planes of the apartment are as shown in Fig. 5.8.

Table 5.6 *Used concrete volume by story.*

Story (floor)	Used concrete volume (m^3)					Strength (MPa)	W/C
Story (floor)	**Column + Wall**	**Slab**	**Sum (Wall+Slab)**	**Story**	**Total**	**Strength (MPa)**	**W/C**
Basement 1st	185	0	185	1	185	35	0.39
1st	220	84	304	1	304	35	0.39
2nd	248	79	327	1	327	35	0.39
3rd	181	47	229	1	229	35	0.39
4th	180	468	649	1	649	35	0.39
5th–9th	178	155	334	5	1,670	35	0.39
10th–19th	178	155	334	10	3,341	30	43
20th–26th	178	155	334	7	2,338	27	46
27th–31st	178	155	334	5	1,670	24	0.50
32nd	406	155	561	1	561	24	0.50
Roof Floor	152	58	211	1	211	24	0.50
Penthouse 1st	191	33	224	1	224	24	0.50
Penthouse 2nd	25	9	34	1	34	24	0.50



(a) Normal plane (5th~31st)



(b) 1st floor plane

Fig. 5.8 *Normal plane (5^{th}~31^{st}).*

5.4.2 Calculating CO_2 Emission from the Concrete Used in the Apartment Construction

The volume and CO_2 emission according to the types of concrete used were needed to calculate the total CO_2 emissions of all concrete used in constructing the apartment. The used concrete volume by floor was roughly divided into the volumes of vertical and floor members. The concrete volume of the vertical members was calculated by summing the volume of the columns and wall area multiplied by the story height (2.9 m) for each floor plan. The concrete volume of the floor member was calculated by summing the volume of the slab area multiplied by the slab thickness (0.2 m) for each floor plan. Table 5.6 shows the volume of each concrete depending on the type of concrete used in the apartment. Table 5.7 shows the CO_2 emissions from the production of 1 m^3

concrete according to the type of concrete used in the apartment. The total CO_2 emissions can be calculated by summing the total volumes multiplied by the CO_2 emissions per unit of each type of concrete used in the apartment. The results of the calculations are listed in Table 5.8.

Table 5.7 *Concrete mixture and calculated CO_2 emission of 1 m^3 concrete by strength.*

MPa	W/C	Unit weight (kg/m^3)						Total CO_2 emission (kg-CO_2/m^3)
MPa	**W/C**	**Water**	**Cement**	**Fly ash**	**Sand**	**Gravel**	**AE Water Reduction Agent**	**Total CO_2 emission (kg-CO_2/m^3)**
24	0.49	174	304	45	848	944	2.09	234
27	0.46	175	328	49	832	934	2.64	252
30	0.43	178	348	61	797	935	3.07	267
35	0.39	179	394	69	759	926	3.70	301

Table 5.8 *CO_2 emission of concrete by strength.*

Design strength	CO_2 emission (kg-CO_2)	
	by strength	**Total**
35 MPa	1,013,261	3,123,729
30 MPa	890,721	3,123,729
27 MPa	588,327	3,123,729
24 MPa	631,420	3,123,729

5.4.3 Calculating CO_2 Absorption of Concrete Used in the Apartment During Its 20-years' Service Life

As mentioned in 5.3.2, the surface area of concrete exposed to air, carbonated depth of concrete, and molar concentration of materials that can react with CO_2 are needed to calculate the CO_2 absorption of concrete during an arbitrary service life. The surface areas of concrete exposed to air in the apartment structure for each plane are shown in Table 5.9. The total surface area of concrete exposed to air according to the types of concrete is listed in Table 5.10.

Table 5.9 *Surface area of concrete exposed to the air by strength and ground plan.*

Story	Surface area (m^2)						Design Strength (MPa)
Story	**Left wall**	**Rear wall**	**Right wall**	**Front wall**	**Slab**	**Inner wall + column**	**Design Strength (MPa)**
Basement 1st	0	0	0	0	596	947	35
1st	0	0	0	0	596	549	35
2nd	53	60	53	76	596	631	35
3rd	54	62	54	77	596	642	35
4th	53	105	53	105	596	1,123	35
5th-9th	53	105	53	105	596	1,116	35
10th-19th	53	105	53	105	596	1,116	30
20th-26th	53	105	53	105	596	1,116	27
27th-31st	53	105	53	105	596	1,116	24
32nd	60	119	60	119	596	1,355	24
Penthouse 1st	50	98	61	98	596	484	24
Penthouse 2nd	50	73	50	73	596	292	24

Table 5.10 *Total surface areas of concrete exposed to air by concrete strength.*

Design strength (MPa)	24	27	30	35
Total surface area (m^2)	14,386	14,204	20,292	17,830

Eq. 5.7 [25] estimates the carbonated depth of concrete from the water to cement ratio (W/C) and the exposure time. It considers W/C, the South Korean climate, and CO_2 concentration in air. The calculated values of the carbonated depth for each concrete over 20 years using the corresponding Eq. 5.7 are listed in Table 5.11.

$$C = (2.823 - 0.548 \log CO_2)\times(0.0303\ W/C - 1.0187)\times(CO_2\cdot t)^{0.5} \qquad \text{Eq. 5.7}$$

Where C is the concrete carbonated depth (mm); CO_2, the CO_2 concentration in the air (=0.035); W/C, the water to cement ratio; and t, the exposure time (years).

Table 5.11 *Carbonated depth by concrete strength in 20 years.*

Design strength (MPa)	24	27	30	35
Carbonated depth (mm)	16.88	12.76	9.66	5.54

Table 5.12 lists the molar concentration of materials that can react with CO_2 according to the type of concrete. Finally, the total CO_2 absorption of concrete used in the apartment was calculated during its 20-years' service life by using Eq. 5.6. The results are listed in Table 5.13.

Table 5.12 *CO_2 molar concentration that could be carbonated in concrete by strength.*

Design strength	Molar concentration of CO_2	Unit
35 MPa	3,575	mol/m^3
30 MPa	2,821	
27 MPa	2,789	
24 MPa	2,749	

Table 5.13 *CO_2 absorption of concrete based on types of concrete after 20 years.*

Design strength	CO_2 absorption of concrete	Unit
35 MPa	15,538	kg-CO_2
30 MPa	24,331	
27 MPa	22,242	
24 MPa	29,373	
Total Quantity	91,484	

5.4.4 Evaluation of CO_2 Balance of Concrete

CO_2 emissions were calculated based on the concrete used and the CO_2 absorption of the concrete used in the apartment building during its 20-years' service life. Based on these values, the CO_2 balance of the apartment building and the CO_2 ratio of emission to absorption were calculated using Eq. 5.1 and 5.8. The results are shown in Table 5.14.

The CO_2 ratio of emission to absorption (%) = (CO_2 absorption/CO_2 emission) ×100 Eq. 5.8

Table 5.14 *Assessment result of CO_2 ratio of emission to absorption.*

	Value	Unit
CO_2 emission quantity	3,123.73	
CO_2 absorption quantity	91.48	ton-CO_2
CO_2 balance	3,032.25	
CO_2 ratio of emission to absorption	2.92	%

5.5 Review of the Method to Improve the CO_2 Balance of Concrete Considering Service Life of RC Structure During Century

The CO_2 balance of concrete for the apartment building during its 20-years' service life was 3,032 tons. The CO_2 ratio of emission to absorption was approximately 2.92%, which is very low. One method for improving the CO_2 balance of concrete is to reduce CO_2 emissions and increase CO_2 absorption. This concept is shown in Fig. 5.9.

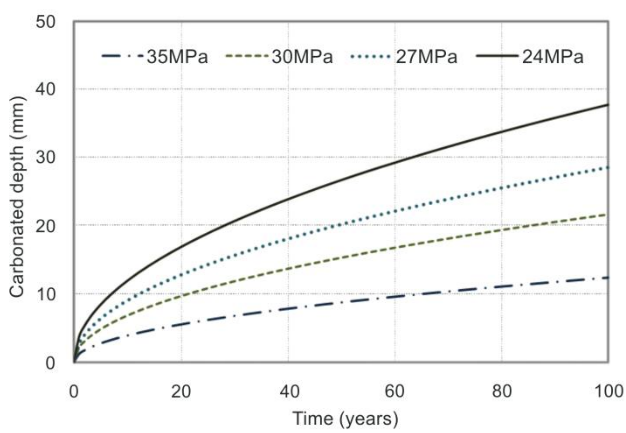


Fig. 5.9 *Carbonated depths by concrete strength by exposure time.*

Methods for reducing CO_2 emissions for the CO_2 balance of concrete are as follows:

1. Reduce the raw materials and cement used in a new construction by extending the service life of the structure.

2. Replace some of the cement in concrete with blended cement, such as fly ash or blast furnace slag.

Methods for increasing CO_2 absorption for the CO_2 balance of concrete are as follows:

1. Extend the service life of RC structures; this increases the carbonated depth of concrete.

2. Recycle waste concrete as sub-base materials or aggregate after deconstruction to increase the carbonated volume of concrete by increasing the surface area of concrete exposed to air.

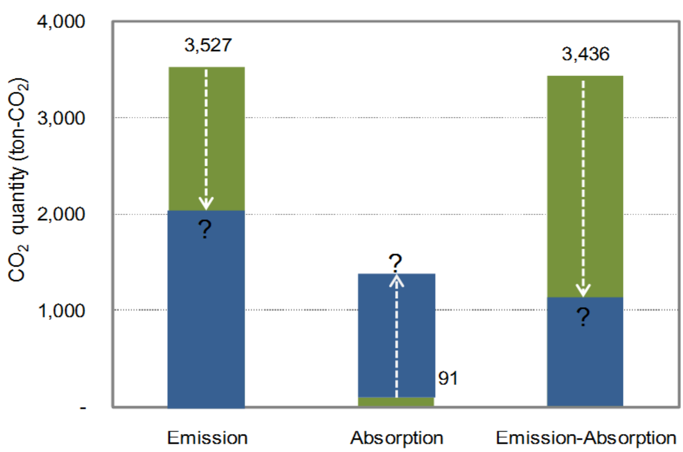


Fig. 5.10 *Concept for improving the CO_2 balance.*

5.5.1 Reduction of CO_2 Emission of Concrete by Extending the Service Life of the Apartment Building

The concept of $LCCO_2$ was used to select the appropriate service life of an apartment over a century. The service life of an apartment was assumed to be 20, 40, 60, 80, or 100 years. Fig. 5.10 shows the calculated $LCCO_2$ according to each service life of the apartment over a century considering reconstruction times after each service life. For the 20-years' service life, the $LCCO_2$ was 17,178 tons over a century; this was five times more than that of the 100-years' service life. One can infer that the number of reconstructions is a crucial factor that affects the increase in $LCCO_2$ because every reconstruction produces a large amount of CO_2. Therefore, extending the service life of an apartment building is very important for reducing CO_2 emissions over a century. The 100-years' service life had an $LCCO_2$ of 3,323 tons, which was the lowest value.

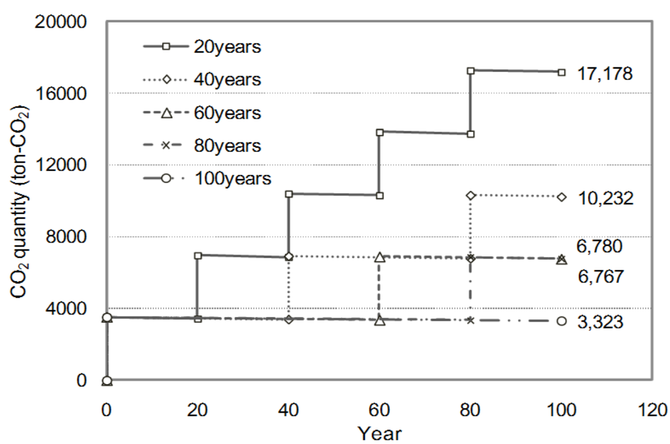


Fig. 5.11 *CO_2 balance analysis according to each service life.*

Fig. 5.11 shows the service life of apartment buildings by countries[26). However, in the case of apartments in South Korea, the life cycle spans mostly 20 to 30 years. There are no cases in which the life cycle of an apartment buildings house exceeds 100 years due to changes in social demands and building safety codes concerning natural disasters or unanticipated accidents[27)].

The appropriate service life for an apartment building to improve its $LCCO_2$ seems to be 60 years with one reconstruction in terms of $LCCO_2$ during a century. The $LCCO_2$ was better for the 60-years' service life of an apartment building than that for the 80-years' service life. This is because the growth of the carbonated depth of concrete attributed to carbonation slows down with time as shown in Fig. 5.6.

5.5.2 Reduction in CO_2 Emission of Concrete by Using Blended Cement in Concrete

Blast furnace slag cement is an industrial by product that can be used as a mineral admixture for cement. Its CO_2 emissions are approximately 28 times lower (0.0265 kg-CO_2/kg) than that of ordinary cement (0.7466 kg-CO_2/kg)[15)]. Therefore, the CO_2 emissions of concrete can be reduced if some of the cement (348 kg cement used for 30 MPa concrete) used in concrete is replaced by blast furnace slag. In this study, the CO_2 emissions of concrete were calculated in terms of increasing the slag-to-cement replacement ratio in 1 m^3 concrete from 0% to 60% in 20% increments.

Table 5.15 lists the mixing proportion of concrete and CO_2 emissions according to slag-to-cement replacement ratios in 1 m^3 of 30 MPa concrete[28)]. The CO_2 emission from 1 m^3 concrete is 267 kg without blast furnace slag. However, this value decreases as more blast furnace slag is used to replace cement.

Table 5.15 *CO_2 emission by replacement ratios of blast furnace slag to the cement.*

MPa	**Replacement ratio (%)**	**Total CO_2 emission (kg-CO_2/m^3)**	**Unit weight (kg/m^3)**						
MPa	**Replacement ratio (%)**	**Total CO_2 emission (kg-CO_2/m^3)**	**W**	**C**	**BS**	**FA**	**S**	**G**	**AE reduction water agent**
30	0	267	178	348	0	61	797	935	3.07
30	20	216	178	278	70	61	797	935	3.07
30	40	166	178	209	139	61	797	935	3.07
30	60	116	178	139	209	61	797	935	3.07
CO_2 emission(kg-CO_2/m^3)			-	0.7466	0.0265	0.196	0.0037	0.0028	0.25

The CO_2 emissions are 116 kg when the slag-to-cement replacement ratio is 60%; thus, this method can reduce CO_2 emissions by 56% compared to concrete without blast furnace slag. Therefore, CO_2 emissions can be reduced by using blast furnace slag in the concrete. If a 60% slag-to-cement replacement ratio becomes obligatory, then the CO_2 emissions from the apartment building in the case study would be reduced to 1,362 tons, which is a reduction in CO_2 emissions of 56% compared to concrete without blast furnace slag (Table 5.16). If the CO_2 absorption of concrete during a 20-years' service life is assumed to be the same as that of the existing building, then a total of 91.48 tons of CO_2 will be absorbed. In this case, the CO_2 ratio of emission to absorption would be 5.6%, which results in an approximately 3% improvement compared to the existing mixture proportion.

Table 5.16 *Total CO_2 emission of the apartment by replacement ratio of the blast furnace slag to the cement.*

Blast furnace slag replacement ratio (%)	**CO_2 emission**	**Unit**
0	3,123,730	kg-CO_2
20	2,536,380	kg-CO_2
40	1,949,030	kg-CO_2
60	1,361,680	kg-CO_2

5.5.3 Increase in CO_2 Absorption of Concrete by Extending the Service Life of the Apartment Building

One method for increasing the CO_2 absorption of concrete is to extend the service life of an apartment building. The CO_2 absorption of the subject apartment building was calculated quantitatively and evaluated according to the service life of the apartment building described in Section 4: 20, 40, 60, 80, and 100 years. The longer service life of the RC structure led to a deeper carbonated depth of the concrete and more carbonated volume, as shown in Fig. 5.6. As a result, the CO_2 absorption increased by approximately 2.2 times, from approximately 91 tons of CO_2 for a 20-years' service life to 204 tons of CO_2 for a 100-years' service life, as shown in Fig. 5.12. Thus, a longer service life for the RC structure increases CO_2 absorption, but the increment is quite small compared to the CO_2 emissions from construction, as shown in Fig. 5.13. Therefore, extending the service life of apartment buildings is very important for reducing CO_2 emissions by preventing unnecessarily early deconstruction.

5.5.4 Increase in CO_2 Absorption of Concrete by Recycling Waste Concrete After Deconstruction of RC Structure

Another method for increasing CO_2 absorption is to recycle waste concrete after deconstruction of an RC structure. If waste concrete is crushed into small pieces, the uncarbonated lump of concrete in the structure is exposed to air and can absorb more CO_2 because the total surface of small-volume.

Concrete would be increased. Fig. 5.15 shows the relation between the surface area and CO_2 absorption of 1 m^3 concrete exposed to air with side lengths ranging from 1 cm to 100 cm. When a side length of 1 m^3 concrete was reduced from 100 cm to 1 cm, the surface area increased 100 times from 6 m^2 to 600 m^2. This means that CO_2 absorption increased 100 times, from 14.64 kg to 1,464 kg for 24 MPa concrete.

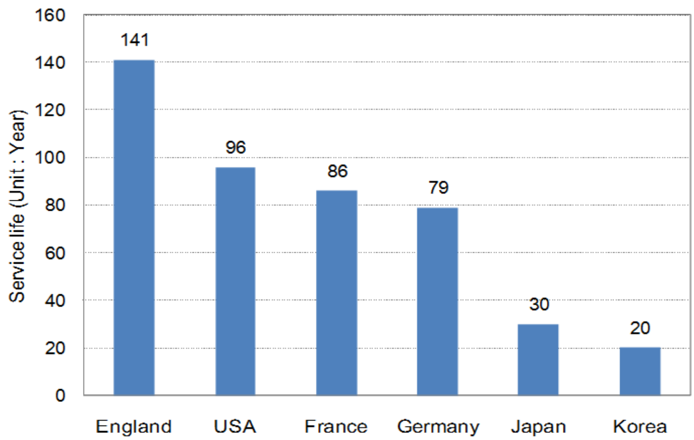


Fig. 5.12 *Service life of apartment house by countries.*

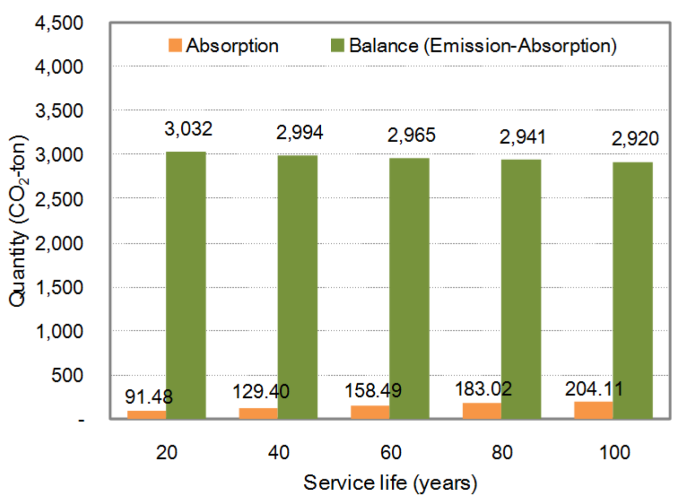


Fig. 5.13 *CO_2 absorption and its balance according to service life.*

Generally, the surface area of concrete in the RC structure that is exposed to air is very limited. This is why the surface area and volume of carbonated concrete in the RC structure is only a small portion of the entire concrete volume. For example, the wall thickness of RC structure such as an apartment in South Korea is typically 20 cm. However, the carbonated depth would only be about 37 mm for 24 MPa concrete after a 100-year service life (Fig. 5.6). In this case, the carbonated ratio to the full thickness would only be approximately 37% even if both sides (inside and outside) of the wall were considered to be carbonated over 100 years.

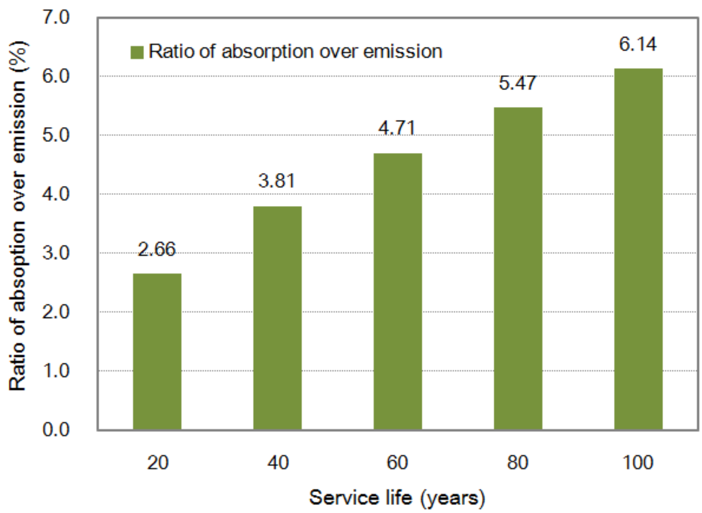


Fig. 5.14 *CO_2 ratio of absorption over emission.*

However, when concrete is crushed into small lumps, the surface area exposed to air is increased 100 times compared to that of uncrushed concrete, as shown in Fig. 5.14. This increases the carbonated volume of concrete in the RC structure to be proportional to the volume of used concrete. A study in Denmark showed that the recycling rate of waste concrete from a building as an aggregate reached 90% and that the CO_2 absorption by recycling waste concrete was approximately 2.4 times more than that of the carbonated concrete volume during the service life of a building[3)].

Therefore, increasing CO_2 absorption by recycling waste concrete should be strongly considered by the construction industry of South Korea. If the CO_2 absorption by recycling waste concrete increased by 2.4 times in South Korea, then the CO_2 absorption for a building during a 20-years' service life would increase from 91.48 tons to 219.55 tons. The CO_2 rate of emission to absorption would increase by approximately 3.48%, from 2.66% to 6.14% (Fig. 5.15).

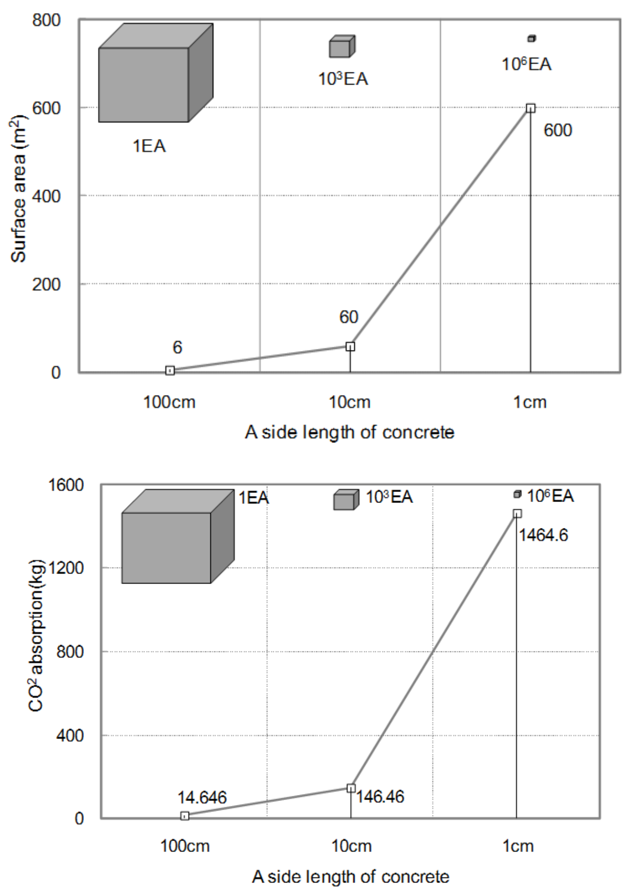


Fig. 5.15 *Changes in surface area and CO_2 absorption by the side-length of $1m^3$ concrete.*

5.6 Review Summary: Improving Effect of $LCCO_2$ with Proposed Methods

Based on the above results, the following sustainable development method based on the life cycle CO_2 balance of concrete is proposed for the construction industry in South Korea:

1. Use of blended cement in concrete is made obligatory to reduce CO_2 emissions.

2. Apartment service life should be at least 60 years to reduce CO_2 emissions from building reconstruction due to early deconstruction.

3. Waste concrete from RC structures should be recycled and reused as aggregates or sub-base materials to increase CO_2 absorption of the waste concrete through carbonation.

The method were applied to actual apartment buildings to review and compare the CO_2 balance for two cases: (1) the concrete of an apartment building razed after 20 years of service life and (2) the concrete of an apartment whose service life is 60 years with 60% of the cement replaced by blast furnace slag and a 90% recycling ratio of waste concrete after demolition. The CO_2 ratio of emission to absorption based on the service life increased by approximately six times more from 2.59% to 19.07%, as shown in Fig. 5.16; case (2) resulted in a CO_2 emission reduction of 702 tons compared to case (1). In addition, the $LCCO_2$ efficiency over a century of a 60-years' service life increased eightfold from 2.59% to 21.25% compared to that of a 20-years' service life, as shown in Fig. 5.17, in terms of the number of reconstructions. The $LCCO_2$ of concrete with a 60-years' service life was reduced by approximately 11,975 tons compared to that of a 20-year service life over a century.

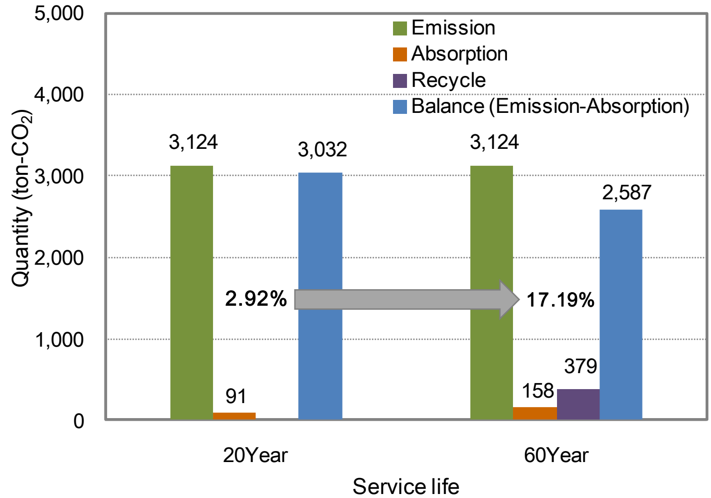


Fig. 5.16 *Calculating CO_2 balance according to service life.*

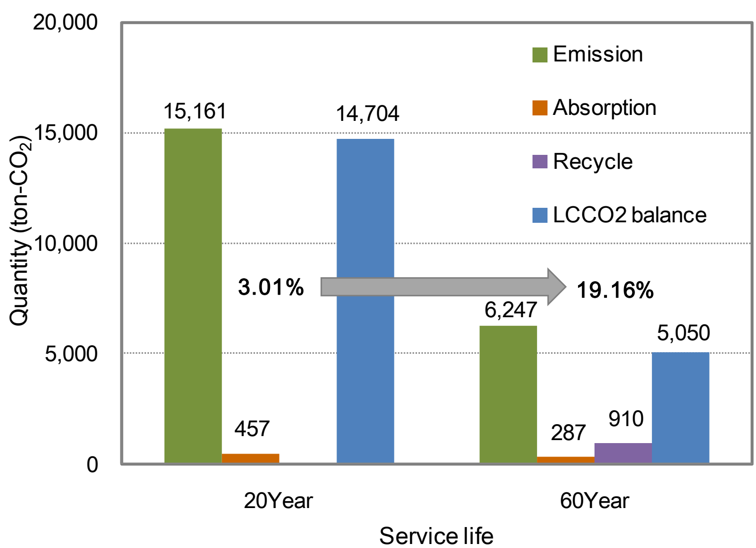


Fig. 5.17 *$LCCO_2$ balance and its efficiency over 100 years according to service life.*

5.7 Summary

In this chapter, CO_2 emission from production of concrete, CO_2 absorption during service life considering carbonation degree and $LCCO_2$ are calculated quantitatively. As a result, conclusions are as follows:

1. CO_2 emission from concrete production can be calculated quantitatively by summarizing values that multiplied CO_2 emission of each material that are used in concrete with used quantities in concrete.

2. CO_2 absorption in concrete during service life is calculated quantitatively using surface area of concrete exposed to the air, carbonation depth with using time, the molar concentration of carbonatable substances in concrete and molecular weight of CO_2.

3. Evaluation method for CO_2 balance and $LCCO_2$ that is studied in this chapter can be used to select optimal material design and service life.

5.8 Conclusions

Evaluation method by indicator has a qualitative assessment limit that instability color change may happen in the carbonation depth anytime. In addition, carbonation depth measurement method by the indicator has a problem that concrete color does not discolored in early progress of carbonation. Above all, carbonation depth measurement method using an indicator may cause prediction error of service life of RC structure when measurement error by measurers has happened because of ambiguous boundary. Therefore, a quantitative evaluation methods and standards for carbonation are required to overcome this problem.

So, this study proposed a quantitative evaluating method that overcomes the limitation of qualitative evaluation, which is carried out using the naked eye with respect to the color change boundary by spraying indicator. Carbonation depth becomes the basic data for estimating the residual life and durability of RC structures.

To achieve this objective, correlation between pH value and quantities of $Ca(OH)_2$, $CaCO_3$ is analyzed experimentally by carbonation weeks, concrete depths through accelerated carbonation experiment in order to propose a quantitative evaluating basis. Quantity of $Ca(OH)_2$ is important to predict service life of concrete against carbonation and cement hydration model can predict it quantitatively to any concrete mix. Therefore, validation for cement hydration model is verified by comparing prediction values and measured values of $Ca(OH)_2$. And then prediction model for carbonation based on FEM is used to predict the service life of RC structure.

Required input parameters such as initial concentration of $Ca(OH)_2$, diffusion coefficient of CO_2, reaction velocity constant, CO_2 concentration in the air for FEMA are decided through literature review. The proposed quantitative evaluation basis in chapter 3 is used to evaluate and predict service life. As a final step, CO_2 emission of concrete considering concrete mix and CO_2 absorption through carbonation during service life for unit volume concrete is calculated quantitatively. And then, CO_2 balance (emission-absorption of CO_2) and $LCCO_2$ is evaluated quantitatively to a real building. The results of this study can be summarized as follows:

1. Proposal of a quantitative evaluation basis for carbonation depth

a) Carbonation depth is determined. Approximately 60% level of the initial concentration of $Ca(OH)_2$ and the point where the ratio of $CaCO_3$, $Ca(OH)_2$ 1:3 is matched the colored point by indicator.

b) Mass loss rate of $CO_2(C_0)$ is 1.0% after hydration and pH value is 10.6 and mass loss rate of $CO_2(C_{max})$ is 27.15% when concrete carbonated fully.

c) Proposed quantitative method for carbonation can evaluate in 1 week carbonation time even though method by indicator cannot evaluate because of uncolored concrete.

2. Prediction of service life to all mixtures of concrete using carbonation degree

a) Hydration model is valid to estimate the amount of $Ca(OH)_2$ after comparing experimental value and predicted value.

b) Predicted value using a point where the concentration of $Ca(OH)_2$ is 60% value shows similar existing result after comparing exiting predicted model.

c) Prediction of service life for carbonation to all mixtures of concrete is possible by the result of FEMA using a hydration model and carbonation degree

3. Proposing of evaluation method for concrete $LCCO_2$ by carbonation degree

a) In terms of CO_2 reduction, evaluation method of $LCCO_2$ and CO_2 balance for concrete with proposed carbonation can be used for determining the mix proportion of concrete and service life of structure

This study has limitations and as such it cannot be used as a method for quantitative evaluation of concrete carbonation, because it is based on only the experimental result for water to cement ratio of 0.45, 0.55 and 0.65 with ordinary Portland cement. In future, an additional investigation for the concrete with fly ash and blast furnace slag will be needed.