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Abstract: Carbon dioxide (CO2) emissions resulting from construction are one of the main factors causing global warming. It is therefore necessary to make efforts to reduce CO2 emissions in the construction industry. Although some researchers have studied CO2 emissions in the industry, there has been a lack of study on the cost of CO2 emissions. Therefore, this study examines and compares the construction costs, including the cost of CO2 emissions, of masonry wall types—including common brick, concrete brick, and fired brick walls. The study found that CO2 emission cost was the highest for brick walls, followed by concrete brick walls. The findings provide information that can be used in engineering methods to determine the cost of CO2 emissions.

11 March, 2015

Title: "**Comparative study on the construction cost including carbon emission cost for masonry walls**

Authors: Sangyong Kim, Seoung-Wook Whang, Gwang-Hee Kim, and Yoonseok Shin

Dear Editor

We sincerely revised the manuscript according to the review comments. Please enclosed find a copy of ***"Comparative study on the construction cost including carbon emission cost for masonry walls"*** by ***"Sangyong Kim, Seoung-Wook Whang, Gwang-Hee Kim, and Yoonseok Shin"*** with 1 figure and 10 tables embedded. We would like to have this manuscript reviewed and accepted by ***Energy and Buildings*****.**

We also completed English Editing Service by Editage.

Should you need to contact me, please use the above address or call me at +82(0)-231-249-9757. You may also contact me by fax at the same number as a telephone or via e-mail at ghkim@kyonggi.ac.kr

Looking forward to receiving the decision of the reviewers as soon as possible. Many thanks.

Yours sincerely,

Sangyong Kim, Seoung-Wook Whang, Gwang-Hee Kim, and Yoonseok Shin

First of all, thanks for the comments from the Editor and particular a very supportive from all reviewers. Please find our responses to the rest of the comments that are useful for improving the quality of the manuscript for technical note. We wish that you are happy with our response letter.

• Reviewer #1

Review comment	Description of review comment
I still miss the time needed for one worker producing 1 m2. Therer are a number of different types of workers, but still, you should explain the time needed for each of them for producing 1 m2.	The reviewer is definitely right. We completely agree with the opinion of the reviewer as well. So, we added the briefly explanation why time needed for each work using one sentence around Table 5.

Comparative study on the construction cost including carbon emission cost for masonry walls

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Abstract

Carbon dioxide (CO_2) emissions resulting from construction are one of the main factors causing global warming. It is therefore necessary to make efforts to reduce CO_2 emissions in the construction industry. Although some researchers have studied CO_2 emissions in the industry, there has been a lack of study on the cost of CO_2 emissions. Therefore, this study examines and compares the construction costs, including the cost of CO_2 emissions, of masonry wall types—including common brick, concrete brick, and fired brick walls. The study found that CO_2 emission cost was the highest for brick walls, followed by concrete brick walls. The findings provide information that can be used in engineering methods to determine the cost of CO_2 emissions.

Author keywords: CO_2 emission; CO_2 emission costs; Energy consumption; Functional unit.

1. Introduction

Main global warming was recognized as a critical issue at the end of the 20th century, and since then, many efforts have been made worldwide to resolve it. The main cause of global warming is the greenhouse gases emitted through the combustion of fossil fuel, which contains the highest amount of CO_2. To reduce greenhouse gases, numerous global efforts have been made, starting with the United Nations Framework Convention on Climate Change at the Rio Summit in 1992. Consistent with the international trend, South Korea, one of the members of the climate change council, introduced the carbon mileage system (CMS) and the greenhouse labeling system.

The construction industry is responsible for more than a quarter of all fossil fuel consumption, and numerous studies have been performed in this industry to actively cope with changes in the internal and external environmental policies[1,2]. Particularly, to estimate the environmental load of building structures, the energy consumption and carbon emissions generated in the entire construction process and the maintenance and dismantling of building structures have been calculated. Further, on this basis, studies have been performed to seek methods to reduce carbon emissions. Kim et al.[1] and Lee and Yang[2] estimated and quantified energy consumption based on the characteristics of construction structures as well as carbon emissions. The energy consumption and carbon emissions were estimated for only a specific amount of construction materials and substances, so it is unreasonable to apply them to a construction project. Building structures involve the use of diverse materials, for which energy consumption and carbon emissions should be calculated separately, because energy consumption and carbon emissions vary for different materials. Moreover, in a construction project, the techniques and materials used are mostly determined by the cost of materials, labor cost, and expenses as per project characteristics and conditions of the construction site. Therefore, the cost of energy consumption and carbon emissionsmust be calculated separately for every construction project, similar to material and labor costs.

In this study, the cost of carbon emissions generated from each individual material of a wall is determined to enable comparison. We recommend that the cost of carbon emissions be added to the construction cost, which includes labor cost, material cost, and other expenses, to formulate an eco-friendly building structure plan that considers carbon emissions besides the conventional construction cost.

2. Research methodology and scope

The construction process involving energy consumption and carbon emissions can be divided into four phases—construction, use and maintenance, dismantling, and disposal of buildings. Of these, in the construction phase, it is most important to encourage an eco-friendly design aimed at reduced environmental load that complies with the climate change council standards, although the use and maintenance and repair phases, which involve maximum energy consumption and CO_2 emissions, are also important. Therefore, the study scope was limited to the carbon emission cost in the construction phase of the school building life cycle.

A building's structure consists of many components, but this study focused on the masonry wall, which is the most commonly used wet wall in Korea for apartment buildings. We considered only three masonry wall types—cement brick, block, and clay brick walls, which are typically used for bearing walls, internal and external partition walls, and decoration. To ensure an objective and accurate comparison, the number and cost of bricks and blocks needed for a $1m^2$ wall were calculated by setting the thickness at 0.5B (half brick), the dimension of the cement and clay bricks at 190×90×57mm, and the dimension of blocks at 100×190×390mm.

We used the following method to calculate and compare carbon emission costs. First, we reviewed studies on energy consumption and carbon emissions and conducted data research to derive the related problems. Second, we reviewed previous studies to examine the method of estimating energy consumption and carbon emissions using the Input-output table (I/O table). Third, the material and labor costs were calculated after determining the quantity of materials and labor needed for each wall. Fourth, based on the material volume used for the estimation, the materials and substances used for each wall type were classified according to the I/O table. This table was applied to the basic unit data of carbon emissions provided in previous studies to determine the cost of estimated carbon emissions based on the costs from InterContinental Exchange (ICE)[3]. Finally, the material cost, labor cost, and carbon emission cost were summed up for each material used in the walls to perform a comparative analysis. Fig. 1 illustrates the methodology of this study.

Insert <Figure 1. Research procedure.> here

3. Literature Review

We reviewed previous studies before conducting ours. In the construction field, most studies involve quantitative analyses of energy consumption and carbon emissions to present basic unit data using life cycle analysis (LCA), as shown in Table 1, and the energy consumption and carbon emission of individual elements by type, work type, and material using these data. Recent studies have presented applicable methods or proposed programs that may be conducive to decision-making in a construction project.

Insert <Table 1. Previous studies of energy consumption and CO_2 emission.> here

Kim et al.[12,13] explained the I/O analysis and an accumulation method for the quantification of energy consumption and pollutant emissions including CO_2 from construction activities. Furthermore, they estimated energy consumption and carbon emissions based on construction activity (rebar concrete construction and masonry construction) using the proposed I/O analysis. Chang et al.[14] developed disaggregated I/O models to calculate the product chain energy of buildings in China. Kimet al.[6] reviewed and re-estimated the basic unit output model for carbon emissions and embodied energy using the I/O table. Moreover, by estimating and presenting the basic unit data based on the calculation of oil and electricity consumed at the construction phase, they established a basic unit database of environmental load appropriate for the domestic market.

In studies on energy consumption and carbon emissions for individual elements, Lee and Chae[15] estimated energy consumption and carbon emissions by construction material/substance and work type using the I/O analysis assuming that construction material and substance input are interrelated with the energy sector at the construction phase. Moreover, at the construction phase of public structures, based on structure type, they estimated the energy consumption and carbon emissions required for the construction material and substance. Kim et al.[12] examined consumption by energy source by extracting samples from office and apartment buildings and presented the basic unit of carbon emissions through their findings. Kim[8] estimated and analyzed energy consumption and carbon emissions by work type, usage phase, and material at the construction phase of apartment buildings, by utilizing the basic unit database of energy consumption and carbon emissions presented in previous studies.

Kim et al.[1] studied program development using the basic unit database of estimated energy consumption and carbon emissions and proposed the properties and composition of the program with which energy consumption and carbon emissions input by phase in the life cycle of building structures. Bourrelleet al.[16] argued an energy payback approach constitute a more adequate way to tackle the environmental challenge net zero energy building. Similarly, while diverse studies have been conducted on energy consumption and carbon emissions, they have analyzed only energy consumption and carbon emissions, and there have been very few studies on determining the cost of carbon emissions especially now when carbon emission credits are being traded.

4. Basic Unit Calculation Method Using the I/O Table

Input-output analysis, a process assessment technique, is a method that explains economic movement based on the input coefficient derived from the I/O table, showing the interdependence of national economies in a tabular form by emphasizing the link structure of production technology between industries. It employs the idea that resources and energy from other industries are used to produce construction materials and substances of a certain kind. To produce product resources, energy and byproducts were specifically analyzed, calculated, and counted in each process to estimate the energy load with a direct or indirect relation to the building structure from about 400 items in the I/O table. Moreover, the aim of the I/O analysis is to analyze the interdependence between industries based on the input coefficient derived from the I/O table, also called ―Leontief analysis” or ―Input-output analysis.”

The following is the process for calculating energy consumption and carbon emissions at the material production phase using the I/O analysis Table[12]. First, the input volume of fuel, the main cause of carbon emissions, and energy consumption was estimated in each part. Second, the rate of combustion was set by fuel type to calculate the input volume contributing to the energy consumption in the form of fuel. Third, the heating value and emission coefficient of CO_2 were multiplied and summed with the input volume obtained earlier, and then the basic unit of direct energy consumption and of direct carbon emissions was calculated by sector. Next, the direct and indirect basic unit was calculated by each sector using the basic unit of the direct sector with Leontief inverse matrix, that is, the production inducement coefficient of $(I\text{-}A)^{-1}$.

5. Cost Calculation of Elements by Wall Type

5.1.Elements by wall type

Table 2 shows the elements of the wallsused to calculate the amount of material used for each wall. Unlike other walls, the element of plaster finish with mortar was included in the cement brick wall.

Insert <Table 2. The composition of the wall types.> here

5.2.Calculation of material cost and labor cost by wall type

The materials and labor needed for a 0.5B wall were calculated by referring to the standard of estimate and itemized unit cost table of 2009.

1) Amount of materials and material cost by wall type

The plaster finish added for the cement brick wall led to an increase in the input volume of cement and sand in it compared with that in block and clay brick walls. The material quantity and cost by wall are shown in Tables 3 and 4.

Insert <Table 3. The material requirement of the wall types (per m^3).> here

Insert <Table 4. The material costs of the wall types (per m^3).> here

Our calculation of material cost by wall type found the cost to be KRW23,514 for clay brick wall, KRW5,071 for cement brick wall, and KRW6,198 for block wall. The material cost of clay brick wall was found to be the highest.

2) Labor and labor cost by wall type

Tables 5 and 6 show calculations of a labor and labor costs by wall type. Labor cost by wall type was calculated as KRW30,399 for clay brick wall, KRW23,650 for cement brick wall, and KRW18,479 for block wall. This study also considered the time needed for each work because the productivity of different types of workers is not equally produced.

Insert <Table 5. The manpower of the wall types (per m^3).> here

Insert <Table 6. The manpower costs of the wall types (per m^3).> here

5.3. Carbon emissions by wall type

1) Selection of basic unit database of carbon emissions

To calculate carbon emissions resulting from the input of materials by wall type, the basic unit data of carbon emissions generated in the production of construction materials was needed. To do this, the basic unit database of environmental load for construction materials established in a previous study was utilized[2,15]. Using the 2000 I/O table and input volume by energy source, the authors estimated a detailed classification of the basic unit data of energy consumption and carbon emissions of construction materials and substances. They required the 2007 I/O table, the most recently published one[2], as the 2005 and 2007 I/O tables do not contain the quantities of –supply cost by division and by item,” which are needed to calculate input volume. Moreover, changes in industrial activities between 1995 and 2000 had no great impact on the basic unit, and a similar tendency is expected in the future[8]. Therefore, this study aims to calculate and compare carbon emission costs by wall type at the construction phase, and data from previous studies was employed to do so, because we considered it reasonable to use the basic unit data obtained using the 2000 I/O table. Table 7 summarizes the basic unit of carbon emissions and energy consumption of the construction materials and substances considered in this study, such as sand, gravel, and bricks.

Insert <Table 7. The energy consumption and CO_2 emission of construction materials.> here

2) Calculation of carbon emissions

Table 8 shows carbon emissions by wall type calculated by applying the basic unit of carbon emissions of the main construction materials and substances presented in Table 7 to the material cost by wall type calculated in Section 5.2.

Insert <Table 8. The CO_2 emission of the wall types (per m^3).> here

Carbon emissions per unit area by wall type were calculated to be 0.05764358t-CO_2 for clay brick wall, 0.01882000t-CO_2 for block wall, and 0.01138697t-CO_2 for cement brick wall, ordered from the highest to the lowest.

5.4. Calculation of carbon emission cost

To determine the cost of the calculated carbon emissions, carbon credits actually traded in the market should be used[17]. Several carbon credit markets regulate the emissions of air pollutants in advanced countries[18]. This study uses the European Union Allowance Unit (EUA) pricing traded under the European Union Emissions Trading System (EU ETS), a global carbon credit trading system, and determines it to be EUR19.73/ton – the average carbon credit between 2005 and 2009 in the Europe Climate Exchange (ECX). Moreover, to convert Euro exchanged in the ECX into Korean Won, this amount was multiplied by KRW1,809.65 – the annual average exchange rate in 2009. Eq. 1 can be used to calculate carbon emission cost.

Carbon emission cost by wall type = Carbon emissions by wall type × Average carbon credit (Ton/EUR) × Average annual exchange rate (EUR/KRW) (1)

Table 9 shows the calculation of carbon emission cost by wall type, applying the annual average exchange rate for Euro and the average carbon credit of ECX. Carbon emission cost by wall type was found to be (from the highest to lowest) KRW2,058 for clay brick wall, KRW672 for block wall, and KRW407 for clay brick wall.

Insert <Table 9. The CO_2 emission costs of the wall types (per m^3).> here

6. Construction cost and carbon emission cost

6.1. Construction unit cost including carbon emission cost

Table 10 compares the sums of carbon emission, material, and labor costs (as calculated in Section 5.2). These sums are found to be KRW55,971 for clay brick wall, KRW29,128 for cement brick wall, and KRW25,349 for block wall.

Insert < Table 10. The comparison of CO_2 emission costs of material and labor cost.> here

6.2. Analysis results

The cost of material, labor, and carbon emission by wall element was calculated and analyzed as below. First, material cost by wall type was calculated to be KRW23,514 for clay brick wall, KRW5,071 for cement brick wall, and KRW6,198 for block wall. Second, in the comparative analysis of labor cost by wall type, this cost was found to be KRW30,399 for clay brick wall, KRW23,650 for cement brick wall, and KRW18,479 for block wall. Although the labor cost for plaster finish was added for the cement brick wall, the unit labor cost was higher for the decorator than for the mason; thus, the overall labor cost appeared to be higher for this wall type. Third, carbon emission cost was the highest for clay brick wall, followed by block wall and cement brick wall. Fourth, the sum of carbon emission, material, and labor costs by wall type was KRW55,971 for clay brick wall, KRW29,128 for cement brick wall, and KRW25,349 for block wall, which followed the same order as that when carbon emission cost was not considered.

Based on the results above, in terms of material cost, the least expensive wall type was cement brick wall, followed by block wall and clay brick wall, while in terms of labor cost, the least expensive wall type was block wall, followed by cement brick wall and clay brick wall. In terms of carbon emission cost, the topic of this study, the least expensive wall type was cement brick wall, followed by block wall and clay brick wall. Specifically, the carbon emission cost of clay brick wall was 5.05 times higher and that of block wall was 1.65 times higher than the emission cost of cement brick wall, indicating a great difference in carbon emission costs by wall type.

7. Conclusion

In this study, a comparative analysis was performed on three wall types: cement brick wall, block wall, and clay brick wall. The carbon emission cost for each wall type was determined, and the material and labor costs were added to this cost to verify if carbon emission must be considered while selecting an engineering technique.

The analysis found that clay brick walls had the highest carbon emission cost, followed by block walls and cement brick walls. The total cost, including carbon emission cost, was the highest for clay brick wall, followed by cement brick wall and block wall, suggesting that carbon emission cost is affected by material cost, but labor cost represents a very large proportion of the overall cost. The carbon emission cost for each wall type was about 1% of the total construction cost, including material and labor costs, and about 6% of the material cost, implying that carbon emission cost accounts for a very large proportion of the entire construction cost. Considering that material cost is typically more than 60% of the entire construction cost, the additional cost of carbon emissions would be quite high. This finding is very importantfrom the environmental perspective,because greenhouse gases can be reduced and global warming resolved by selecting an engineering technique or material that involves less CO_2 emission during construction projects, and from the economic perspective, because the carbon emission cost that might add to the existing construction cost can be saved.

This study provides a fundamental approach to determine the proportion of carbon emission cost in the construction cost, including material and labor costs, when selecting an engineering technique and materials for a construction project, with the aim of promoting eco-friendly design and decreasing the environmental load. Future studies must conduct a comparative study by estimating the carbon emission cost for diverse techniques, using the basic unit data of objective energy consumption and carbon emissions, and considering the impact of these emissions on the environment in the LCC.

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Nomenclature

CMS = Carbon Mileage System

ECX = Europe Climate Exchange

EUA = European Union Allowance

EU ETS = European Union Emission Trading System

ICE = InterContinental Exchange

I/O = Input / Output

LCA = Life Cycle Analysis

TOE = Tone of Oil Equivalent

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Highlight

- Review the needs toward building zero-carbon-emission projects.
- Cost of energy consumption and carbon emissions is calculated separately.
- Cost of carbon emissions generated from each individual material of a wall is determined to enable comparison.
- Cost of carbon emission is to formulated an eco-friendly building structure plan besides the conventional construction cost.

Figure(s)

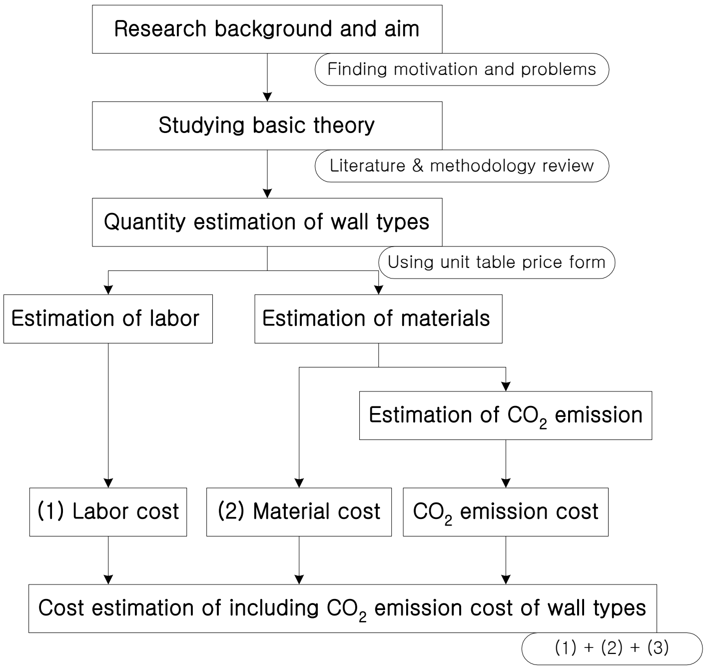


Figure 1. Research Procedure

Table(s) with Caption(s)

Classification	Content
Studies on energy consumption and carbon emission estimations	Presentation of a quantification methodology and estimation of energy consumption and carbon emissions [4]
	Estimation of energy consumption and carbon emissions emitted for each work type, construction type, and transport type [5]
	Review and presentation of basic unit estimation models for energy consumption and carbon emissions at the construction material production phase [6]
Studies on energy consumption and carbon emissions of individual elements	Estimation of energy consumption and carbon emissions by substance and construction material for each work type [2]
	Presentation of carbon emissions as basic unit by examining consumption by energy source of apartment buildings and office buildings [7]
	Characteristics assessment of energy consumption and carbon emissions depending on materials used for each work type at the construction phase of an apartment building [8]
Studies on program development and application	Quantitative comparative analyses of energy consumption and carbon emissions for an internal wall [9]
	Presentation of properties and composition of a program for analyzing energy consumption and carbon emissions [10]
	Quantitative comparative analyses of energy consumption and carbon emissions by floor component using a program [11]

Table 1. Previous studies of energy consumption and CO_2 emission

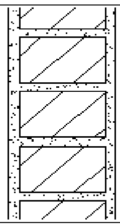
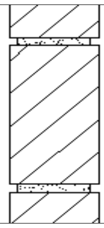
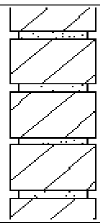
	Type		
Wall types	Cement brick wall	Block wall	Clay brick wall
Composition of section			
Composition of materials	Sand, cement, cement brick	Sand, cement, block	Sand, cement, clay brick
Mortar	Brickwork+plaster	Brickwork+masonry joint	Brickwork+masonry joint
Plasterer work	○	×	×

Table 2. The composition of the wall types

	Materials	Unit	Requirement
Cement brick wall	Sand[1)]	m^3	0.0345
	Cement[1)]	kg	16.0125
	Cement brick	copy	75
Block wall	Sand[2)]	m^3	0.0085
	Cement[2)]	kg	3.0645
	Block	copy	13
Clay brick wall	Sand[2)]	m^3	0.0206
	Cement[2)]	kg	9.5625
	Clay brick	copy	75

1) Mortar(brickwork+plaster) included

2) Mortar(brickwork+masonry joint) included

Table 3. The material requirement of the wall types (per m^2)

	Materials	Quantity	Unit price	Price (KRW)	Total (KRW)
Cement brick wall	Sand	0.0345	12,500	431	5,071
	Cement	16.0125	79	1,265	
	Cement brick	75	45	3,375	
Block wall	Sand	0.0085	12,500	106	6,198
	Cement	3.0645	79	242	
	Block	13	450	5,850	
Clay brick wall	Sand	0.0206	12,500	258	23,514
	Cement	9.5625	79	756	
	Clay brick	75	300	22,500	

Table 4. The material costs of the wall types (per m^2)

	Title	Unit	Requirement
Cement brick wall	Masonry worker	person	0.135
	Plastering worker		0.09
	General worker		0.075
	General worker (mortar mixing)		0.01875
Block wall	Masonry worker		0.15
	General worker		0.076
Clay brick wall	Decorate brick worker		0.2175
	General worker		0.1125
	General worker (mortar mixing)		0.01875
	General worker (mortar polishing)		0.0225

Table 5. The requirement of worker by the wall types (per m^2)

	Title	Quantity	Unit price	Price (KRW)	Total (KRW)
Cement brick wall	Masonry worker	0.135	89,437	12,074	23,650
	Plastering worker	0.08	66,622	5,330	
	General worker	0.075	66,622	4,997	
	General worker (mortar mixing)	0.01875	66,622	1,249	
Block wall	Masonry worker	0.15*	89,437	13,416	18,479
	General worker	0.076*	66,622	5,063	
Clay brick wall	Decorate brick worker	0.2175	92,669	201,56	30,399
	General worker	0.1125	66,622	7,495	
	General worker (mortar mixing)	0.01875	66,622	1,249	
	General worker (mortar polishing)	0.0225	66,622	1,499	

Table 6. The manpower costs of the wall types (per m^2)

Construction materials	Energy consumption (TOE[1)]/million KRW)	CO_2 emission ($t\text{-}CO_2$/million KRW)
Sand	0.110	0.354
Gravel	0.110	0.354
Crushed aggregate	0.360	1.154
Clay brick	0.786	2.546
Cement	1.784	6.616
Ready-mix concrete	0.858	3.152
Block	0.867	3.196
Brick	0.867	3.196

1) TOE = Tone of Oil Equivalent

Table 7. The energy consumption and CO_2 emission of construction materials

	CO_2 emission (t-CO_2)		
	CO_2 Emission of materials		Total
Cement brick wall	Sand	0.00015266	0.01138697
	Cement	0.00044781	
	Cement brick	0.01078650	
Block wall	Sand	0.00003770	0.01882000
	Cement	0.00008570	
	Block brick	0.01869660	
Clay brick wall	Sand	0.00009116	0.05764358
	Cement	0.00026743	
	Clay brick	0.05728500	

Table 8. The CO_2 emission of the wall types (per m^2)

	CO_2 emission ($t\text{-}CO_2$)	Average market price of CO_2 emission	Annual average of exchange rate (KRW)	CO_2 emission cost (KRW)
Cement brick wall	0.01138697	19.73(EUR/ton)	1,809.65	407
Block wall	0.01882000			672
Clay brick wall	0.05764358			2,058

Table 9. The CO_2 emission costs of the wall types (per m^2)

	Existing construction costs				CO_2 emission costs		Total (KRW)	Rate (%)
	Material cost (KRW)	Labor cost (KRW)	Total (KRW)	Rate (%)	(KRW)	Rate (%)		
Cement brick wall	5,071	23,650	28,721	100.00	407	100.00	29,128	100.00
Block wall	6,198	18,479	24,677	85.92	672	165.11	25,349	87.02
Clay brick wall	23,514	30,399	53,913	187.71	2,058	505.65	55,971	192.16

Table 10. The comparison of CO_2 emission costs of material and labor cost