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Predicting the CO_2 Emission of Concrete Using Statistical Analysis

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Abstract: Accurate assessment of CO_2 emission from buildings requires gathering CO_2 emission data of various construction materials. Unfortunately, the amount of available data is limited in most countries. This study was conducted to present the CO_2 emission data of concrete, which is the most important construction material in Korea, by conducting a statistical analysis of the concrete mix proportion. Finally, regression models that can be used to estimate the CO_2 emission of concrete in all strengths were developed, and the validity of these models was evaluated using 24 and 35MPa concrete data. The validation test showed that the error ratio of the estimated value did not exceed a maximum of 5.33%. This signifies that the models can be used in acquiring the CO_2 emission data of concrete in all strengths. The proposed equations can be used in assessing the environmental impact of various construction structural designs by presenting the CO_2 emission data of all concrete types.

Keywords: Sustainable construction, CO_2 emission, Life cycle assessment, Statistical analysis

I. INTRODUCTION

Greenhouse gas (GHG) emission has become a global issue alongside global warming. Various efforts have been exerted in the construction industry to reduce GHG emission, including numerous studies on life cycle assessment (LCA), which is aimed at controlling and reducing the amount of GHGs emitted from buildings. LCA is a representative methodology used in assessing the environmental impact of a product during its life cycle [1, 2]. It generally targets products from factories or services, but recently it is also being actively used in assessing the environmental impact of buildings. Based on the LCA results of various construction materials, reduced emission of GHG, particularly CO_2, throughout the lifespan of buildings from construction to their disposal has been the objective of many studies.

In the construction industry, LCA is used as a tool to assess the environmental impact of a building, such as the amount of CO_2 it emits [3, 4]. Among various design alternatives, LCA is used in supporting the process of selecting the most environment-friendly design [5, 6]. Until now, however, it has been impossible to completely assess the environmental impact of buildings that used various types of construction materials. Thus, the assessment of a building's CO_2 emission has been limited to the same defined assessment scope or level. In other words, previous studies have examined the amount of CO_2 emitted by a building based on the assessment results under incomplete but identical conditions.

Therefore, to obtain more accurate and detailed results, it is essential to have a life cycle inventory (LCI) consisting of CO_2 emission data that have been defined and examined in a detailed way. One such method is acquiring CO_2 emission data from each material used in constructing a building.

Concrete, the most essential building construction material, is unfortunately also the one that emits the largest amount of CO_2 during production. In the construction industry, concrete has various strengths, and the structural-design alternatives include concrete with various strengths. This indicates that assessing the CO_2 emission of all structural-design alternatives requires CO_2 emission data on all strengths and types of concrete. To date, however, CO_2 emission data on concrete have been limited. To illustrate, the available LCI data in South Korea include only those of 21 and 24MPA concrete, as presented by the Ministry of Knowledge Economy (MKE). As a preliminary effort to acquire the CO_2 emission data of all construction materials, this study aimed to propose detailed CO_2 emission data for concrete, which also happens to contribute the most to the amount of CO_2 emitted by buildings.

To estimate construction cost and duration, studies have examined various methods ranging from statistical methods such as regression analysis to artificial neural networks or genetic algorithms [7-14].

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Since the regression model can predict or explain the changes in the dependent variables based on those variables' relation with the independent variables [15], it can be used in proposing the CO_2 emission data of concrete according to strength. Further, there has yet to be a study that used statistical analysis based on the collected data to propose CO_2 emission data. This study aimed to use statistical analysis to propose the CO_2 emission data of all strengths and types of concrete to enable the assessment of various structural-design alternatives. Towards this end, this study (1) defined the factors contributing to a change in the concrete strength and to the difference in CO_2 emission by strength; (2) performed statistical analysis using the concrete mix design data collected from various concrete producers; and (3) verified the validity of the model to predict CO_2 emission of concrete using data that were not used in the statistical analysis.

II. FACTORS CONTRIBUTING TO CO_2 EMISSION OF CONCRETE

To acquire CO_2 emission data of concrete according to strength, the elements that affect concrete strength must first be examined. What elements change as the concrete strength changes and how much change in CO_2 emission is caused by the changes in such elements should first be evaluated. In this study, the related literature was reviewed to identify the factors contributing to a change in concrete strength, and among the identified factors, the factors affecting the CO_2 emission of concrete were subsequently determined.

A. Factors affecting change in concrete strength and CO_2 emission

The processes from manufacturing concrete to the construction of a building using concrete can be divided into three stages: production of raw materials for the concrete, mixing of the produced raw materials, and field construction using the mixed concrete. In each of these stages, there are factors that may lead to a change in concrete strength. Such factors present in each stage may also include factors that can change the amount of CO_2 emitted. In this study, it was assumed that the CO_2 emission would change based on the factors that may cause concrete strength to change.

The factors that may cause concrete strength to change at each stage were identified. First, concrete strength differs according to the materials mixed. Concrete strength is affected by the quality of the cement and aggregate, and by the mix of fly ash and ground-granulated blast-furnace slag (GGBS), among others [16]. While the quality of the cement and aggregate affects concrete strength, it is not included in the concrete mix design report presented at the concrete production stage. Consequently, it is impossible to acquire data that include the quality of the cement and aggregate. The quality of the cement and aggregate was disregarded in the analysis of the CO_2 emission by concrete strength in the present study.

Concrete strength is also affected by the mix of cementitious materials including fly ash as well as GGBS [16]. The amount of cement used in identical-strength concrete types may change according to the amount of GGBS and fly ash, which in turn will result in a change in the amount of CO_2 emitted by concrete. As the concrete mix design report identifies the amounts of cement, GGBS, fly ash, and other raw materials in concrete, the differences in such amounts can be verified from the concrete mix table. Consequently, GGBS and fly ash were defined as the analysis targets in this study.

The water-cement and fine-aggregate ratios can affect concrete strength in the concrete-batching process [16]. The difference in these ratios signifies the difference in the amounts of raw materials mixed, which results in a difference in CO_2 emission. Like GGBS and fly ash, the concrete mix design report shows these two ratios, and the differences in such ratios can be determined through the concrete mix table..

Finally, factors affecting concrete strength also exist in the field construction process using concrete. Curing condition and temperature have been known to lead to a change in concrete strength [16], but these factors are out of the scope of estimation or adjustment in the design stage. Thus, it is difficult to consider curing condition and temperature in the design stage so they were excluded from the analysis targets in this study.

B. CO2 emission of each raw material

To acquire the CO_2 emission data of concrete according to strength, it is necessary to acquire the CO_2 emission data of each raw material as well as the mix proportion of the raw materials based on concrete strength. As mentioned in section 2.1, this study assumed that the quality of raw materials is the same in all concrete types, so the representative CO_2 emission factor of each raw material should be presented. This representative factor can be derived from the literature review. Previous studies have proposed the CO_2 emission factors of raw materials comprising concrete [17, 18], which have already been verified and can thus be used in this study. Instead of performing an additional process to acquire the CO_2 emission factor of each raw material, the CO_2 emission factor proposed by previous studies was used. Table 1 shows the CO_2 emission factors of raw materials proposed by previous studies.

TABLE I
CO_2 EMISSION FACTOR OF RAW MATERIALS

	CO_2 Emission Factor	Source
Coarse Aggregates	0.0408	[18]
Fine Aggregates	0.0139	[18]
Cement	0.82	[18]
Fly ash	0.027	[18]
GGBFS	0.143	[18]
Water	0.00011174	[19]
Admixture	0.25	[17]

III. STATISTICAL ANALYSIS OF THE CO_2 EMISSION OF CONCRETE ACCORDING TO STRENGTH

The difference in the amounts of raw materials used in producing concrete affects concrete strength and CO_2 emission. This signifies that the change in concrete strength results from the amount of raw materials used in producing the concrete, which in turn causes concrete CO_2 emission to change. This study hypothesized that based on a certain principle, a change in concrete strength will result in a change in the CO_2 emission. This study aimed to discover such principle via statistical analysis, and subsequently determine the CO_2 emission data of concrete by strength.

A. Data collection and normalization

Determining the CO_2 emission data according to concrete strength requires information on the mix proportion of the raw materials comprising concrete. The concrete mix design report provided by South Korean concrete producers includes information on seven raw materials (coarse aggregates, fine aggregates, cement, fly ash, GGBS, water, and admixture). In this study, the concrete mix design reports on concrete with the strength most widely used in the South Korean construction industry were collected. Since the concrete mix design changes according to the concrete slump value and maximum aggregate size, these two factors were also considered. The collected concrete mix design reports on concrete with the strength most widely used in South Korea showed that the maximum size of the aggregates included in all concrete types is identical: 25 mm. The study analyzed concrete with a 25 mm maximum aggregate size and concrete slump values of 80, 120, or 150 mm. To obtain reasonable results, concrete mix design reports were collected from various concrete producers.

TABLE II
NUMBER OF CONCRETE DATA

Concrete Strength	Concrete Slump Value (mm)		
	80	120	150
18MPa	8	14	17
21MPa	8	13	13
24MPa	8	13	21
27MPa	8	8	14
30MPa	3	3	14

As shown in Table 2, concrete mix design reports where concrete had strengths of 18, 21, 24, 27, and 30 MPa were collected from 11 concrete producers. The amounts of raw materials according to concrete strength were determined. Among the three concrete types, concrete with a slump value of 150 mm was explained in detail in this study. Results of the analysis were obtained and proposed based on the data of three types of concrete used in South Korea.

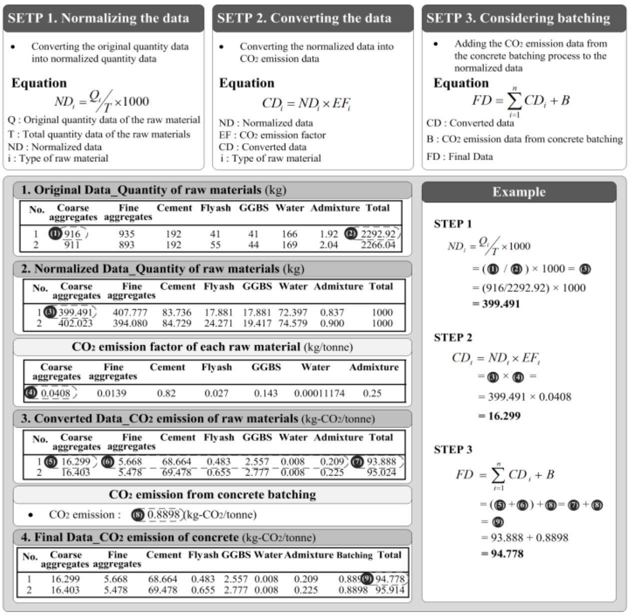

FIGURE I
PROCESS OF COLLECTING DATA FOR ANALYSIS

Data collected were normalized prior to analysis. The concrete mix design reports collected in this study expressed the amounts of raw materials in kg to produce $1m^3$ concrete. Although it is generally known that $1m^3$ concrete weighs 2,300 kg, the weight of $1m^3$ concrete in fact differs based on the collected data. To obtain accurate analysis results, the amounts of raw materials used to produce $1m^3$ concrete were converted into the identical kg unit. Accordingly, the collected data were normalized based on the process shown in Fig. 1.

First, the collected daitted byta showed that the total weight of $1m^3$ concrete differed according to the weights of the raw materials used to produce the concrete. Therefore, the amount of each raw material used in producing 1kg concrete was calculated by dividing the amount of raw material in each data (1) by the total weight of $1m^3$ concrete (2). The result was converted into the value for 1tonne concrete for convenience in the subsequent process. Next, the normalized data (3), the weight data of the raw materials used in producing 1tonne concrete, should be converted into CO_2 emission data to determine the amount of CO_2 emitted by concrete. In other words, by reflecting the CO_2 emission factor by raw material (4) on the normalized amount of each raw material, the data for analyzing the CO_2 emission of concrete (5) can be acquired. The result shown in Table 1 was used as the CO_2 emission factor of the raw materials. The CO_2 emission from the concrete-batching process (8) was additionally reflected to calculate the final amount of CO_2 emitted during the production of concrete (9).

TABLE III
NORMALIZED DATA OF 21MPA CONCRETE (UNIT: *KGCO$_2$/TONNE*)

No.	Coarse aggregates	Fine aggregates	Cement	Fly ash	GGBFS	Water	Admixture	Total
1	16.43	5.46	75.39	0.529	2.804	0.008	0.230	100.85
2	16.44	5.32	74.90	0.715	2.966	0.008	0.243	100.59
3	16.11	5.54	99.05	0.362	0.000	0.008	0.286	121.36
4	16.53	5.37	77.45	0.552	2.925	0.008	0.170	103.00
5	16.01	5.46	100.49	0.446	0.000	0.008	0.330	122.74
6	16.82	5.20	79.48	0.554	2.934	0.008	0.172	105.16
7	16.61	5.37	92.25	0.539	0.000	0.008	0.232	115.01
8	16.62	5.29	104.57	0.303	0.000	0.008	0.243	127.04
9	16.11	5.47	104.37	0.293	0.000	0.008	0.329	126.58
10	15.30	5.78	102.53	0.291	0.000	0.008	0.476	124.38
11	15.79	5.52	103.54	0.374	0.000	0.008	0.491	125.72
12	16.61	5.29	102.53	0.374	0.000	0.008	0.243	125.06
13	16.21	5.37	104.78	0.386	0.000	0.008	0.284	127.04

The amount of CO_2 emitted from the concrete-batching process can be calculated based on the amount of electricity, water, or fuel consumed in operating the machines and facilities in the batch plant. In this study, concrete production and the amounts of electricity, water, and fuel that were used were collected from a representative South Korean concrete producer. Based on such data, the amount of CO_2 emitted in the concrete-batching process was calculated. For the CO_2 emission factor of electricity and fuel, the energy conversion factor and fuel equivalent to the regulated use of energy in South Korea [19] and the carbon emission factor of [20] were referred to in this study. For the CO_2 emission factor of water, the LC data reported by ME was used. The results showed that the batching process produces 0.8898 kgCO_2/tonne. While this figure is negligible compared to the amounts of CO_2 emitted from raw materials, a more accurate CO_2 emission factor of concrete can be proposed by reflecting this result on the analysis. Shown in Table 3 are the normalized data of 21MPa concrete resulting from such process.

B. Statistical analysis of the CO2 emission data of concrete

In this study, the hypothesis that based on a certain principle, change in concrete strength results in a change in the amount of CO_2 emitted by concrete was verified via statistical analysis. For the statistical analysis, SPSS 18.0 was used.

Prior to the statistical analysis, the characteristics of the factors affecting concrete strength were examined based on the changes in concrete strength. First, the changes in the amounts of GGBS and fly ash, which were defined as factors affecting CO_2 emission, were verified. GGBS and fly ash are used as substitute materials for cement in concrete. The amount of cement changes based on the amounts of GGBS and fly ash used in concrete. Therefore, rather than comparing the amount of GGBS and fly ash, more accurate results can be obtained by verifying the ratio of GGBS and fly ash to the amount of cementitious materials. Accordingly, in this study, the amounts of GGBS and fly ash were not the variables examined, but the ratio of cement to the total cementitious materials (C/T ratio). An examination of the C/T ratio of the normalized dataset showed that the set was divisible into two groups, despite the identical concrete strengths. As shown in Fig. 2, the dataset was divided into the C/T ratio data that remained at around 90% (group 1) and at around 70% C/T ratio data (group 2). This signifies that two concrete types are most commonly used in South Korea. Statistical analysis was conducted with the dataset divided into two groups based on the C/T ratio.

Next, the water-cement and fine-aggregate ratios were examined. As shown in Fig. 3(a), the water-cement ratio decreased as concrete strength increased. Unlike GGBS and fly ash, however, the data in the cases with identical concrete strengths were not divided into groups. This indicates that in South Korea, concrete with a certain water-cement ratio is used based on concrete strength. There was no need to conduct a statistical analysis by dividing the dataset based on the water-cement ratio. As shown in Fig. 3(b), the fine-aggregate ratio did not show any characteristic based on the change in concrete strength. There was no steady change based on the change in concrete strength or on the dataset in the cases with identical concrete strengths that were divided into groups.

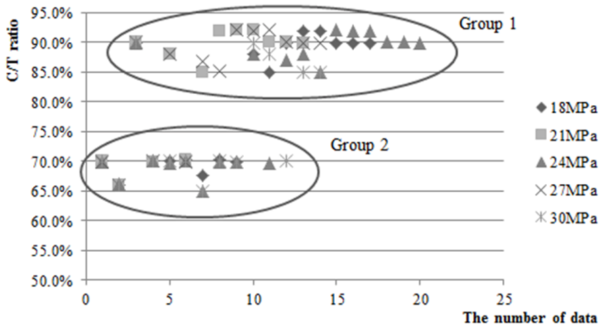

FIGURE II
CATEGORIZATION OF CONCRETE BY C/T RATIO

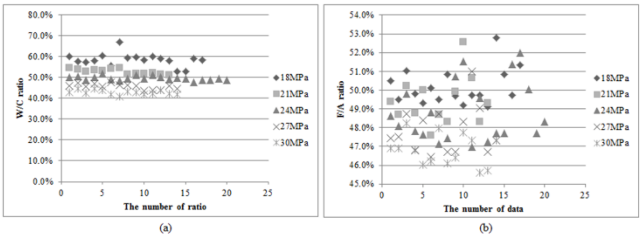

FIGURE III
CATEGORIZATION OF 150-MM-SLUMP CONCRETE BASED ON THE (A) WATER-CEMENT RATIO AND (B) FINE-AGGREGATE RATIO

In this study, the dataset was divided into two concrete groups based on the C/T ratio, and each concrete group was subjected to statistical analysis. Consequently, the dataset was also divided based on the concrete slump values, and a total of six groups were subjected to separate analyses. The process that was carried out after the statistical analysis shall be explained by group 1, with a 150-mm slump, which represents the most widely used concrete strength with the largest data.

1) Mann-Whitney test

This study hypothesized that the amount of CO$_2$ emitted changes steadily based on the change in concrete strength. This hypothesis is based on the fact that concrete data are clearly divided based on concrete strength. Therefore, before analyzing the change in CO$_2$ emission by concrete strength, a homogeneity test of the data divided by concrete strength was performed to determine whether the CO$_2$ emission of concrete can be divided into groups based on concrete strength or not.

In statistics, a homogeneity test of samples generally employs analysis of variance (ANOVA). For a smaller number of variables, however, a non-parametric test is more appropriate [21, 22]. Having collected 20 or less data in terms of concrete strength for statistical analysis, a non-parametric test was carried out instead in this study. It is appropriate to compare each dataset by concrete strength to perform a homogeneity test of the dataset, the Mann-Whitney test, which can be used to verify the amount of overlap between two independent samples [21].

Table 4 shows the results of the homogeneity test. If the p-value is smaller than the 0.05 significance level, the null hypothesis can be rejected [21, 22]. Thus, in all the homogeneity tests, the null hypothesis was rejected. All the concrete data were found to be distinguished by concrete strength.

TABLE IV
Results (P- Value) of Mann-Whitney test

	18MPa	21MPa	24MPa	27MPa	30MPa
18MPa		0.003	0.000	0.000	0.003
21MPa			0.002	0.000	0.003
24MPa				0.000	0.002
27MPa					0.005
30MPa					

2) Descriptive statistics

Table 5 shows the summary statistics of the data variables: the mean value, standard error of the mean (SEM), standard deviation (SD), confidence interval (CI), etc. First, to verify the difference in CO$_2$ emission according to concrete strength, the mean value was examined. As shown in Table 5, the mean CO$_2$ emission tended to increase from 18 to 30 MPa. A considerably small value resulted in all the concrete-strength cases in terms of SD. This indicates that the data can be grouped by concrete strength, which complements the results presented in section 3.2.1. Thus, it is clear that the data regarding the CO$_2$ emission of concrete are divisible by concrete strength. Thus, while this result may not point to accurate data regarding the amount of CO$_2$ representing all the concrete types, the mean CO$_2$ emission according to concrete strength is sufficiently significant.

Furthermore, to verify the uncertainty of the mean CO$_2$ emission of concrete, the CI, which was calculated based on the assumption that samples generally follow a normal distribution, was examined. If the samples are big, they are assumed to still follow a normal distribution although they may be slightly off the norm [22]. If the number of variables is small or if there is no information on the distribution, it should be determined if the samples follow a normal distribution [22]. A normality test was also conducted on the sample variables.

TABLE V
Summary statistics for data variables (Group 1 with slump 150mm) (Unit: *kg-CO$_2$/tonne*)

Title	18MPa	21MPa	24MPa	27MPa	30MPa
Sample Size (n)	9	9	11	10	5
Mean of CO$_2$ emission	115.28	124.77	131.47	140.94	150.24
Standard Deviation	5.811	3.849	3.322	4.076	5.317
Low Level 95% CI	110.82	121.81	129.24	138.02	143.64
Upper Level 95% CI	119.75	127.73	133.71	143.86	156.84
Shapiro-Wilk W test	0.904	0.811	0.918	0.962	0.883
P-value	0.276	0.027	0.306	0.804	0.323
Normal ?	Yes	No	Yes	Yes	Yes

Many researchers argue that the Shapiro-Wilk W test is the most reliable in verifying the normality of small to medium-sized samples [21]. According to the SAS manual, if the number of samples is 50 or less, it is more appropriate to conduct the Shapiro-Wilk W test than the Kolmogrov Smirnov test [23]. In this study, the Shapiro-Wilk W test was conducted, and the results are shown in Table 4. If the p-value is equal to or smaller than the significance level of 0.05, the null hypothesis will be rejected. Thus, in all the concrete strengths except for 21MPa concrete, the null hypothesis was not rejected. It was confirmed that the dataset in all the concrete strengths followed a normal distribution. Even though the 21MPa concrete did not follow a normal distribution, CI verification with a 0.05 significance level showed that the CO$_2$ emission values according to concrete strength rarely overlapped with one another. This means that the CO$_2$ emission factor of concrete is clearly distinguished by concrete strength. It can be determined that the mean value presented by the analysis can be used as the CO$_2$ emission level that represents each concrete strength. A similar result was shown in the descriptive statistics on the data included in group 2. Table 6 shows the results of analysis for group 2.

TABLE VI
Summary statistics for data variables (Group 2 with slump 150mm) (Unit: *kg-CO$_2$/tonne*)

Title	18MPa	21MPa	24MPa	27MPa	30MPa
Sample Size (n)	8	4	9	4	9
Mean of CO$_2$ emission	96.13	103.29	109.14	116.89	124.75
Standard Deviation	1.855	2.136	2.387	2.534	3.171
Low Level 95% CI	94.58	99.89	107.30	112.86	122.32
Upper Level 95% CI	97.69	106.69	110.97	120.92	127.19
Shapiro-Wilk W test	0.971	0.896	0.903	0.8470	0.985
P-value	0.903	0.412	0.267	0.2180	0.986
Normal ?	Yes	Yes	Yes	Yes	Yes

3) Regression analysis

Using descriptive analysis, the mean CO_2 emission was extracted as the CO_2 emission data of concrete with five strengths. A construction project, however, uses concrete with various strengths. Therefore, a more accurate assessment of the CO_2 emission for the entire structural design requires the presentation of the CO_2 emission data based on all strengths and types of concrete.

Regression analysis can deduce the relation between the independent and dependent variables and can be used in predicting or explaining the change in the dependent variables [15]. In this study, simple regression analysis was performed, based on Table 5 and 6, to predict the CO_2 emission of concrete with the strengths that were not included in the collected data. The amount of CO_2 emitted by concrete was set as a dependent variable, and the concrete strength was pegged as an independent variable.

Table 7 and Fig. 4 show the results of the simple regression analysis of the six concrete groups in this study. The explanatory power of the regression model can be verified by R-square (R^2) — i.e., the closer R^2 is to 1, the larger the independent variable's explanatory power of the dependent variable becomes [24, 25]. As the R^2 values of all the groups were over 0.99, the results of the regression analysis were reliable. As shown in Fig. 4, the results were clearly separated according to the concrete group.

TABLE VII
RESULTS OF SIMPLE REGRESSION ANALYSIS

Concrete Slump (mm)	Model (Group)		Unstandardized Coefficients		Standardized Coefficients	R^2
			B	Std. Error	Beta	
150	1	(Constant)	63.672	2.161		0.997
		Strength	2.87	0.089	0.999	
	2	(Constant)	53.369	1.725		0.997
		Strength	2.361	0.071	0.999	
120	1	(Constant)	63.672	2.161		0.997
		Strength	2.87	0.089	0.999	
	2	(Constant)	53.369	1.725		0.997
		Strength	2.361	0.071	0.999	
80	1	(Constant)	63.672	2.161		0.997
		Strength	2.87	0.089	0.999	
	2	(Constant)	53.369	1.725		0.997
		Strength	2.361	0.071	0.999	

These results can be expressed by each of the following equations, where y is the CO_2 emission factor of concrete and x is the concrete strength. Considering the concrete slump value and C/T ratio, the CO_2 emission of concrete can be predicted — i.e., equations (1) to (6) can be used to determine the CO_2 emission values of 80- to 120- and 150-mm-slump concrete when each is included in group 1 or 2, respectively.

$$y = 63.672 + (x \times 2.161) \tag{1}$$

$$y = 53.369 + (x \times 2.361) \tag{2}$$

$$y = 62.41 + (x \times 2.8329) \tag{3}$$

$$y = 52.986 + (x \times 2.2398) \tag{4}$$

$$y = 59.396 + (x \times 2.7703) \tag{5}$$

$$y = 48.031 + (x \times 2.2803) \tag{6}$$

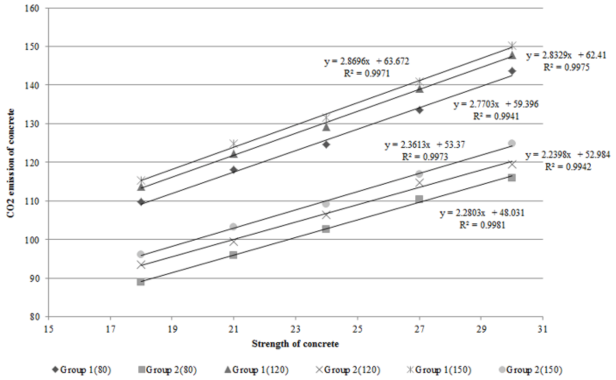

FIGURE IV
RESULTS OF SIMPLE REGRESSION ANALYSIS

IV. VALIDATION OF THE REGRESSION MODEL

Using the equations from the simple regression analysis, the CO_2 emission of concrete according to strength can be calculated. In this study, the validity of the six equations was verified by comparing the CO_2 emission values from the equations and the original CO_2 emission of concrete.

For complete verification, the test should compare the predicted CO_2 emission value to the amount of CO_2 emitted in the actual concrete production process. Since it is impossible to determine the accurate value in reality, the value obtained from calculating the CO_2 emission of the raw materials comprising concrete and of the amount of CO_2 emitted in the batching process was used as the original CO_2 emission value.

The validation process was divided into two parts. First, to verify the accuracy of the equations, the equations were verified based on the data obtained in the five different-strength cases. In other words, the equations were verified using the 24MPa concrete data acquired from a concrete producer, which were not included in the regression analysis. Results of the analysis of the C/T ratios of the collected data showed that data #1 and 7 belonged to group 2, while the rest belonged to group 1. Thus, the data were divided into two groups, where equations (1) and (2) were used. Table 8 shows the validation results of the seven cases in this study. The comparison of the predicted CO_2 emission value and the original CO_2 emission value showed that the maximum error rate was 5.33%, indicating the regression model's excellent performance.

TABLE VIII
CO_2 EMISSION RESULTS AND ERROR RATES FOR THE 150-MM-SLUMP 24MPA CONCRETE

No.	Group	CO_2 Emission (kg CO_2/tonne)	CO_2 Emission by Equation (kg CO_2/tonne)	Error Rate
1	2	109.2921	110.033	0.67
2	1	130.2373	132.552	1.75
3	1	133.6330	132.552	0.82
4	1	131.3463	132.552	0.91
5	1	125.4839	132.552	5.33
6	1	133.5675	132.552	0.77
7	2	106.9934	110.033	2.76

Second, to verify the prediction performance of the regression model, a validation test of concrete that was not included in the five different-strength cases was carried out. The same validation test was carried out using the data for 35MPa concrete. The results showed an error rate of 0.24%, which means that the regression model can be used in determining the CO_2 emission of concrete that exceeds the scope of the collected data.

The prediction performance of the regression model was verified using only one dataset: 35MPa concrete. The regression model was not verified on high-strength concrete, such as 50 or 80MPa concrete. Due to insufficient data collected, a validation test was not carried out on 80- and 120-mm-slump concrete. Additional data are needed and a validation test should be carried out in the future to improve the reliability of the prediction performance of the proposed equations.

V. CONCLUSION

This study aimed to propose the CO_2 emission factor of concrete, which is a fundamental structural material, based on strength using statistical analysis. A statistical analysis of the concrete mix proportion data collected from representative South Korean concrete producers was conducted. Results yielded a regression model that could predict the CO_2 emission of concrete according to strength based on the C/T ratio and slump value. Moreover, validation of the prediction performance of the proposed regression model showed a considerably low error rate.

With the proposed regression model, the CO_2 emission values of concrete types with various strengths used in South Korea can be calculated. The CO_2 emission of concrete generated by the proposed regression model can be used in the environmental-impact assessment of various structural-design alternatives proposed in the design stage, to support the process of selecting the most environment-friendly design.

A limitation of this study is that the proposed regression model was based only on simple linear-regression analysis. While the proposed model showed considerably accurate results in the validation test with regard to certain datasets, its prediction performance was not verified with high-strength concrete like 50 or 80MPa concrete. For future research, more data on high-strength concrete should be collected and used. Rather than using only the simple linear-regression model, the log model (an index model) and the second-order model, among others, should also be used. Furthermore, the proposed model does not represent all the concrete types being used in South Korea because the data collected and used in this study were limited. Specifically, only the representative concrete types that are generally being used in construction projects in South Korea were used in this study. Special concrete types like cold- or hot-weather concrete were not considered. The data collected were also limited to the concrete types being used in the metropolitan area. Despite its high prediction performance, the proposed regression model has limitations in presenting results that consider the seasonal factors or various production conditions in South Korea. For future research, data on the concrete types being used nationwide should be collected and used, and more accurate and inclusive results should be presented.

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REFERENCES

[1] R. Crawford, “Life Cycle Assessment in the Built Environment”, Taylor & Francis, New York, 2011.

[2] R. Horne, K. Verghese, T. Grant, “Life Cycle Assessment : Principles, Practice and Prospects”, CSIRO Publishing, 2009.

[3] H. Yan, Q. Shen, L. C. H. Fan, Y. Wang, L. Zhang, “Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong”, *Building and Environment*, vol. 45, no. 4, pp. 949-955, 2010.

[4] X. Li, Y. Zhu, Z. Zhang, “An LCA-based environmental impact assessment model for construction processes”, *Building and Environment,* vol. 45, no. 3, pp. 766-775, 2010.

[5] R. J. Cole, “Energy and greenhouse gas emissions associated with the construction of alternative structural systems”, *Building and Environment,* vol. 34, no. 3, pp. 335-348, 1999.

[6] W. Kloepffer, “Life cycle Sustainability assessment of products”, *International Journal of Life Cycle Assessment,* vol. 13, no.2, pp. 89-94, Mar 2008.

[7] D. J. Lowe, M. W. Emsley, A. Harding, “Predicting construction cost using multiple regression techniques”, *Journal of Construction Engineering and Management,* vol. 132, no. 7, pp. 750-758, 2006.

[8] T. Hegazy, A. Ayed, “Neural network model for parametric cost estimation of highway projects”, *Journal of Construction Engineering and Management,* vol. 124, no. 3, pp. 210-218, 1998.

[9] G.-H. Kim, K.-I. Kang, “A Study on Predicting Cost Estimation of Apartment Building Using Neural Network's Architecture Optimized by Genetic Algorithms”, *JOURNAL OF THE ARCHITECTURAL INSTITUTE OF KOREA Structure & Construction,* vol. 20, no. 2, pp. 81-88, 2004.

[10] A. A. Abu Hammad, S. M. A. Ali, G. J. Sweis, R. J. Sweis, “Statistical analysis on the cost and duration of public building projects”, *Journal of Management in Engineering,* vol. 26, no. 2, pp. 105-112, 2010.

[11] C. Koo, T. Hong, C. Hyun, “The development of a construction cost prediction model with improved prediction capacity using the advanced CBR approach”, *Expert Systems with Applications,* vol. 38, no. 7, pp. 8597-8606, 2011.

[12] C. Ji, T. Hong, C. Hyun, “CBR revision model for improving cost prediction accuracy in multifamily housing projects”, *Journal of Management in Engineering,* vol. 26, no. 4, pp. 229-236, 2010.

[13] C. Koo, T. Hong, C. Hyun, K. Koo, “A CBR-based hybrid model for predicting a construction duration and cost based on project characteristics in multi-family housing projects”, *Canadian Journal of Civil Engineering,* vol. 37, no. 5, pp. 739-752, 2010.

[14] T. Hong, C. Hyun, H. Moon, “CBR-based cost prediction model-II of the design phase for multi-family housing projects”, *Expert Systems with Applications,* vol. 38, no. 3, pp. 2797-2808, 2011.

[15] R. Freund, “Regression analysis: statistical modeling of a response variable”, Elsevier Academic Press, Burlington, MA, 2006.

[16] S. Mindess, J. F. Young, D. Darwin, “Concrete”, 2^{nd} ed., Upper Saddle River, NJ: Prentice Hall, 2003.

[17] S. Tae, C. Baek, S. Shin, “Life cycle CO_2 evaluation on reinforced concrete structures with high-strength concrete”, *Environmental Impact Assessment Review,* vol. 31, no. 3, pp. 253-260, 2011.

[18] D. J. M. Flower, J. G. Sanjayan, “Greenhouse gas emissions due to concrete manufacture”, *International Journal of Life Cycle Assessment,* vol. 12, no. 5, pp. 282-288, 2007.

[19] Ministry of Environment. Korea LCI Database Information Network, http://www.edp.or.kr/lcidb/english/co2db/co2db01.asp, Accessed 15 April 2011

[20] IPCC, "2006 IPCC Guidelines for National Greenhouse Gas Inventories: In Energy, vol. 2." IPCC, http://www.ipcc-nggip.iges.or.jp, Accessed 6 April 2011

[21] W. J. Conover, "Practical nonparametric statistics", John Wiley & Sons, Inc., New York, 1999.

[22] Walpole, "Probability & statistics for engineers & scientists", Thomson Brooks/Cole, Belmont, California, 2007.

[23] Dmitrienko, "Pharmaceutical Statistics Using SAS", SAS Institute, Cary, NC, 2007.

[24] G. J. Treloar, "Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method", *Economic Systems Research,* vol. 9, no. 4, pp. 375-391, 1997.

[25] Seber, "Linear regression analysis", Wiley, New York, 2003.