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Article

Propose of Mix Design Method for CO_2 Reduction Concrete Using the Regression Analysis

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Abstract: As argued by 'Declaration of Concrete Environment (2010)' of Korea and 'Declaration of Asian Concrete Environment (2011)' of six Asian countries, concrete as a single material has lately shown extremely large impact on environmental issues such as climate change. Assessment of environmental impact from concrete material and production has considerable importance. Concrete is a major material used in the construction industry that emits a large amount of substances with environmental impacts during its life cycle. Accordingly, technologies for the reduction in and assessment of the environmental impact of concrete from the perspective of Life Cycle Assessment must be developed. At present, the studies in relation to greenhouse gas emission from concrete are being carried out globally as a countermeasure against climate change. In this study, CO_2 reduction concrete mix design algorithm was designed using correlation analyses, and its carbon emission and cost reduction performances were assessed. Using correlation analyses, the concrete strength, water/cement (w/c) ratio and fine aggregate/total aggregate (s/a) ratio, and CO_2 emissions were identified as major variables of concrete mix design that influenced other variables. Also, this study aims to evaluate the CO_2 emission reduction performance of the algorithm-deduced CO_2 reduction concrete mix design, and therefore, the CO_2 emissions of the CO_2 reduction concrete mix design are compared with those of the actual concrete mix design applied to the construction of the office building A in South Korea.

Keywords: concrete; sustainability; regression analysis mix design; CO_2 emission; cost

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1. Introduction

With the increasing interest in climate changes worldwide, however, the development of concrete mix designs that consider the reduction of CO_2 emissions, in addition to the physical properties such as strength and durability, has become necessary [1].

The major construction materials accounting for more than 90% of building greenhouse gas (GHG) emissions include concrete, rebar, insulation, concrete brick, glass and gypsum board [2]. Among the CO_2 emissions generated by these major construction materials, concrete accounts for 70% [3].

Several studies have been conducted to determine concrete mix designs through optimization methods. Majority of these studies are concerned with the estimation of target strength or the determination of high-strength and lightweight concrete mix designs [4]. In Korea, standard specifications for ready-mixed concrete (RMC) consider the criteria of strength, durability, water tightness, workability, water/cement (w/c) ratio, slump, and fine aggregate/total aggregate (s/a) ratio [5]. However, a standard for carbon-dioxide (CO_2) emission by RMC has not yet been set. A CO_2 emission standard is difficult to establish, mainly because there are numerous variables of the concrete mix influencing CO_2 emissions, and the physicochemical compositions of materials used to prepare the mix vary depending on their source and their proportions in the mix. Consequently, a large number of variables must be considered in order to determine concrete mix designs that reflect the environmental load of CO_2 emissions, and it is practically impossible to derive a mathematical

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model that can accurately define the outcome of the interactions of all these variables. To overcome these limitations, this study proposed a CO_2 reduction concrete mix design algorithm by performing correlation analyses to rationally minimize CO_2 emissions. This study aims to evaluate the CO_2 emission reduction performance of the algorithm-deduced CO_2 reduction concrete mix design, and therefore, CO_2 emissions of the concrete mix design are compared with those of the actual concrete mix design applied to the office building in South Korea.

2. Literature review

To develop a mix design method for concrete to reduction CO_2 emission, this chapter presented methodologies about mix design technique and life cycle CO_2 emission assessment etc.

Trend of research was analyzed as below.

The goal that expected from Raharjo et al. research is to obtain the optimal material composition of the mixture that produce the maximum compressive strength but cheaper and competitive in price [6].

Berndt et al. has shown that selection of concrete constituents and appropriate mix design can be used to minimize CO_2 emissions associated with large wind turbine foundations without compromising strength and performance requirements [7]. Andreas et al. aimed at empirically identifying a material parameter (or a number of parameters) that defines the carbonation resistance of mortar and concrete produced with cements containing mineral additions [8].

Peter et al. introduced the commonly used methods of mix design (mixture proportioning) from the United States, and the United Kingdom. The basic principles that are common to all systems are discussed, and then the two methods are considered in detail, stage by stage [9]. Talha et al. presented a systematic approach for selecting mix proportions for alkali activated fly ash-based geopolymer concrete (GPC). The proposed mix design process is developed for low calcium Class F fly ash activated geopolymers using sodium silicates and sodium hydroxide as activator solutions [10]. Kim et al. evaluated the appropriateness and the reduction performance of the low-carbon-emission concrete mix design system and the deduced mix design results using an evolutionary algorithm (EA), the optimal mix design method, which minimizes the CO_2 emission of the concrete mix design [11]. Ramin et al. presented the experimental results of an on-going research project to produce geopolymer lightweight concrete using two locally available waste materials – low calcium fly ash (FA) and oil palm shell (OPS) – as the binder and lightweight coarse aggregate, respectively [12]. Linoshka et al. investigated a cleaner production of pervious concrete containing waste FA, a solid waste unless otherwise utilized, in combination with other admixtures of nano-iron oxide (NI) and WR. The mix design with the percentages of water-to-binder (w/b), FA/B, NI/B and WR/B was optimized for the desired permeability and compressive strength [13]. Hong et al. proposed an integrated model for assessing the cost and CO_2 emission (IMACC) at the same time. IMACC is a model that assesses the cost and CO_2 emission of the various structural-design alternatives proposed in the structural-design process. To develop the IMACC, a standard on assessing the cost and CO_2 emission generated in the construction stage was proposed, along with the CO_2 emission factors in the structural materials, based on such materials' strengths [14].

3. Mix design algorithm of CO_2 reduction concrete

3.1 Algorithm process

The major features of the CO_2 reduction concrete mix design algorithm are its inputs: strength, water/binder (w/b) ratio, sand aggregate/total aggregate (s/a) ratio, and the proportion of admixture (%), and the resulting concrete mix design, which exhibits the intended physical properties and required reduction in CO_2 emission. To develop the algorithm, we first compiled a database of different concrete mix designs provided by Korean RMC suppliers. Key influential factors – CO_2 emissions and cost-effectiveness – were then extracted from the correlation analyses of the different concrete mix designs. Finally, regression analyses were performed on the derived influential factors to deduce equations expressing the relationship between CO_2 emissions, binder, and fine aggregates.

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The regression equations were derived using four different concrete mix designs: plain, with fly ash (FA), ground granulated blast furnace slag (GGBS), and both FA and GGBS.

3.2 Establishment of a concrete mix design database

A total of 800 concrete mix designs supplied by 10 RMC suppliers in Korea were investigated as shown in Table 1. The concrete mix designs had varying strength levels (18, 21, 24, 27, 30, 35, 40, 50, and 60 MPa) with variables such as plain cement, mixing water, coarse and fine aggregates, and admixtures. Further, the size of coarse aggregate, strength, and w/b and s/a ratios were investigated. Approximately 800 combinations of concrete strength and admixture type (GGBS/FA/GGBS+FA) were included in the database.

3.3 CO_2 emissions assessment

A system boundary was established for the life cycle CO_2 emission evaluation of concrete. The system boundary was selected as the product stage of concrete (cradle to gate) based on ISO 14044 [20] and ISO 21930 [21]. The product stage of concrete is divided into the raw material stage, the transportation stage, and the manufacturing stage [22]. The raw material stage refers to CO_2 emission during the production of major components of concrete such as cement, aggregate, and water. The transportation stage's CO_2 emission occurs during the transportation of raw materials to the ready-mixed concrete manufacturing plant. The manufacturing stage's CO_2 emission comes from electricity and oil used in the concrete batch plant. The system boundary for life cycle CO_2 emission of concrete is shown in Figure 1. Also, Figure 2 is the production process of concrete.

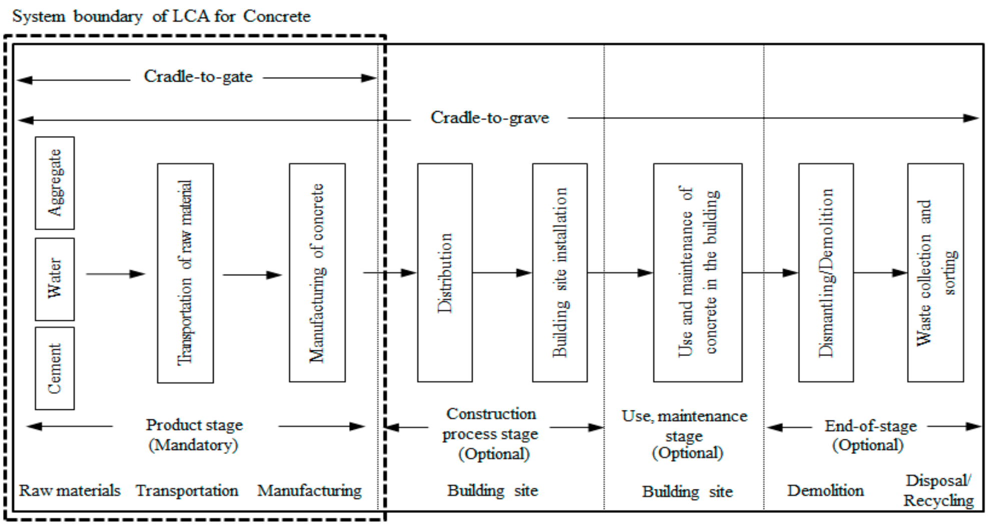

Figure 1. System boundary of the life cycle assessment (LCA) for concrete.

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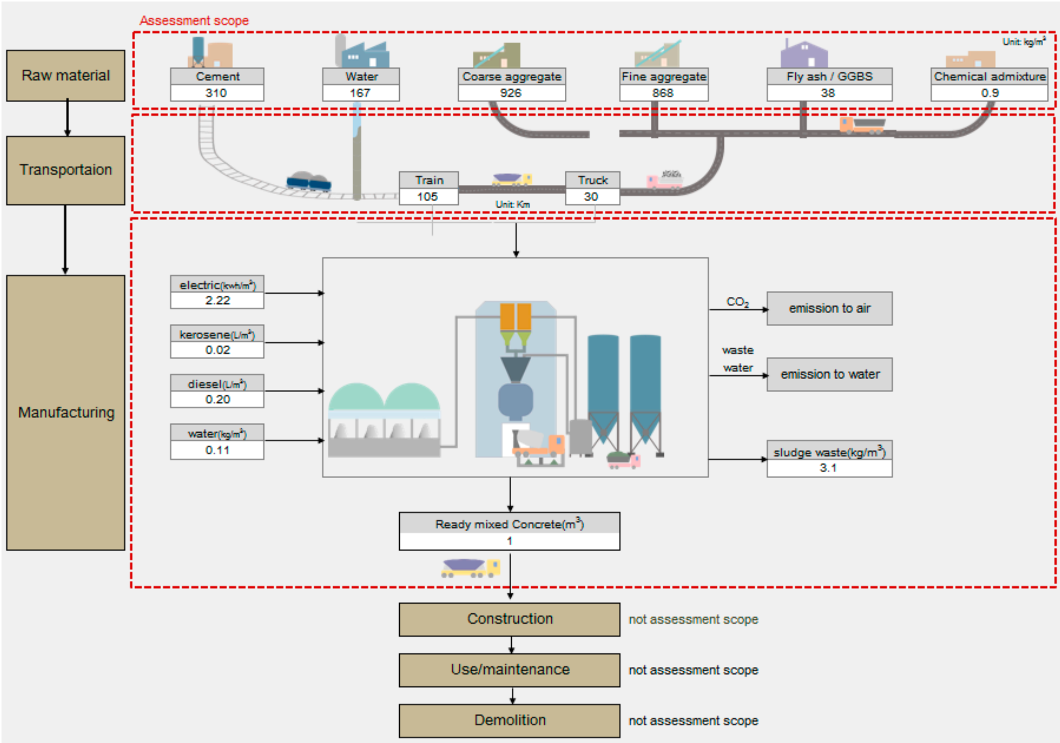

Figure 2. The production process of concrete according to LCA.

CO_2 emissions of concrete mix designs were evaluated by calculating the cumulative product of the amount of each material in the concrete mix and the intensity of CO_2 emission from the respective materials. The intensities of CO_2 emissions were drawn from the life cycle inventory (LCI) databases used in Korea [15] and other countries [16]. Intensities of CO_2 emissions from plain cement, mixing water, and coarse and fine aggregates were drawn from the Korean LCI database, whereas the intensities for admixtures (GGBS, FA, and chemical admixtures), for which no Korean LCI databases were available, international LCI databases were used as shown in Table 2 [17, 18].

Table 1. Example of concrete mix design Database

Strength (MPa)	W/B (%)	S/a (%)	Mix design (kg/m³)							CO_2 emission (kg-CO_2/m³)
			G	S	OPC	FA	GGBS	W	AE	
21	52.7	49.9	906	893	293	33	0	172	1.63	282.4
24	45.7	47.5	910	818	188	38	151	172	2.26	187.5
:	:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:	:
50	30.5	45	866	728	477	64	0	165	7.03	457.7
50	30.3	44	914	715	457	31	30	163	6.46	439.0

w/b: water binder ratio s/a: fine aggregate ratio OPC: ordinary portland cement FA: fly ash W: water
GGBS: ground granulated blast furnace slag G: coarse aggregate S: fine aggregate AE: chemical admixture

Table 2. CO_2 emission factor and reference

Constituent material	CO_2 emission factor	Reference
ordinary portland cement	0.944kg-CO_2/kg	Korea national LCI DB
coarse aggregate	0.0014kg-CO_2/m³	Korea national LCI DB
fine aggregate	0.0001kg-CO_2/m³	Korea national LCI DB
ground granulated blast furnace slag	0.0418kg-CO_2/kg	Ecoinvent
fly ash	0.0153kg-CO_2/kg	Ecoinvent
water	0.0001kg-CO_2/kg	Korea national LCI DB
chemical admixture	0.25kg-CO_2/kg	Ecoinvent

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3.4 Correlation analysis

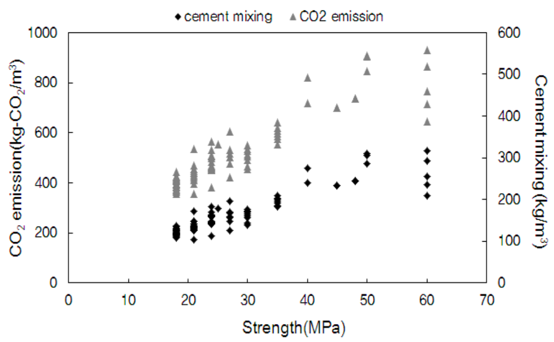
Correlation analyses [19] were performed considering 13 variables, including target strength (MPa) of the concrete mix design, w/b and s/a ratios (%), slump (mm), plain cement, mixing water, fine aggregate, and admixture contents (kg/m^3), as well as CO_2 emissions (kg-CO_2/m^3)' and cost (KRW/m^3) [20]. Variables w/b and s/a ratios, slump, CO_2 emissions, and cost were found to be highly correlated with concrete strength as shown in Table 3. For instance, with increase in concrete strength, the w/b ratio decreased, whereas aggregate content, CO_2 emissions, and cost increased. Variables highly correlated with the w/b ratio were concrete strength, plain cement content, slump, s/a ratio, CO_2 emissions, and cost. Variables highly correlated with plain cement content were concrete strength, w/b and s/a ratios, fine aggregate content, slump, CO_2 emissions, and cost. Variables highly correlated with fine aggregate content were strength, w/b and s/a ratios, plain cement content, CO_2 emissions, and cost. Variables highly correlated with CO_2 emissions were strength, the w/b and s/a ratios, plain cement and fine aggregate contents, slump, and cost. For instance, with increase in CO_2 emissions, concrete strength, and plain cement and fine aggregate contents increased, whereas cost and the w/b ratio decreased. Variables highly correlated with cost were concrete strength, w/b and s/a ratios, plain cement and fine aggregate contents, slump, and CO_2 emissions. The unit prices of concrete materials were excluded from the analyses because they significantly varied from one company to another. Thus, from the 12 different variables that were subject to correlation analyses, four variables were found to be most highly correlated: concrete strength (MPa), w/b (%), s/a (%), and CO_2 emissions. Regression equations were then deduced from these four key variables as shown in Figure 2.

(a) Analysis of the concrete strength, CO_2 emissions, and plain cement content

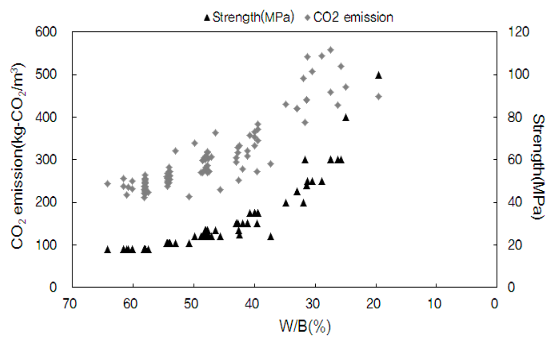
(b) Analysis of the w/b ratio, CO_2 emissions, and concrete strength

(c) Analysis of the w/b and s/a ratios, and plain cement content

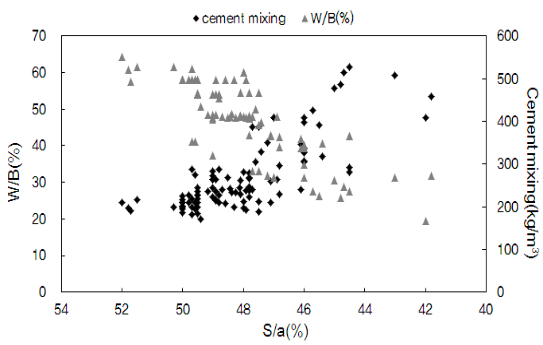
(d) Analysis of CO_2 emissions, plain cement content, and the s/a ratio



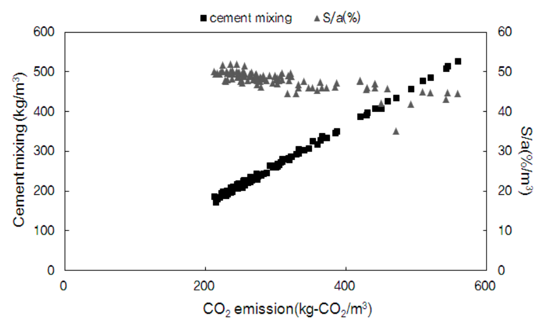
(a) analysis of strength and CO_2 emission, cement



(b) analysis of w/b and CO_2 emission, strength



(c) analysis of fine aggregate ratio and w/b, cement



(d) analysis of CO_2 emission and cement, fine aggregate ratio

Figure 2. Results of correlation analyses of the key variables of the concrete mix design

Table 3. Results of correlation analyses of concrete mix designs

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	w/b	S/a	slump	strength	OPC	W	GGBS	FA	G	S	AE	CO_2	COST
w/b	1.000	0.835	0.433	0.968	0.905	0.005	0.010	0.096	0.155	0.892	0.730	0.907	0.940
S/a	0.835	1.000	0.262	0.850	0.814	0.118	0.024	0.126	0.131	0.935	0.630	0.816	0.816
slump	0.433	0.262	1.000	0.451	0.433	0.059	0.069	0.008	0.333	0.344	0.415	0.417	0.432
strength	0.968	0.850	0.451	1.000	0.898	0.003	0.040	0.106	0.148	0.903	0.781	0.902	0.938
C	0.905	0.814	0.414	0.898	1.000	0.164	0.244	0.043	0.154	0.860	0.670	0.998	0.940
W	0.005	0.118	0.059	0.003	0.164	1.000	0.223	0.198	0.321	0.211	0.054	0.181	0.155
GGBS	0.010	0.024	0.069	0.040	0.244	0.223	1.000	0.053	0.079	0.014	0.130	0.245	0.144
FA	0.096	0.126	0.008	0.106	0.043	0.198	0.053	1.000	0.146	0.171	0.026	0.037	0.027
G	0.155	0.131	0.333	0.148	0.154	0.321	0.079	0.146	1.000	0.115	0.115	0.163	0.192
S	0.892	0.935	0.344	0.903	0.860	0.211	0.014	0.171	0.115	1.000	0.685	0.866	0.883
AE	0.730	0.630	0.415	0.781	0.670	0.054	0.130	0.026	0.115	0.685	1.000	0.674	0.706
CO_2	0.907	0.816	0.417	0.902	0.998	0.181	0.245	0.037	0.163	0.866	0.674	1.000	0.952
COST	0.940	0.816	0.432	0.938	0.940	0.155	0.144	0.027	0.192	0.883	0.706	0.952	1.000

w/b: water/binder ratio s/a: fine aggregate/total aggregate ratio OPC: ordinary portland cement W: water
GGBS: ground granulated blast furnace slag FA: fly ash G: coarse aggregate S: fine aggregate
AE: chemical admixture

3.5 Derivation of concrete mix design regression equations

The key variables that were found to have high degrees of correlation were subjected to regression analyses. Regression equations expressing relationships between the amounts of CO_2 emissions, binder, and the fine aggregate were derived based on the presence of admixture in the concrete mix design, i.e., in four variations: without admixture, with FA or GGBS only, and with both FA and GGBS [21].

3.5.1 Equation for CO_2 emission

A regression equation was derived to deduce the CO_2 emission depending on the target strength (MPa), w/b(water/binder ratio), s/a(sand aggregate/total aggregate ratio), admixture mix ratio(%). To this end, we derived a regression equation, thereby setting the w/b ratio as the dependent variable and the concrete strength, w/b(%), s/a(%) and admixture mixing ratio(%) as independent variables. Using the amount of CO_2 emission calculated from this equation, the binder amount can be deduced.

[Plain]

variable CO_2 (kg-CO_2) = 680.87 + (strength(MPa)*3.05) + (w/b(%)*-7.72) + (s/a(%)*-0.13)

[OPC+FA (Fly ash)]

variable CO_2 = 512.25 + (strength*6.38) + (w/b*-0.41) + (s/a*-4.98) + (FA(%)*-5.31)

[OPC+GGBS (Ground granulated blast furnace slag)]

variable CO_2 = 617.29 + (strength*1.12) + (w/b*-0.55) + (s/a*-3.65) + (GGBS(%)*-7.53)

[OPC+GGBS+FA]

variable CO_2 = 662.31 + (strength*1.67) + (w/b*-4.29) + (s/a*-1.87) + [(GGBS+FA)]*-4.08)

3.5.2 Equation for binder amount (B)

A regression equation was derived to deduce the binder amount based on the target strength (MPa), w/b ratio, S/a ratio and CO_2 emission. To this end, we derived a regression equation, thereby setting the content of binder as the dependent variable and the concrete strength, w/b, s/a, admixture

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mixing ratio and CO_2 emission as independent variables. Using the binder amount calculated from this equation and the CO_2 emission calculated from the previous equation and the input information, mixing water content can be deduced.

[Plain]
variable B(kg) = 0.69 + (strength(MPa)*0.219) + (w/b(%)*-0.51) + (s/a(%)*-0.001) + (CO_2(kg-CO_2)*0.958)

[FA(Flyash)]
variable B = 91.1 + (strength*1.846) + (w/b*-0.063) + (s/a*-1.893) + (CO_2*0.894)

[GGBS(Ground granulated blast furnace slag)]
variable B = 857.3+ (strength*1.225) + (w/b*-6.471) + (s/a*-2.645) + (CO_2*-6.535)

[GGBS+FA]
variable B = 437.3 + (strength*3.244) + (w/b*-3.274) + (s/a*-1.576) + (CO_2*-0.236)

3.5.3 Equation for fine aggregate content (S)

A regression equation was derived to deduce fine aggregate content based on the target strength (MPa), w/b ratio, s/a ratio and admixture mixing ratio. To this end, we derived a regression equation, thereby setting the fine aggregate content as the dependent variable and the concrete strength, w/b, s/a, binder and CO_2 emission as independent variables. Using the fine aggregate content calculated from this equation and the s/a ratio calculated from the previous equation and the input information, the coarse aggregate content can be deduced.

[Plain]
variable S(kg) = 716.922 + (strength(MPa)*2.177) + (w/b(%)*-2.413) + (s/a(%)*0.135) + (B(kg)*-11.118) + (CO_2(kg-CO_2)*210.48)

[FA(Flyash)]
variable S = 158.029 + (strength*0.847) + (w/b*0.144) + (s/a*17.588) + (B*-0.529) + (CO_2*0.027)

[GGBS(Ground granulated blast furnace slag)]
variable S = -754.711 + (strength*-5.289) + (w/b*0.84) + (s/a*29.83) + (B*0.256) + (CO_2*0.47)

[GGBS+FA]
variable S = 600.05 + (strength*2.654) + (w/b*-0.772) + (s/a*-11.351) + (B*-0.963) + (CO_2*-0.963)

3.5.4 Equation for chemical admixture content

The amount of chemical admixtures (kg/m^3) was generally applied as 0.5 ~ 1% of the amount of ordinary normal cement.

4. Process of deriving CO_2 reduction concrete mix design

4.1 Input of assessment information

As shown in Fig. 3, assessment information is input first to derive a CO_2 reduction concrete mix design via correlation analyses. Inputs include concrete strength, w/b and s/a ratios, and admixture

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type and rate (%). The assessment information input is directly transferred to the matching regression equation embedded into the system [22].

4.2 Binder deduction (kg/m³)

The assessment information input is transferred to the regression equation for CO_2 emissions, which significantly vary with admixture content or its absence. The amount of CO_2 emissions thus deduced is transferred to the regression equation for deducing binder content, and the admixture type and rate yield the plain cement and admixture contents.

4.3 Water deduction (kg/m³)

From the binder content derived in 4.2 and the w/b ratio input in 4.1, the mixing water content of the concrete mix design is automatically deduced.

4.4 Fine aggregate deduction (kg/m³)

The values deduced from the assessment information input in 4.1, and those deduced from the regression equation relating CO_2 emissions and binder content are transferred to the regression equation for deducing fine aggregate content of the target concrete mix design.

4.5 Coarse aggregate deduction (kg/m³)

Fine aggregate contents deduced from 4.4 and the s/a ratio input in 4.1 serve as the basis for deducing coarse aggregate content of the target concrete mix design.

4.6 Chemical admixture deduction (kg/m³)

Chemical admixture content is deduced using the regression equation that relates binder and mixing water contents in the range of 0.6–1.4%. This is because an adequate range was set via correlation analysis of the concrete mix design determined.

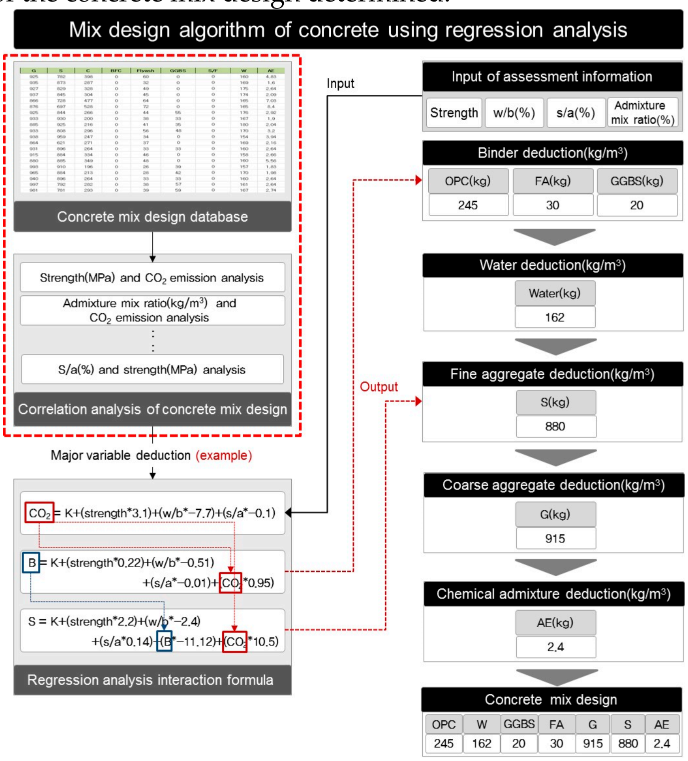

Figure 3. Process flowchart of CO_2 reduction concrete mix design algorithm

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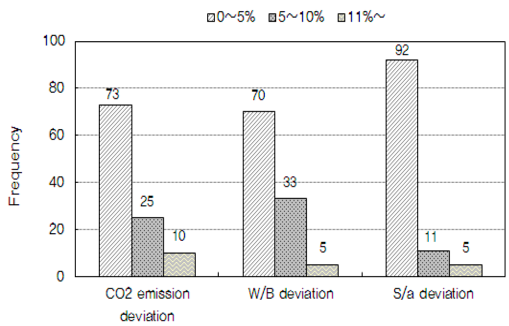
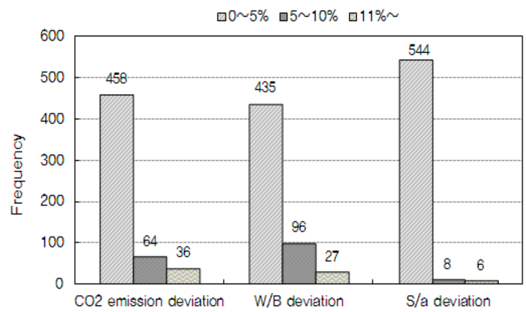
Figure 4 outlines the results of the reliability test of the concrete mix design derived using the CO_2 reduction algorithm. The test was performed by feeding the concrete strength, w/b and s/a ratios, and admixture type and rate of approximately 800 mix designs as inputs to the proposed algorithm, followed by the analysis of the average values of CO_2 emissions, and the w/b and s/a ratios of the plain cement mix design. These average values were then compared with those of the model mix design constructed using the CO_2 reduction mix design system. Analyses were conducted on plain (N = 108), FA (N = 558), GGBS (N = 17), and FA + GGBS (N = 103) algorithm-deduced CO_2 reduction mix designs.

As shown in Fig. 4(a), the reliability test revealed that 98 out of 108 plain cement mix designs had deviations of ≤ 10% from the model mix design in terms of CO_2 emissions. The deviations for the w/b and s/a ratios were ≤ 10% in 103 plain cement mix designs. Of these, 70 mix designs showed deviations of ≤ 5% for the w/b ratio and 92 mix designs showed the same deviation for the s/a ratio. As shown in Fig. 4(b), the reliability test results for FA mix designs revealed that 522 out of 558 mix designs had deviations of ≤ 10% for CO_2 emissions. In particular, deviations of ≤ 5% were observed for the w/b ratio of 435 mix designs and for the s/a ratio of 544 mix designs. This demonstrated high reliability. Fig. 4(c) shows the reliability test results of GGBS mix designs; 15 out of 17 mix designs showed deviations of ≤ 10% for CO_2 emissions, and 15 and 17 mix designs showed deviations of ≤ 10% in the w/b and s/a ratios, respectively. High reliability was demonstrated as all 17 mix designs showed a deviation of ≤ 10% for the s/a ratio. Fig. 4(d) shows the reliability test results of FA+GGBS mix designs; 96 out of 103 mix designs showed deviations of ≤ 10% for CO_2 emissions, and 97 and 103 mix designs showed deviations of ≤ 10% for w/b and s/a ratios, respectively. With all 103 mix designs showing deviations of ≤ 10% for s/a ratios, FA+GGBS mix designs demonstrated very high reliability.

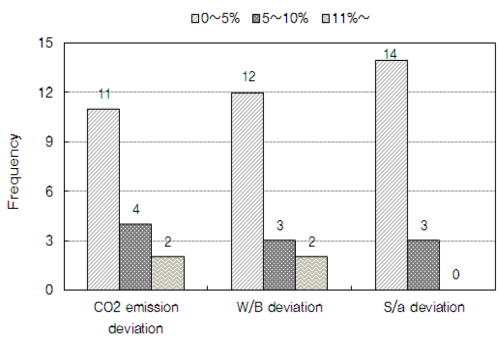
The results of the overall analysis revealed that CO_2 emissions, and the w/b and s/a ratios of the algorithm-deduced v mix designs showed low error rates (%), compared with those of the model mix design. Although there were cases where the average CO_2 emissions, and the w/b and s/a ratios of the CO_2 reduction mix designs showed deviations of ≥ 10%, compared with those of the model mix design, yet the former accounted for ≤ 7% of all cases. The reliability of the concrete mix design deduced by the CO_2 reduction concrete mix design algorithm was thus verified.



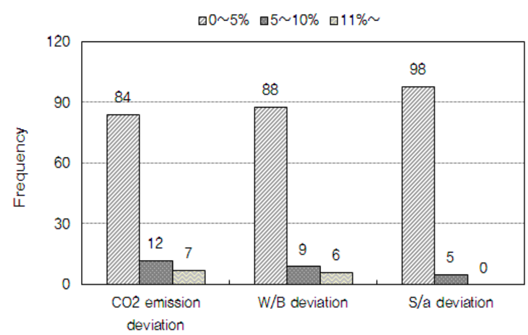
(a) Plain mix design



(b) FA mixing design



(c) GGBS mixing design



(d) FA+GGBS mixing design

Figure 4. Reliability test of CO_2 reduction Concrete mix design

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5. Case study

It is a 12-storey building with five underground floors and has a gross floor area of 462,000 m^2. Information was collected on material amounts for all of the seven standard concrete types, which were used in the construction of the building and were supplied by eight RMC producers in Korea. Based on this information, CO_2 emissions and cost-effectiveness were evaluated. Furthermore, a CO_2 reduction concrete mix design was deduced under the same conditions, and the analysis and comparison of CO_2 emissions and cost-effectiveness of the CO_2 reduction mix design and the actual mix design were performed.

5.1 Method

Table 6 outlines the results of the assessment of CO_2 emissions and cost-effectiveness of the actual mix design for the material amounts of each standard concrete used in the construction of the example building.

Table 6. Assessment method

Category	Actual mix design	This study
Assessment amount	Actual use [m^3]	
Applied CO_2 emission intensity	Korean and European LCI databases	
Unit price per material	Korean product price data	
Assessment items	Assessment and analysis of the overall CO_2 emissions	
	Assessment and analysis of the CO_2 emissions by strength level	

5.2 Result

5.2.1 Analyses of CO_2 emissions and cost-effectiveness

As shown in Table 7, the concrete used for the construction of the example building were analyzed and assessed. The assessment revealed that 35,013,372 and 32,395,708 kg of CO_2 were emitted from the actual mix design and the CO_2 reduction mix design, respectively. CO_2 emitted from the CO_2 reduction mix design was 7.48% less than that emitted from the actual mix design as indicated in Table 8. In particular, the standard types 25-18MPa-150 and 25-24MPa-210 demonstrated reductions of 11% and 8%, respectively, in case of the CO_2 reduction mix design, whereas the standard types 25-45MPa-600 and 25-48MPa-600 showed similar CO_2 emissions in case of both the actual and CO_2 reduction mix designs. Furthermore, the analysis of cost-effectiveness revealed that it was possible to reduce the material costs by approximately 1.5% when the CO_2 reduction mix design was applied against the total material cost of 9,567,240,410 KRW for the actual mix design as indicated in Table 9. For standard types 25-24MPa-210 and 25-30MPa-150, which are in high demand, cost reductions of 50,982,102 and 56,058,408, respectively, were assessed to be possible.

Table 7. Assessment result of CO_2 emission and Cost for concrete mix design

Concrete standard strength(MPa)-slump(mm)	w/b (%)	s/a (%)	Amount [m^3]	Category	Company	Mix design [kg/m^3]							CO_2 emission [kg-CO_2/m^3]	COST [KRW/m^3]
						C	G	S	F/A	GGBS	W	AE		
18-150	59	50	2,088	Actual mix design	A	258	887	916	39	0	177	1.34	245.8	71,629
	61	51	2,088		B	216	885	925	41	35	180	2.04	207.8	68,850
	54	52	2,088		C	271	864	969	37	0	169	2.16	258.2	73,619
	60	51	2,088		D	197	895	932	42	42	171	1.41	190.1	67,471
	60	47	2,088		E	213	965	884	28	42	170	1.98	205.2	69,317
	61	47	2,088		F	246	950	860	43	0	178	1.59	234.7	70,840
	57	51	2,088		G	209	891	958	28	42	160	1.95	201.3	68,843
	59	50	2,088	This study (CO_2 reduction		239	908	938	36	0	164	1.7	227.7	70,800
	61	51	2,088			156	933	975	28	27	130	1.1	150.5	64,674

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	54	52	2,088	mix design)		237	870	976	32	0	148	1.7	225.6	70,392
	60	51	2,088			135	943	982	58	0	118	0.9	130.4	63,118
	60	47	2,088			209	1039	951	35	34	167	1.5	201.5	72,362
	61	47	2,088			244	966	874	43	0	176	1.7	232.5	71,364
	57	51	2,088			210	849	913	35	35	161	1.5	201.6	66,646
24-210	47	48	10,182	Actual mix design	A	268	932	872	34	34	160	3.05	257.1	73,326
	48	47	10,182		B	266	925	835	44	55	176	2.92	256.2	72,796
	48	49	10,182		C	264	931	896	33	33	160	2.64	253.1	73,411
	47	49	10,182		D	284	931	896	17	34	160	2.68	271.8	74,959
	48	48	10,182		E	264	940	896	33	33	160	2.64	253.1	73,636
	47	48	10,182		F	272	957	902	34	34	160	2.72	260.8	75,003
	48	49	10,182		G	264	908	875	33	33	160	2.64	253.1	72,311
	47	48	10,182	This study (CO_2 reduction mix design)		245	941	881	62	0	146	1.7	234.1	71,159
	48	47	10,182			232	1190	1074	86	0	154	1.6	222.8	81,582
	48	49	10,182			243	930	895	61	0	147	1.7	231.8	70,991
	47	49	10,182			277	918	884	50	0	156	1.9	263.9	73,453
	48	48	10,182			244	934	890	61	0	148	1.7	232.9	71,087
	47	48	10,182			246	938	884	61	0	145	1.7	234.7	71,180
	48	49	10,182			242	930	896	61	0	147	1.7	231.6	70,979

Table 8. Analyses of CO_2 emissions and reduction ratio

Concrete standard strength(MPa)-slump(mm)	CO_2 emissions (kg-CO_2)		CO_2 emission reduction rate (%) with respect to the actual mix design
	Actual mix design	This study	
18-80	73,255	68,836	6.03
18-150	3,222,355	2,861,129	11.21
24-210	18,383,462	16,822,918	8.49
30-120	42,146	40,190	4.64
30-150	10,693,385	10,021,201	6.29
45-600	1,093,352	1,080,835	1.14
48-600	1,505,415	1,500,596	0.32
Total	35,013,372	32,395,708	7.48

Table 9. Analyses of cost and reduction ratio

Concrete standard strength(MPa)-slump(mm)	Cost (KRW)		Cost reduction rate (%) with respect to the actual mix design
	Actual mix design	This study	
18-80	23,777,687	23,573,156	0.86
18-150	1,024,308,072	1,000,901,633	2.29
24-210	5,248,230,444	5,197,248,342	0.97
30-120	10,868,235	10,649,910	2.01
30-150	2,691,590,502	2,635,532,094	2.08
45-600	244,109,140	239,097,075	2.05
48-600	324,356,330	318,741,579	1.73
Total	9,567,240,410	9,425,743,790	1.48

5.2.2 Analyses of CO_2 emissions and cost-effectiveness by strength level

CO_2 emissions and the cost-effectiveness of the actual and CO_2 reduction mix designs were analyzed and compared based on strength level. As indicated in Table 10, the average reductions achieved by the mix design to reduction CO_2 were 0.3–11% more than that achieved by the actual mix design.

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Table 10. CO_2 emissions and reduction rates by strength level of concrete mix designs

Concrete standard strength(MPa)-slump(mm)	Division	CO_2 emission [kg-CO_2/m^3]			CO_2 emission reduction rate (%) with respect to the actual mix design
		Max.	Min.	Aver.	
18-80	Actual	249.7	188.1	216.5	6.1
	This study	235.6	174.8	203.4	
18-150	Actual	258.3	190.1	220.5	11.2
	This study	232.5	130.5	195.8	
24-210	Actual	271.9	253.1	257.9	8.5
	This study	263.9	222.9	236.1	
30-120	Actual	351.6	250.5	295.9	4.6
	This study	346.6	213.6	282.2	
30-150	Actual	364.8	258.2	305.1	6.1
	This study	343.4	231.8	286.4	
45-600	Actual	371.1	370.7	370.9	1.2
	This study	368.1	365.1	366.6	
48-600	Actual	391.1	390.7	390.9	0.3
	This study	391.8	386.9	389.7	

As shown in Figs. 5 and 6, the main factors influencing CO_2 emissions of the actual and low-carbon mix designs were identified to be the mix amounts of plain cement, GGBS, FA, and fine aggregate. In the case of the actual mix design, an increase in strength level tended to increase the mix amounts of plain cement and admixture (GGBS and FA) and the decrease in that of the fine aggregate. However, in the case of the concrete mix design to reduction CO_2 emission, an increase in strength level did not affect the mix amounts of plain cement and admixtures, but slightly increased the mix amount of fine aggregate.

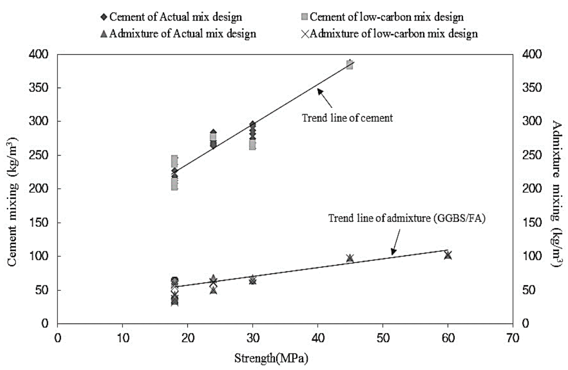

Figure 5. Amount of cement and admixture by actual and CO_2 reduction mix design

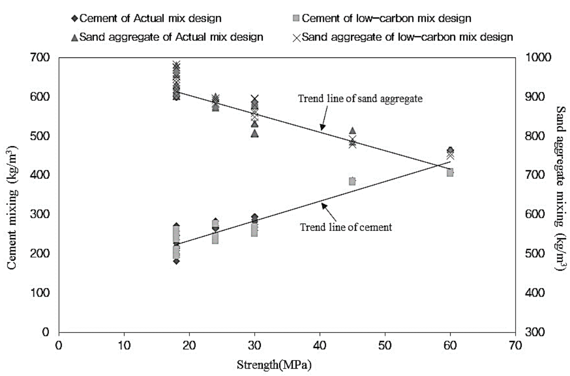

Figure 6. Amount of cement and fine aggregate by actual and CO_2 reduction mix design

In addition, as shown in Table 11, the low-carbon mix design outperformed the actual mix design in terms of cost-effectiveness, by demonstrating reduction rates ranging between 0.9% and 2.1%. In the actual mix design, an increase in the strength level tended to increase the mix amounts of plain cement and admixture, while that of fine aggregate tended to decrease. This resulted in increased costs because of the increased amount of plain cement and admixture. However, the low-carbon mix design did not incur such increase in costs because the mix amounts of materials were maintained at the minimum level at which they satisfied the targeted physical properties.

Table 11. Cost-effectiveness and reduction rates by strength level of concrete mix designs

Concrete standard	Division	Cost [KRW/m^3]	Cost reduction rate (%)

strength(MPa)-slump(mm)		Max.	min.	aver.	with respect to the actual mix design
25-18-80	Actual mix design	72,774	67,254	70,265	0.9
	This study (low-carbon mix design)	72,733	67,377	69,661	
25-18-150	Actual	73,619	67,471	70,081	2.3
	This study	72,362	63,119	68,480	
25-24-210	Actual	75,003	72,311	73,635	0.9
	This study	81,582	70,980	72,919	
25-30-120	Actual	79,581	72,782	76,322	2.0
	This study	79,409	69,620	74,789	
25-30-150	Actual	80,298	73,060	76,789	2.1
	This study	79,203	71,334	75,189	
25-45-600	Actual	83,709	81,901	82,805	2.1
	This study	81,190	81,019	81,105	
25-48-600	Actual	84,796	83,452	84,224	1.7
	This study	82,888	82,605	82,766	

5. Discussion and limitations

The significance and limitations of the findings in this study are presented, and possible future directions are discussed.

The importance of reducing the CO_2 emission of concrete is being recognized. The findings of this study are significant in that can be applied to concrete industry in South Korea. Moreover, method reducing CO_2 emission of concrete can be conducted, and the strategy for reducing the embodied environmental impact can be sought.

Limitations of this study include 1. Consideration of assessment factors for durability (service life), 2. Experimental verification of the alternative concrete mix design to reduction CO_2 emission.

1. Consideration of assessment factors for durability (service life),

In this study, deterioration phenomena was not considered as an assessment factor for durability of concrete in order to develop a CO_2 reduction mix design algorithm. Since durability (service life) of concrete differs according to deterioration phenomenon, differences may arise by admixture (Ground granulated blast slag, GGBS) mixing on the same type of concrete. For example, when durability assessment is done only based on carbonation, durability (service life) of concrete is slightly reduced by mixing of admixtures (GGBS). On the contrary, chloride damage can show increase in durability (service life) of concrete from mixing of admixtures according to previous research.

Therefore, durability (service life) can be changed by admixture ratio (%) of concrete with the same mix design depending on the type of deterioration phenomenon. Through future study, durability (service life) of concrete will be assessed by considering various deterioration phenomena such as carbonation and chloride damage at the same time.

2. Experimental verification of the mix design method to reduction CO_2 emission.

The mix design method to reduction CO_2 emission was proposed in this study. However, it would be necessary to verify, through experiment, physical durability performance (compressive strength, carbonation and chloride etc.) of the mix design. In the future, mix design of concrete derived using the method reducing CO_2 emission will be conducted the compressive strength and carbonation etc. experiments.

6. Conclusion

In this study, a CO_2 reduction concrete mix design algorithm was designed using correlation analyses, and its carbon emission and cost reduction performances were assessed.

Using correlation analyses, the concrete strength, w/b and s/a ratios, and CO_2 emissions were identified as major variables of concrete mix design that influenced other variables. The key variables were then subjected to regression analyses, and the regression equations for CO_2 emissions and binder and fine aggregate amounts were derived.

Using the derived regression equations, we developed the CO_2 reduction concrete mix design algorithm and system. The reliability of the proposed algorithm was verified by demonstrating that the CO_2 reduction mix design exhibited a very low error rate compared with the model mix design constructed previously.

It was discovered that the actual mix design applied to the construction of the example building emitted 35,013,372 kg of CO_2, while CO_2 emitted by the CO_2 reduction mix design was only 32,395,708. Thus, the CO_2 emitted in the case of the CO_2 reduction mix design was approximately 7.48% less than that emitted in case of the actual mix design. It was also discovered that it was possible to reduce material costs by approximately 1.5% when the CO_2 reduction mix design was applied, as opposed to the total material costs of 9,567,240,410 KRW in the case of the actual mix design.

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