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GHG emission quantification for pavement construction projects using a process-based approach

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Abstract

Climate change and greenhouse gas (GHG) emissions have attracted much attention for their impacts upon the global environment. Initiating of new legislation and regulations for control of GHG emissions from the industrial sectors has been applied to address this problem. The transportation industries, which include operation of road pavement and pavement construction equipment, are the highest GHG-emitting sectors. This study presents a novel quantification model of GHG emissions of pavement construction using process-based analysis. The model is composed of five modules that evaluate GHG emissions. These are: material production and acquisition, (2) material transport to a project site, (3) heavy equipment use, (4) on-site machinery use, and, (5) on-site electricity use. The model was applied to a hypothetical pavement project to compare the environmental impacts of flexible and rigid pavement types during construction. The resulting model can be used for evaluation of environmental impacts, as well as for designing and planning highway pavement construction.

Keywords: Environmental sustainability, Carbon emissions, Pavement construction, Process-based analysis, Highway projects

1. Introduction

The issue of GHG emissions has become the main discussion point when considering the environmental impact and global climate change. Several contributing organizations have been obligated to lower GHG emissions released to the atmosphere over the past decade. Since the Kyoto Protocol was initiated in 1997, the effort in reducing GHG emissions has been significantly stimulated among nations. In the transportation industry, there have been several attempts related to this environmental concern, including the Moving Ahead for Progress in the 21st Century Act (MAP-21). This new law was passed by the United States government and requires U.S. transportation agencies to integrate national performance-based goals, including the environmental sustainability in highway planning efforts [1].

Although the road operation phase has a higher environmental impact than the construction phase, an accumulation of GHG emissions through the construction process shows a very significant level of impact and a need for mitigation. The literature shows approximately 20% of overall global warming potential from construction operations [2] in pavement projects. Therefore, considering the environmental impact of a road construction project can provide transportation planners with holistic perspectives of how the construction will affect the environment and society.

To evaluate the environmental impact, several software programs have been developed and many studies have been conducted to facilitate planners in making decisions at the early project phase; see [3] and [4]. However, most of the software tools have been developed based on the availability of very high-detailed input data [5]. This burden prevents planners from an accurate assessment of the environmental impact, as some of the required input is not available in the transportation database system [6]. Even though there were some efforts in developing the assessment framework based on the availability of input data, (see [5] and [7]), some activities, such as on-site electricity usage for a site office, were neglected. In fact, these activities can be included to construct a more comprehensive calculation of GHG emissions. Also, a general scheme that can facilitate the environmental impact assessment for both flexible and rigid pavement structures is needed to support transportation planners in performing more effective decisions in an early planning phase.

To address the aforementioned research gaps, this study demonstrates the development of the GHG emission quantification model that is capable of evaluating GHG emissions from different construction processes of a road pavement project. The model consists of five modules: (1) material production and acquisition; (2) material transportation to project site; (3) heavy equipment usage; (4) on-site machine usage; and (5) on-site electricity usage. In this paper, the process-based approach was applied to construct the model as this method is suitable for analyzing direct impacts of known conditions [8] and provides a highly

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accurate result [9]. Figure 1 represents the schematic framework of the GHG emission quantification model.

2. Process-based analysis

This approach is generally utilized for known conditions in which the data, such as internal company records and public data sources, is available [8]. It is a potential approach that can be used for considering the specific process in detail, for example, the construction transportation process with the data of all material loads delivered and the transportation distance. The process flow diagram is created to help identify the process, as well as the input and output required for data collection [8]. In this method, all known and related sub-processes need to be included in the diagram. Also, the data can be collected from the actual or generic data depending on the data availability. Due to the specificity of this method, it is suitable for examining the direct impacts or downstream processes, such as the on-site construction, and material transportation to the construction site, to which the analyst intentionally pays attention.

The result from the process analysis tends to have high level of accuracy. Nevertheless, it is time and cost consuming, as the process data need to be comprehensively collected [9]. This difficulty in obtaining the data is mentioned as one of the main obstacles. Therefore, the generic data is sometimes used for analysis, as it consumes less time than the data directly collected from the process. The reliability, however, is taken into account as the main and unavoidable issue when using the generic data [9]. As such, a recommendation needs to be carefully stated, particularly regarding the effect of data selection on an analysis result.

Based on the literature review, the process analysis has been found in many pavement-related studies. It is used for calculating the fuel consumption of the construction equipment in [7], because of an appropriateness in analyzing specific processes of constriction activities. The further study is addressed by proposing the framework for GHG emissions quantification from both material and equipment aspects due to asphalt pavement construction [5]. Similarly, the process-based approach is implemented for studying energy consumption in asphalt and reinforced concrete pavement construction. The system boundary is identified from material acquisition to the placement in the construction site [10].

In addition to the aforementioned implications, this approach is applied in the building construction project. The amount of carbon emission is assessed related to the equipment used in constructing the post-tensioned slab foundation [11] based on the field data. Moreover, [12] employed the life-cycle process approach for evaluation the carbon dioxide emission due to the office building façade, in which the different types of façade are compared to reach the environmental objective.

3. Existing models and frameworks for GHG emission quantification

As aforementioned, several models and frameworks have been proposed to facilitate the environmental impact estimate for highway transportation projects. Table 1 summarizes the list of the existing models and frameworks with the comparisons of their processes that were considered during the analyses. Although this paper aims to take into account only during the construction phase, the details through the life cycle are compared to demonstrate the differences among the existing works.

As shown in Table 1, considering the project construction phase, most of the models or frameworks focus on the material manufacturing and transportation. Those existing works leave a room to include some significant construction activities into the environmental impact estimation. For example, the on-site machine usage and electricity usage for indirect and miscellaneous activities (e.g. electricity power used in the site office) should be

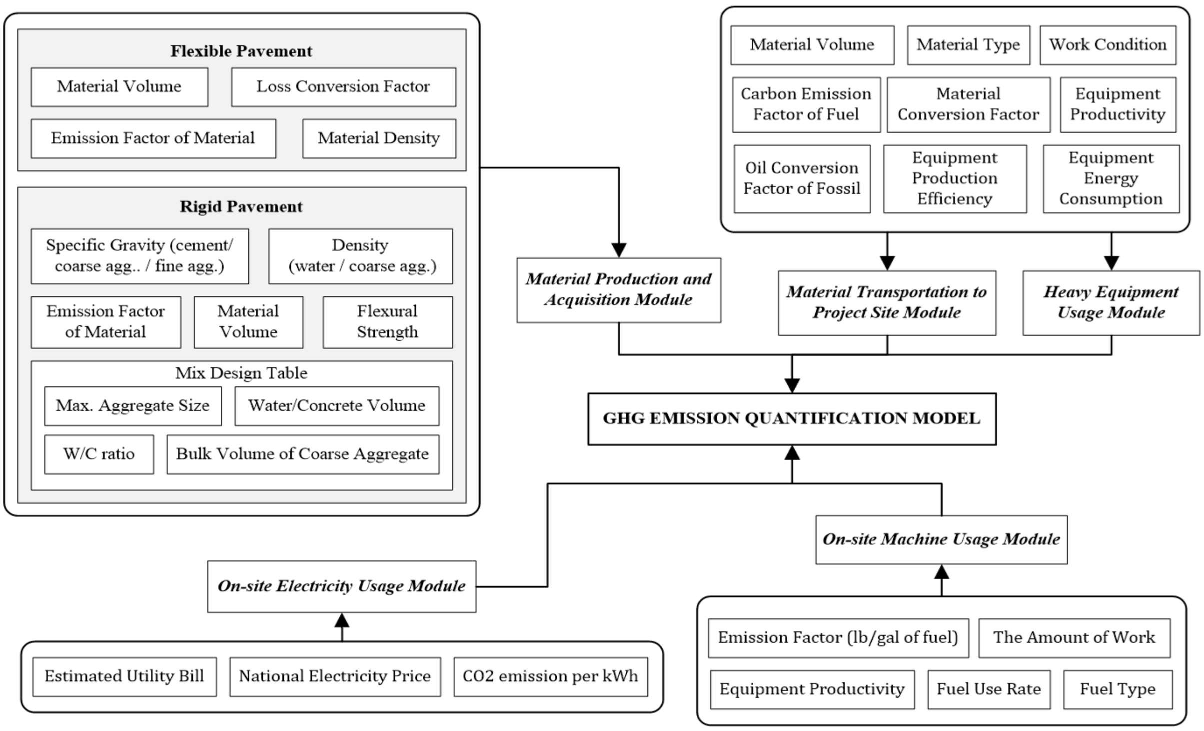

Figure 1 Schematic framework of the GHG emission quantification model

Table 1 Summary of the existing models or frameworks

Models / Frameworks	Process / Stage								Reference
	Materials Manufacturing	**Material Transportation**	**Support Sectors**	**On-site Equipment**	**Production & Maintenance of Equipment**	**On-site Electricity Usage**	**Operation & Maintenance**	**Demolition / End-of-Life**	
Kim et al. (2012a)	√	√		√					[5]
Kim et al. (2012b)		√		√					[7]
Zapata and Gambatese (2005)	√	√		√			√	√	[10]
Athena Pavement LCA (2013)	√	√		√			√		[13]
Athena Institute (2006)	√	√							[14]
Matthews et al. (2001)	√	√			√		√		[15]
Park et al. (2003)	√			√			√	√	[16]
Treloar et al. (2004)	√		√	√		√	√	√	[17]
White et al. (2010)	√	√							[18]

included to provide a more comprehensive perspective to transportation planners.

However, it is worth mentioning that some processes in Table 1 may be difficult to identify with the direct and specific conditions, such as support activities and equipment production and maintenance. This group of processes is suitable for the calculation at a highly-aggregated level by using the other approaches, such as the input-output analysis. Consequently, indirect processes will be omitted from this study and a proposed framework will be inclusively covered all important direct activities in the highway project construction. To this end, the purpose of this paper is to seek for a comprehensive framework that assists in identifying all direct impacts from the highway construction on the environment by including the impacts from materials manufacturing, material transportation, on-site equipment usage, on-site electricity usage, and on-site machine usage.

4. GHG emission quantification model

As aforementioned, the GHG emission quantification model is proposed in order to facilitate an estimation of environmental impact in terms of GHG emissions that results from a construction of a transportation project. The model is composed of five calculation modules, in which the detail of each module is presented in the following subsections.

4.1 Material production and acquisition

This module was developed for evaluating the environmental impact of the material production and acquisition process in pavement construction. In this section, the calculation algorithm is generalized for both flexible and rigid pavement structures, as shown in Equation (1):

$$\mathrm{GHG_{Production}} = \sum_{i=1}^{I} Q_i * (1 + LCF_i) * EF_i \qquad (1)$$

where Q_i = quantity of material (i); LCF_i = loss conversion factor of material (i) that covers the material loss from the construction activity if applicable; and EF_i = emission factor of material (i).

It is noteworthy that several input variables are needed for calculating required material quantities from the concrete mix design in rigid pavement, such as the required concrete strength and percentage of cementitious material replacement. Some necessary input variables can be directly obtained from the project design document, such as material volume and material type.

4.2 Material transportation to the project site

This module aims to evaluate the environmental impact as a result of construction material transported from manufacturing plants or borrow pits to the construction site. GHG emissions here are generated based on the engine combustion of the hauling equipment during the material delivery. Equation (2) represents the algorithm and input variables necessary for the calculation:

$$\mathrm{GHG_{Transportation}} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} \frac{Q_i}{P_{ij}} * FCR_{jk} * EF_k \qquad (2)$$

where Q_i = quantity of material (i) that is reflected by the material type and its conversion factor in estimating the loose volume of material; P_{ij} = productivity of equipment (j) in delivering material (i) that can be calculated based on Equation (3); FCR_{jk} = fuel consumption rate of equipment (j) by using the fuel type (k); and EF_k = emission factor of fuel type (k).

$$P_{ij} = \frac{EC_j \ x \ WE_{ij}}{CT_{ij}} \qquad (3)$$

where EC_j = capacity of equipment (j); WE_{ij} = work efficiency in delivering material (i) with equipment (j); and CT_{ij} = cycle time of equipment (j) in delivering material (i).

4.3 Heavy equipment usage

In this section, a similar approach used in the previous module was adopted by focusing on the heavy equipment used within the area of the construction site. The calculation here emphasized heavy equipment, which uses the fossil fuel as an energy source. The examples of equipment are excavator, compactor, paver, grader, bulldozer, and scraper for any construction activities, such as site clearing, material replacement, paving, excavation, and compaction.

Equation (2) can be adopted to calculate GHG emissions from all equipment operating on the jobsite. However, the equipment productivity can be differently calculated from the previous module, since several types of equipment involved in this section have their own characteristics that make their productivity calculations different. For example, the grader's productivity is estimated based on a grading width, lift thickness, and grader speed, while the calculation of the compactor's productivity requires a roller width, number of passes, and compactor speed as input parameters.

4.4 On-site machine usage

This module facilitates the GHG emission calculation of fuel-consumed machines used on-site, such as a concrete drilling machine and saw-cutting machine. These machines are separately categorized from heavy equipment in the previous module, since they have a different method in estimating the productivity. The estimation can be initiated by considering the usage time of a machine that can be obtained from total quantity of work and the machine productivity. Finally, GHG emissions can be calculated from the machine usage time, fuel consumption rate based on the specific type of fuel used in the machine, and the emission factor associated to the fuel type, as shown in Equation (4):

$$\text{GHG}_{\text{Machine}} = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\frac{QW_{jl}}{P_{jl}}\, x\, FCR_{jk}\, x\, EF_k \qquad (4)$$

where QW_{jl} = quantity of work (l) that is performed by using machine (j); P_{jl}= productivity of machine (j) in performing work (l) that can be obtained from on-site records or field observation data; FCR_{jk} = fuel consumption rate of equipment (j) by using the fuel type (k); and EF_k = emission factor of fuel type (k).

4.5 On-site electricity usage

The objective of this module is to estimate GHG emissions generated from the electricity usage on the construction jobsite, such as the temporary lightning, the jobsite office electricity, and other electricity-consuming machines. Equation (5) represents an estimation of GHG emissions as a result of the on-site electricity usage:

$$\text{GHG}_{\text{Electricity}} = \frac{EB}{NEP}\, x\, ER \qquad (5)$$

where EB = estimated electricity bill; NEP = national average electricity price; and ER = emission factor ratio (e.g. kg. of CO_2 equivalent/kWh).

As the environmental impact will be estimated at the early planning phase, it is impossible to know an actual amount of electricity usage at that time. The estimation, therefore, is performed by relying on the project manager's experience or the historical data from the past projects. The national average electricity price can be retrieved from the statistical data, such as the national energy statistics or the International Energy Agency [19]. Likewise, the emission factor per kWh of electricity can be obtained from the historical statistics (see [20]).

Considering all input required in this model, some suggestions could be executed to reduce a number of input parameters and increase the simplicity of the model. For instance, there are several variables required for the GHG calculation of the rigid pavement structure during the material production and acquisition stage in the module 1. In order to simplify the calculation, the amount of concrete or reinforced concrete may be accessed from bill of quantities (BOQ) without using an estimation of raw material, such as cement, fine aggregate, and course aggregate, which can decrease the number of required variables by 5 to 7 variables. Furthermore, an estimation of equipment productivity can be implemented with the high-aggregated input variables. Instead of analyzing the inputs of all equipment models, the statistical approach may be applied in this case based on the manufacturer's data to facilitate an estimation by using only data of major equipment characteristics, such as equipment size and working conditions. As a result, based on these two simplifications, the proposed model can lead to a significant reduction in input variables as it requires few variables for calculation, which are material type, material quantity, transportation distance, working conditions, equipment size, and estimated electricity bill.

5. Case study

This section presents an application example of a hypothetical pavement construction project. Two different design structures of the flexible and rigid pavements were analyzed to investigate the impacts of their different construction processes on GHG emissions in transportation projects. The analysis was performed based on the same functional unit of pavement structures (1 square kilometer). The structures of both pavement types are designed to provide the same strength to support an identical traffic load. The material was assumed to deliver between a plant and construction jobsite with a 10-kilometer distance. The working conditions on the jobsite were assumed to be favorable. Also, it is given that the contractor is likely to use large and heavy equipment to increase the productivity and speed up the project's completion. Figure 2 presents the design structures of flexible and rigid pavements in this paper.

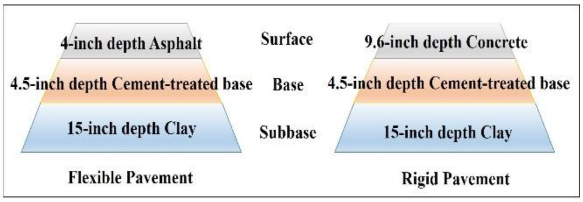

Figure 2 Design structures used in the hypothetical case study

In this paper, the total on-site electricity bill was subjectively assumed and inputted in the on-site electricity usage category to test the performance and capability of the calculation algorithm in estimating the associated GHG emissions as a result of electricity consumption on the jobsite. The result from this category is not subject for comparison with the other categories. A measurement unit of GHG emissions is demonstrated in a ton of carbon dioxide (CO_2) equivalent. Also, CO_2 contributes the highest of all GHG emissions (about 82%) in the atmosphere, according to the U.S. Energy Information Administration [21]. As such, this study mainly focuses on the amount of CO_2 generated to the atmosphere from construction processes in transportation projects.

To illustrate the usage and application of the model, the detail calculation is exemplified in relevant to each module. First, two examples of the flexible and rigid pavements are given to demonstrate the amount of GHG emissions due to the material production and acquisition (Module 1). Table 2 presents the emission factor and material quantity of each material used in the case study.

Flexible Pavement

The amount of GHG emissions on the surface layer that is constructed with the asphalt concrete material can be calculated as below. The material density and loss conversion factor of asphalt concrete are 2% and 2.35 ton/m^3, respectively, according to [5] and [22].

(1000 m x 1000 m x 0.1 m) x (1+ 2%) x 2.35 ton/m3 x 0.0319 kg of CO_2/kg
= 23.97 x 10^7 x 0.0319 = 7,646.43 ton CO_2

Table 2 Material quantities and emission factors used in the case study

Raw Material	Material Quantity (kg)	Emission Factor	References
Asphalt Concrete	23.97 x 10^7	0.0319	[5]
Cement	10.752 x 10^7	0.944	[22]
Fly Ash	13.44 x 10^6	0.0196	[23]
Blast Furnace Slag	13.44 x 10^6	0.0265	[23]
Water	44.88 x 10^6	0.000102	[22]
Fine Aggregate	14.016 x 10^7	0.0013	[23]
Coarse Aggregate	27.696 x 10^7	0.004	[23]
Admixture	-	Negligible	[24]
Concrete Mixing	-	Negligible	[25]
Steel	10,000	2.34	[22]

Remark: Emission factor is in unit of kilogram of CO_2 equivalent per one kilogram of material.

Table 3 GHG emissions from construction activities on the flexible and rigid pavements

Category	GHG Emissions (ton CO_2 equivalent)	
	Flexible Pavement	Rigid Pavement
Material Production and Acquisition	15,121	113,860
Material Transportation to Site	3,460	4,391
Heavy Equipment Usage	2,133	2,384
On-site Machine Usage	427	477
On-site Electricity Usage	673	673

Rigid Pavement

Similarly, the amount of GHG emissions for the surface layer of the rigid pavement structure can be estimated as follows.

[(10.752 x 10^7 x 0.944) + (13.44 x 10^6 x 0.0196) + (13.44 x 10^6 x 0.0265) + (44.88 x 10^6 x 0.000102) + (27.696 x 10^7 x 0.004) + (14.016 x 10^7 x 0.0013) + (10,000 x 2.34)]
= 103,647,090 kg of CO_2
= 103,647 ton CO_2

For Module 2, the amount of GHG emissions from the material transportation process is calculated by mainly focusing on emissions as a result of fuel combustion from hauling equipment or dump trucks. The steps start from calculating the equipment productivity rate based on the manufacturer data, and then the number of hours required to complete the work. After that, the GHG emissions will be estimated based on the fuel consumption rate of equipment and fuel emission factor. For example, the project is assumed to use hauling equipment to deliver clay (bank density = 1,245 kg/m^3 [26]) for constructing the subbase layer. Suppose that the project employs dump trucks with a productivity of 30-ton/hr under favorable working conditions along a 10-km delivering distance. Given the loss conversion factor of clay is 6% [26], total amount of clay can be calculated as follows.

(1000 m x 1000 m x 0.38 m) x 1,245 kg/m^3 x (1+6%) = 501,486 ton

Suppose that the dump truck consumes 35.95 liter of diesel per one working hour. The emission factors of diesel and gasoline are 2.668 and 2.345 kg/liter, respectively [27]. Therefore, total amount of CO_2 emissions in this situation is (501,486 ton/30 ton per hr) x (35.95 liter per hr) x (2.668 kg of CO_2 per liter) = 1,603 ton of CO_2

The similar approach will be applied in Module 3 and 4 to estimate GHG emissions resulting from the usage of equipment and machine in the construction jobsite. The GHG emissions can be evaluated based on the work quantity, productivity of equipment or machine, fuel consumption rate, and the emission factor, which depends on the fuel type. However, the detail calculation will be exempted here as the similar example was already given in the previous module.

In Module 5, GHG is presumed to be emitted as a result of electricity use for an activity in the construction jobsite, such as lighting around the jobsite, and the power used in the site office. As electricity production consumes very huge amount of fossil fuels, electricity use contributes to large share of GHG emissions. In this study, the number on electricity bill will be converted by the electricity unit price to a number of unit usage. The amount of GHG emissions will then be calculated by referring to the ratio of national average GHG emissions per one unit of electricity, as shown in the following example.

Assume that the project was constructed in 2014 and had total electricity bill as $100,000 through the construction period. With the average electricity price as 10.44 cents/kWh in 2014 [28] and emission factor of 7.03 x 10^{-4} ton CO_2/kWh [29], the amount of CO_2 emissions from the electricity usage can be calculated as follows.

($100,000 /$10.44x10^{-2} per kWh) x (0.703 kg CO_2/kWh) = 673 ton of CO_2

The result of the case study shows that the rigid pavement project tends to emit higher GHG emissions during the construction when compared to the flexible pavement. This finding is consistent with the amount of global warming potential analyzed in [14]. Figure 3 illustrates the amount of GHG emissions from the different construction processes in flexible and rigid pavements. The emissions were here calculated based on a 1-square kilometer functional unit. In fact, the impact can significantly increase for a construction project that has a larger pavement area.

Table 3 presents the GHG emissions of two types of pavement structures in the case study that are estimated based on the proposed model. The result expresses a similar trend as in [18] especially in the material production and material transportation categories. The GHG emissions in the rigid pavement structure show approximately five times higher than the emissions from flexible pavement construction. This major difference is from the material production and acquisition process, as a manufacturing process to produce concrete is likely to consume more energy and generate a more negative environmental impact than asphalt production [18]. However, the ratio is slightly different from the other framework's (see [18]) that indicates approximately 7.5 times higher in the material production and transportation of the rigid structure. For the other construction processes, the difference in GHG emissions among two types of structure is small. However, variations between two structures in each process can be different from Table 3 if some factors are changed. For instance, the difference may be larger if the flexible pavement project tends to adopt the eco-efficient and environmental-friendly equipment fleet.

It is noteworthy that the difference in GHG emissions between two pavement structures for Module 1 results from large variations in material emission factors. The case study shows an insignificant difference in the material quantities between two structures. Given that both cases employ similar types of equipment for construction, the total numbers of working hours to complete a job are similar. As a result, there is no significant difference between the flexible and rigid pavements in GHG emissions due to fuel consumption of equipment usage.

Additionally, the analysis results show that, among all construction activities, the material production and acquisition process significantly contributes to GHG emissions, with the largest portion more than 70% in the flexible pavement and 90% in the rigid pavement (see Figure 3). This confirms the significance of material selection to global climate change in construction projects. An estimation of total GHG emissions for a highway construction can be approximated by adopting these two proportions if the emission from the material production is known. With this finding, it highlights an importance of using recycled material in construction to help lowering a production of pavement material and therefore reducing a large amount of GHG emissions during the material production process. For example, recycling an aged concrete pavement for a subbase or base structure of a new road section can help lowering needs of producing ready-mixed concrete and cement in the plants, which requires huge amounts of fuel and heat.

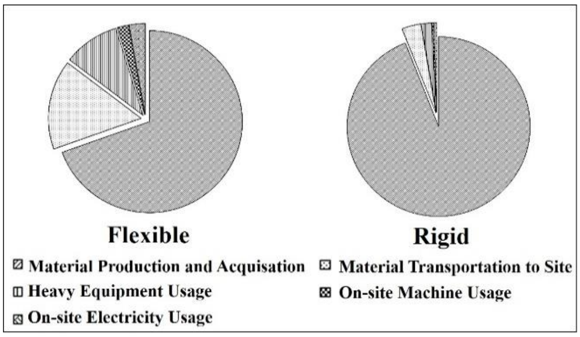

Figure 3 Pie charts showing GHG emissions in each construction process

The material transportation and on-site heavy equipment usage are the next contributors. The emissions generated from these two construction processes are very close in this study. Figure 3 shows that their contributions are relatively low in proportion to the material production, which is in agreement with the results from [5], [14], and [16]. Nevertheless, they have a few difference regarding the percentages of GHG emissions among all processes. This is a consequence of identifying different analysis processes. The proposed model takes into consideration only GHG emissions during the construction phase, while [16] considers the life-cycle impact.

However, the GHG emissions from these two categories, material transportation and on-site heavy equipment usage, can be varied depending on several actual factors and the uncertainty that occurs on the jobsite, for example, working conditions, transportation distance, a project manager's abilities and a driver's skill at controlling equipment. Merely the result of this study, it would be difficult to claim a less significance in GHG emissions from the on-site electricity when compared to others, since the amount of electricity usage can be actually different from the one assumed in the case study. However, past literature shows a consistent result that GHG emissions from on-site electricity tends to be insignificant ([8], [30], and [31]).

The results from this study provide perceptions to transportation planners and decision makers about the impact of highway construction processes on the environment. They also present the impact from different types of highway projects. However, this study mainly focuses only on the environmental impact during the construction operations and does not take into consideration other dimensions in making decisions for highway construction, such as a construction cost and budget, expected public benefits as a result of transportation improvement from new road construction, etc.

6. Conclusions

This paper presents the development of the GHG emission quantification model that is capable of evaluating the impact of different construction processes throughout the construction phase on the environment. The model consists of five modules that include (1) material production and acquisition; (2) material transportation to the project site; (3) heavy equipment usage; (4) on-site machine usage; (5) on-site electricity usage. Process-based analysis was adopted in this study, as it has been proven to be suitable for identifiable conditions and its potential in generating a highly accurate result. The model was applied to a hypothetical pavement construction project that was assumed to be newly constructed. Two different alternatives - flexible and rigid pavement - are analyzed and compared to investigate their environmental impacts resulting from construction operations. The results show a higher GHG emissions in rigid pavement compared to flexible pavement. In addition, the material production and acquisition process contributes the most in GHG emissions among all construction processes.

This paper enables efficient and effective decision making in highway construction. During the design phase, transportation agencies can select the least-generating GHG emission materials for the project construction to facilitate the environmental sustainability goal of the national law and legislation in highway planning efforts. Moreover, transportation planners and decision makers can apply the developed model to find the environmental impact with an integration of the result from the life cycle analysis to establish the most effective highway program for new construction and rehabilitation especially under the limited budget allocation. Further implication can be stated during the construction phase with an application of the model in selecting an environmental-friendly construction technique and method. For example, as project owners, transportation agencies may request contractors to use local material or select nearer material resources to reduce the GHG emissions resulting from transportation.

However, some improvements can be performed based on this study. For example, some construction components can be added in the scope of the study to provide a more comprehensive framework in evaluating the environmental impact, such as administrative service to support construction activities and equipment maintenance. The model can be also expanded to consider the indeterministic and uncertain nature of highway decisions and input variables. Moreover, the life cycle analysis can be performed by including other project phases, such as the operation and demolition phase, to allow an analyst to observe more holistic view of environmental impact on a road.

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