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Evaluation Model for Particulate Matter Emissions in Korean Construction Sites

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Abstract: Particulate matter (PM) has caused serious environmental issues in Asia, and various policies for systematic management of PM based on evaluation of the characteristics of emissions are being discussed. In Korea, where the damage of PM from construction sites is severe, only regulatory policies according to the concentration are being implemented; however, there is no policy for the quantitative management of PM. Therefore, this study aimed to derive and propose an emission evaluation model to be used for the establishment of management policies for construction site PM emissions in South Korea by assuming structures as manufactured products. Therefore, this study derived a method of calculating the PM10, PM2.5, NOx, SOx, and VOCs emission factors for each type of equipment in construction sites and then estimated annual total emissions. In addition, this paper put forth a method for offsetting emission permission standards as the criteria for evaluating the adequacy of the estimated emissions. Finally, a model algorithm was proposed for evaluating emissions in advance during the construction planning phase by comparing the PM10, PM2.5, NOx, SOx, and VOCs emissions in construction sites with established standards; the supplementary point of the algorithm is discussed for further studies.

Keywords: construction site; particulate matter; emission factor; emissions; emission standards

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1. Introduction

Particulate matter (PM) is largely classified, based on its diameter, as PM10 (<10 µm) and PM2.5 (<2.5 µm). Since PM is classified by physical diameter, it includes direct emissions generated by combustion, fugitive dust generated by physical acts, and secondary substances generated by toxic chemicals such as NOx, SOx, and VOCs. PM induces serious damage and causes various diseases and death based on the level of penetration into the human body [1]. In particular, PM is emerging as a serious problem in Asia and is being considered from various perspectives as a threat to human health [2–5]. South Korea, in particular, is facing serious PM problems due to a combination of external factors, such as the air quality of East Asia and Asian dust storms, and internal factors such as urbanization and increasing traffic [6]. According to the Ministry of Environment (ME), the leading domestic cause of PM is industrial sites, generating 38% of the total domestic PM2.5 emissions, followed by construction machinery and logistics, which generate 16% of the total emissions. Thus, these two factors together account for 54% of domestic PM2.5 emissions [7,8]. In particular, the PM generated from construction sites is important in the management of PM at the national level, as it is included in both of the two largest causes, and a separate emission management system is required.

The number of complaints due to the generation of PM in industrial sites in South Korea from 2011 to 2015 amounted to approximately 89,000, 90% of which were associated with construction site dust, indicating severe damage caused by the dust generated from construction work [9]. The population density of South Korea is 515 persons/km^2 as of 2019, which is relatively high, compared with global levels. In particular, the population is dense in downtown areas around Seoul, leading to severe damage due to dust from construction sites.

Despite such severity, there are limitations to the current construction site dust regulation and management systems of South Korea. The Clean Air Conservation Act, which is the highest law related to air quality in South Korea, specifies 11 types of dust-generating businesses. Construction sites, as one of these businesses, are required to report to the local government and must install facilities and take necessary measures to suppress dust generation [10]. However, management is difficult, as concentration-oriented regulations are applied to a wide area of regional units, not construction site units. Consequently, the South Korean government has recognized the need for quantitative management of PM and has enforced the Special Act on the Improvement of Air Quality in Atmospheric Management Area since April 2020, which mandates management methods based on total emissions, rather than concentration [11]. However, this act only regulates the management of business site emissions. Methods to manage PM emissions from construction sites have not been enacted, and a clear evaluation method for construction site PM emissions has not been suggested.

Therefore, this study aims to develop an evaluation model for PM emissions from construction sites as part of promoting national health through the establishment of a Korean construction site PM emissions management system. Therefore, this study suggests a method for calculating construction site PM emissions and setting emission permission standards and finally proposes an emission evaluation model.

2. Literature Review

2.1. Construction Site PM Status of South Korea

The South Korean ME largely classifies air pollutant emission sources into 13 categories and calculates PM emissions for ten categories (energy industry combustion, non-industrial combustion, manufacturing industry combustion, production process, road-mobile pollution sources, non-road-mobile pollution sources, waste treatment, other area sources, fugitive dust, and biological combustion) [12]. Among these, the categories directly related to construction site PM are fugitive dust and non-road-mobile pollution sources. Analyzing PM10 emissions for one year in 2017 (the latest data) for these two categories using the air pollutant emissions statistics by emission source provided values of 109,932 t/yr and 16,194 t/yr, respectively. These values correspond to 50.3% and 7.4% of all PM10 emissions and rank first and third among all the emission source categories. In particular, the amount of PM10 generated in construction sites is calculated through construction work among the detailed items of the fugitive dust category and construction equipment among the detailed items of the non-road-mobile pollution sources category, which amounted to 36,553 t/yr and 6086 t/yr. This value is the highest in the fugitive dust category and second highest in the non-road-mobile pollution sources category, implying that construction site PM in South Korea is a serious issue (Figure 1). Road-mobile pollution sources, such as trucks (dump trucks, concrete mixer trucks), that were not classified separately as construction work or construction equipment items are not reflected in these results.

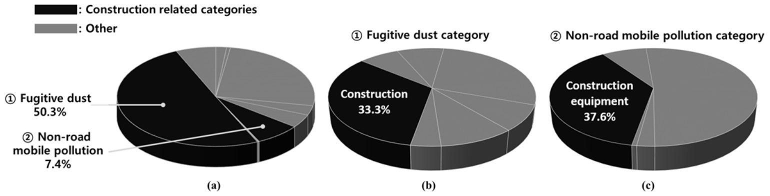

Figure 1. PM10 emission ratio by construction PM emission source categories: (**a**) PM10 ratio of fugitive dust and non-road-mobile pollution sources category, (**b**) PM10 ratio of construction work in the fugitive dust category, and (**c**) construction equipment PM10 in the non-road-mobile pollution sources category.

2.2. Management Method for Construction Site PM

PM management methods can be divided into emission management and concentration management. Representative systems for managing emissions include Cross-State Air Pollution Rules (CSAPR) of the United States Environmental Protection Agency (US EPA, Washington, DC, USA) and the National Emission Ceiling Directive (NECD) of the European Union (EU, Maastricht, The Netherlands). The CSAPR calculates SOx and NOx quantities, the source materials of fine PM mainly emitted from power plants, and links them to the emissions trading system. The NECD regulates the upper limits for PM2.5 emissions along with the SOx and NOx emissions [13,14]. Among Asian countries, Japan enforces the Air Pollution Control Act to regulate emissions of soot and dust from fixed pollutants, including SOx, and regulates NOx emissions and PM caused by automobiles by enforcing the Automotive NOx and PM Law [15,16]. Similar to these systems, South Korea enforces the total volume control of air pollutants in businesses as part of the Special Act on the Improvement of Air Quality in Air Management Areas, which allocates the standards for SOx, NOx, and total suspended particles (TSP) emissions in businesses as of 2020 [17]. The systems that control emission concentrations of PM include Winter Emergency Measures in Italy; Fine Dust Alarm in Germany; and South Coast Air Quality Management District, Bay Area Air Quality Management District, and National Ambient Air Quality Standards (NAAQS) in the US [18–22]. In Asia, China is attempting to control PM concentrations through the establishment of three-year action plans for cleaner air [23]. These policies focus on PM concentrations and regulate the operation of PM sources when a certain PM concentration is exceeded. South Korea also has a policy related to emergency reduction measures for PM management based on centration. This system establishes PM2.5 concentration standards for the current and following days and restricts business operations if the concentration standard is exceeded [24]. Table 1 compares the representative emissions and concentration management systems of South Korea.

Table 1. Air pollutant management methods of South Korea.

Classification	Air Pollutant Management Methods	
	Emission Management	**Concentration Management**
Related policies	Air Pollutant Emission-Cap Management for Industrial Work Place (ME, 2020)	Emergency Reduction Measures for Ultra-Fine Dust (ME, 2019)
Object of management	Annual total emissions	Concentration
Management unit	kg/yr	$\mu g/m^3$
Management criteria	Permitted emissions	PM concentrations of current and following days
Target substances	NOx, SOx, TSP Emissions	PM2.5
Inclusion of construction site	No	Yes
Characteristic	Preventive management	Post management

Currently, in South Korea, construction site PM is managed based on concentration through PM emergency reduction measures. However, this concentration-oriented management system has limitations in effectively reducing the amount of PM emissions, with temporary measures that are implemented when the PM concentration is high. In particular, the momentary concentration of PM in air is often high even when the emissions are low, as shown in Figure 2, or the momentary concentration of PM may meet the standard even when the emissions are high. Thus, it has limitations in effectively managing PM emitted from construction sites [25].

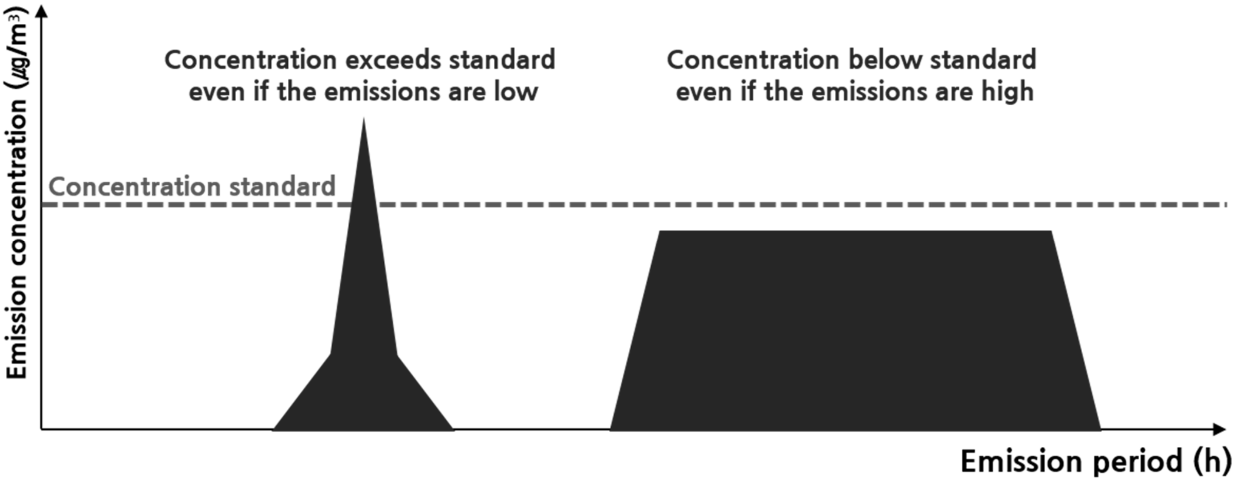

Figure 2. Limitation of management based on concentration (schematic diagram).

Conversely, by calculating and managing the PM emissions of construction sites, the emissions can be quantitatively predicted and reduced, thus encouraging active PM management at the site. Thus, this study proposes emissions management as an appropriate method of PM control at construction sites.

2.3. Research Scope

The life cycle of buildings can be divided into manufacturing, construction, operation and maintenance, and demolition and disposal stages in accordance with the ISO 21930:2017 [26]. The Heavy Construction Operation Chapter of the EPA AP-42 also largely divides the construction phases for calculation of construction site PM into demolition and debris, site preparation, and general construction [27]. Since the PM at construction sites is generated from the movement and construction behavior of construction equipment, this study limited the scope to the construction phase, and the scope of the system was set to the construction site.

3. Methods

3.1. Building an Emission Factor Database for Calculating Construction Site PM Emissions

The methods for calculating PM emissions from construction sites can be divided into primary, secondary, and fugitive emissions. Primary emissions refer to PM emitted directly into the air, while secondary emissions refer to PM generated indirectly due to NOx, SOx, and VOCs emitted from construction equipment. Alternatively, fugitive PM emissions refer to PM generated physically by construction activities, not by the burning of fuel by construction equipment, unlike the previous two emission methods. Thus, this section outlines the PM emission methods of construction sites, as shown in Table 2, and describes the building of an emission factor database for each emission method.

Table 2. Classification of construction site PM emission methods.

Classification	**Construction Site PM Emission Methods**		
	Primary Emissions	**Secondary Emissions**	**Fugitive Emissions**
Object of measurement	Construction equipment	Construction equipment	Construction activities
Target substances	PM10, PM2.5	NOx, SOx, and VOCs	PM10, PM2.5

3.1.1. Primary Emissions

The emission factors for primary PM emissions generated by the operation of construction equipment at construction sites have been previously developed by the US EPA and EU EEA [28,29]. The National Institute of Environmental Research (NIER, Incheon, Korea) of South Korea has also developed and is using PM10 emission factors for trucks (dump truck, concrete mixer truck, and trailer) and nine types of construction equipment (bulldozer, excavator, loader, forklift, crane, concrete pump, roller, air compressor, and drilling machine), and PM2.5 emission factors by applying the PM2.5/PM10 fraction. Thus, we selected the primary PM emission factor of construction sites in compliance with the factors presented by the NIER [30,31].

3.1.2. Secondary Emission

The secondary PM emissions generated from construction sites can be evaluated based on the quantities of NOx, SOx, and VOCs directly emitted from construction equipment. The NIER presents NOx, SOx, and VOCs direct emission factors for trucks and nine types of construction equipment as in the case of primary PM emissions. Thus, we selected the secondary PM emission factor of construction sites in compliance with the emission factors presented by the NIER [30,31].

3.1.3. Fugitive Emission

Research on fugitive dust emissions generated by the activities of construction equipment at construction sites has been conducted based on the emission factor calculation method suggested by the Heavy Construction Operation Chapter of the US EPA AP-42 [27]. As a result, the US MRI classified construction works into residential, non-residential, and road construction and developed PM emission factors with the construction area and period as parameters. Based on them, the EU EEA and NIER of South Korea have developed and are using their own emission factors [29–31]. However, if PM emissions are calculated using these factors, the calculated PM emissions increase linearly with the construction area and period, thus failing to reflect the various environments of construction sites. For example, if two nonresidential construction sites are planned with the same construction area and period but have different structure height and underground depth, resulting in different expected amounts of activities of construction equipment, they generate the same result of emissions if the emissions of fugitive PM are calculated using the above-mentioned emission factors. Therefore, we derived emission factors based on the activity rate resulting from the movements and operations of construction equipment using the calculation method for fugitive PM emission factors for construction sites of the US EPA AP-42. Variables for the calculation method such as silt content, mean wind speed, and moisture content were applied by referring to the Korean values suggested in the report of NIER [9,32].

3.2. Method for Calculating PM Emissions from Construction Sites

The US EPA AP-42 expresses the general equation for calculating emissions using the emission factors in Equation (1) [28].

$$E = A \times EF \times \left(\frac{1 - ER}{100}\right) \tag{1}$$

where E denotes emissions, A denotes activity rate, EF denotes emission factor, and ER denotes the overall emission reduction efficiency (%). The total emissions can be calculated by summing the calculation results of this equation for each piece of equipment. However, in this study, the activity rate of each piece of construction equipment to A, and the standard for ER must be developed in further research, as there is no standard for ER. Therefore, we suggest Equation (2) for calculating emissions as follows:

$$E_t = \frac{\sum_i^m \sum_j^n A_{i,j} EF_{i,j} \left(\frac{1 - ER_{i,j}}{100}\right)}{y} \tag{2}$$

where E_t denotes the total emissions (kg/yr), i denotes the construction equipment, j denotes activities, and y denotes the construction period (a). Equation (2) is used to calculate the primary emissions, secondary emissions, and fugitive emissions.

3.3. Method for Setting Emission Permission Standard for PM

Appropriate emission standards must be established to actively reduce the amount of PM emitted from construction sites. The total volume control of air pollutants for businesses by the ME of South Korea manages the emission of air pollutants by allocating permitted emissions to each business. This emission allocation method is used to present a new yearly emissions standard to each business [17]. However, construction sites have difficulty complying with this system because they are not the type of business that continuously produces specific products at a specific location. Thus, this study conducted research to apply the emission permission standard equation for businesses to construction sites using Equation (3) as follows:

$$E_c = C \times P \tag{3}$$

where E_c denotes the permitted emissions (kg/yr), C denotes the unit emissions of the latest year (kg/unit), and P denotes the allocation factor unit amount, which reflects the mean production quantity (unit/yr). When this is applied to a construction site, the allocated emissions of domestic construction sites can be calculated by assuming each site as a place of business and the unit area of the structure as a product. This study set the appropriate PM emissions standards for construction sites using this method. For the basic data to derive the unit emissions of the latest year, the air pollutant emission statistics data from 2017 were used. Consequently, the construction site emission permission standard equation was derived from Equation (4).

$$E_c = C \times P = \frac{E_{latest}}{a_{latest}} \times \frac{a}{y} \tag{4}$$

where E_{latest} denotes the total emissions of the latest year (kg/yr), a_{latest} denotes the domestic total construction permission area of the latest year (m^2), and a denotes the gross area of the construction site (m^2). Hence, C indicates the domestic unit emissions of the latest year (kg/m^2-yr) and P indicates the annual mean gross area of the construction site to be allocated (m^2/yr).

4. Results

4.1. Emission Factor Database

The main source of PM at construction sites is the activity of construction equipment. Thus, the database must be constructed by classifying the emission factors by the construction equipment and activity. Therefore, this study built a database for calculating construction site PM emissions using the method for calculating emission factors, as shown in Table 3.

4.2. Emission Permission Standards for PM

To establish the emission permission standards for PM, the domestic unit emissions must be calculated based on the domestic total emissions of the most recent year and the building permit area, as described in Section 4.1. First, to calculate the domestic total emissions of construction sites of the latest year, the emissions corresponding to the construction site among domestic emissions must be classified separately. Therefore, this study classified the emissions sources corresponding to construction sites among the emission sources of the air pollutant emissions statistics for 2017 (Table 4) [12].

Table 3. Database of PM emission factor by construction equipment and activity.

Equipment (Loading Weight)	Activities	Construction Site Particulate Matter Emission Factor (kg/unit)									
		Primary Emissions [a]			Secondary Emissions [b]				Fugitive Emissions [c]		
		PM10	PM2.5	Unit	NOx	SOx	VOCs	Unit	PM10	PM2.5	Unit
Bulldozer	Bulldozing	2.20×10^{-4}	2.02×10^{-4}	kWh	3.67×10^{-3}	2.60×10^{-6}	1.10×10^{-4}	kWh	4.15×10^{-3}	2.81×10^{-3}	ton
Loader	Loading	2.20×10^{-4}	2.02×10^{-4}	kWh	3.67×10^{-3}	2.60×10^{-6}	1.10×10^{-4}	kWh	8.74×10^{-4}	1.32×10^{-4}	ton
Excavator	Dragline	1.90×10^{-4}	1.75×10^{-4}	kWh	3.54×10^{-3}	2.60×10^{-6}	1.30×10^{-4}	kWh	3.36×10^{-3}	2.10×10^{-4}	ton
	Loading								8.74×10^{-4}	1.32×10^{-4}	
Crane	Lifting	1.20×10^{-4}	1.10×10^{-4}	kWh	3.45×10^{-3}	2.54×10^{-6}	1.60×10^{-4}	kWh	N/A	N/A	-
	Travel								4.50×10^{-1}	4.50×10^{-2}	VKT
Concrete pump	Pumping	2.00×10^{-5}	1.84×10^{-5}	kWh	2.00×10^{-3}	2.54×10^{-6}	4.60×10^{-4}	kWh	N/A	N/A	-
Roller	Compacting	3.40×10^{-4}	3.13×10^{-4}	kWh	3.80×10^{-3}	2.65×10^{-6}	2.20×10^{-4}	kWh	4.92×10^{-2}	4.92×10^{-3}	ton
Compressor	Compressing	1.00×10^{-4}	9.20×10^{-5}	kWh	3.41×10^{-3}	2.54×10^{-6}	1.70×10^{-4}	kWh	N/A	N/A	-
Boring machine	Drilling	1.20×10^{-4}	1.10×10^{-4}	kWh	3.40×10^{-3}	2.60×10^{-6}	1.20×10^{-4}	kWh	7.26×10^{-2}	1.45×10^{-2}	hole
Fork lift (3 t)	Lifting	2.80×10^{-4}	2.58×10^{-4}	kWh	3.69×10^{-3}	2.65×10^{-6}	1.70×10^{-4}	kWh	N/A	N/A	-
	Travel								4.50×10^{-1}	4.50×10^{-2}	VKT
Dump truck (8 t)	Travel	4.30×10^{-4}	3.96×10^{-4}	km	1.96×10^{-2}	2.46×10^{-4}	7.46×10^{-4}	km	5.56×10^{-1}	5.56×10^{-2}	VKT
Dump truck (25 t)	Travel	4.30×10^{-4}	3.96×10^{-4}	km	1.96×10^{-2}	3.85×10^{-4}	7.46×10^{-4}	km	9.29×10^{-1}	9.29×10^{-2}	VKT
Concrete mixer truck (15 t)	Travel	4.30×10^{-4}	3.96×10^{-4}	km	1.96×10^{-2}	2.46×10^{-4}	7.46×10^{-4}	km	7.38×10^{-1}	7.38×10^{-2}	VKT
Trailer (20 t)	Travel	4.30×10^{-4}	3.96×10^{-4}	km	1.96×10^{-2}	3.85×10^{-4}	7.46×10^{-4}	km	8.40×10^{-1}	8.40×10^{-2}	VKT

[a,b] NIER, 2015. [c] Methodology from US EPA, AP-42, 1995. Variables from NIER, 2008. N/A: not available; VKT: vehicle kilometer traveled (equal to km).

Table 4. Classification of construction site emission sources.

Classification of Construction Site Emission Sources		
Large	**Medium**	**Small**
A. Non-road-mobile pollution sources	A-1. Construction equipment	-
B. Road-mobile pollution sources	B-1. Freight trucks	B-1-①. Dump trucks
		B-1-②. Concrete mixer trucks
C. Fugitive dust	C-1. Residential facilities	-
	C-2. Non-residential facilities	-

Furthermore, after analyzing the building permit area data of the South Korean Ministry of Land Infrastructure and Transport, the total gross area for residential buildings permitted in 2017 was 70,254,000 m^2, while the total gross area for nonresidential buildings was 101,618,000 m^2 (a_{latest} in Equation (4)) [33]. As the primary, secondary, and fugitive emissions of PM10, PM2.5, NOx, SOx, and VOCs were not divided by building type (residential and non-residential), each emission value was allocated in terms of permitted area of residential and non-residential building, and the total emissions (E_{latest} in Equation (4)) of each building type were calculated. Thus, the unit emissions of residential and non-residential buildings by the emission method and substance were calculated (Table 5). This value corresponds to C in Equation (4), which is used as a coefficient for obtaining the permitted emissions. The permitted emissions of the construction site were determined by inputting the gross area (a in Equation (4)) and construction period (y in Equation (4)) of the construction site.

Table 5. Calculation of unit emissions for residential and non-residential construction sites to establish emission permission standards.

Unit: kg/yr, kg/m^2-yr											
Building Type		**Residential Buildings**					**Non-Residential Buildings**				
[a] **Permitted Area (m^2)**		**70,254,000**					**101,618,000**				
Emission Sources		**PM10**	**PM2.5**	**NOx**	**SOx**	**VOCs**	**PM10**	**PM2.5**	**NOx**	**SOx**	**VOCs**
Primary emissions (kg/yr)	A-1	2.49×10^{6}	2.29×10^{6}	-	-	-	3.60×10^{6}	3.31×10^{6}	-	-	-
	B-1-①	1.48×10^{5}	1.36×10^{5}	-	-	-	2.14×10^{5}	1.97×10^{5}	-	-	-
	B-1-②	4.03×10^{4}	3.71×10^{4}	-	-	-	5.83×10^{4}	5.36×10^{4}	-	-	-
Secondary emissions (kg/yr)	A-1	-	-	4.66×10^{7}	2.91×10^{4}	5.99×10^{6}	-	-	6.74×10^{7}	4.22×10^{4}	8.66×10^{6}
	B-1-①	-	-	4.94×10^{6}	1.98×10^{3}	2.21×10^{5}	-	-	7.14×10^{6}	2.86×10^{3}	3.20×10^{5}
	B-1-②	-	-	1.36×10^{6}	5.57×10^{2}	5.99×10^{4}	-	-	1.97×10^{6}	8.05×10^{2}	8.66×10^{4}
Fugitive emissions (kg/yr)	C-1	8.36×10^{6}	8.36×10^{5}	-	-	-	-	-	-	-	-
	C-2	-	-	-	-	-	2.82×10^{7}	2.82×10^{6}	-	-	-
[b] Total emissions (kg/yr)		1.10×10^{7}	3.30×10^{6}	5.29×10^{7}	3.16×10^{4}	6.27×10^{6}	3.21×10^{7}	6.38×10^{6}	7.65×10^{7}	4.59×10^{4}	9.06×10^{6}
[c] Unit emissions (kg/m^2-yr)		1.57×10^{-1}	4.70×10^{-2}	7.53×10^{-1}	4.50×10^{-4}	8.92×10^{-2}	3.16×10^{-1}	6.28×10^{-2}	7.53×10^{-1}	4.52×10^{-4}	8.92×10^{-2}

[a] a_{latest}: permitted area; [b] E_{latest}: total emissions; [c] C: unit emissions.

4.3. Proposal for PM Emissions Evaluation Model for Construction Sites

Based on the discussion in Section 4.2, this study established an emission evaluation system for managing the total PM volume for construction sites in South Korea. First, a construction plan was established according to the construction type. According to the construction plan, the area of the construction site (a in Equation (4)), construction period (y in Equations (2) and (4)), construction material quantity, and earthwork volume can be obtained. Among these, construction material quantity and earthwork volume can be used as basic data for calculating the work volume and movement amount in the construction work, from which the activity rate of each piece of equipment (A in Equation (2)) for the calculation of emissions can be derived. However, the emission reduction technology variable for the calculation of emissions (ER in Equation (2)) must be defined through a separate study.

The emission evaluation process can be largely divided into emission calculation and permitted emissions standard processes. The emissions calculation process calculates the total emissions, Et, of PM10, PM2.5, NOx, SOx, and VOCs predicted to be generated in a year at the construction site by linking the emission factors database (EF in Equation (2)) with the construction plan information. In addition, the permitted emissions standard process calculates the annual emissions E0 of PM10, PM2.5, NOx, SOx, and VOCs that can be permitted at the construction site. Ultimately, Et is evaluated based on E0 to control PM generation at the construction site from the design stage. Based on this process, this study proposed the construction site PM emissions evaluation system model (Figure 3).

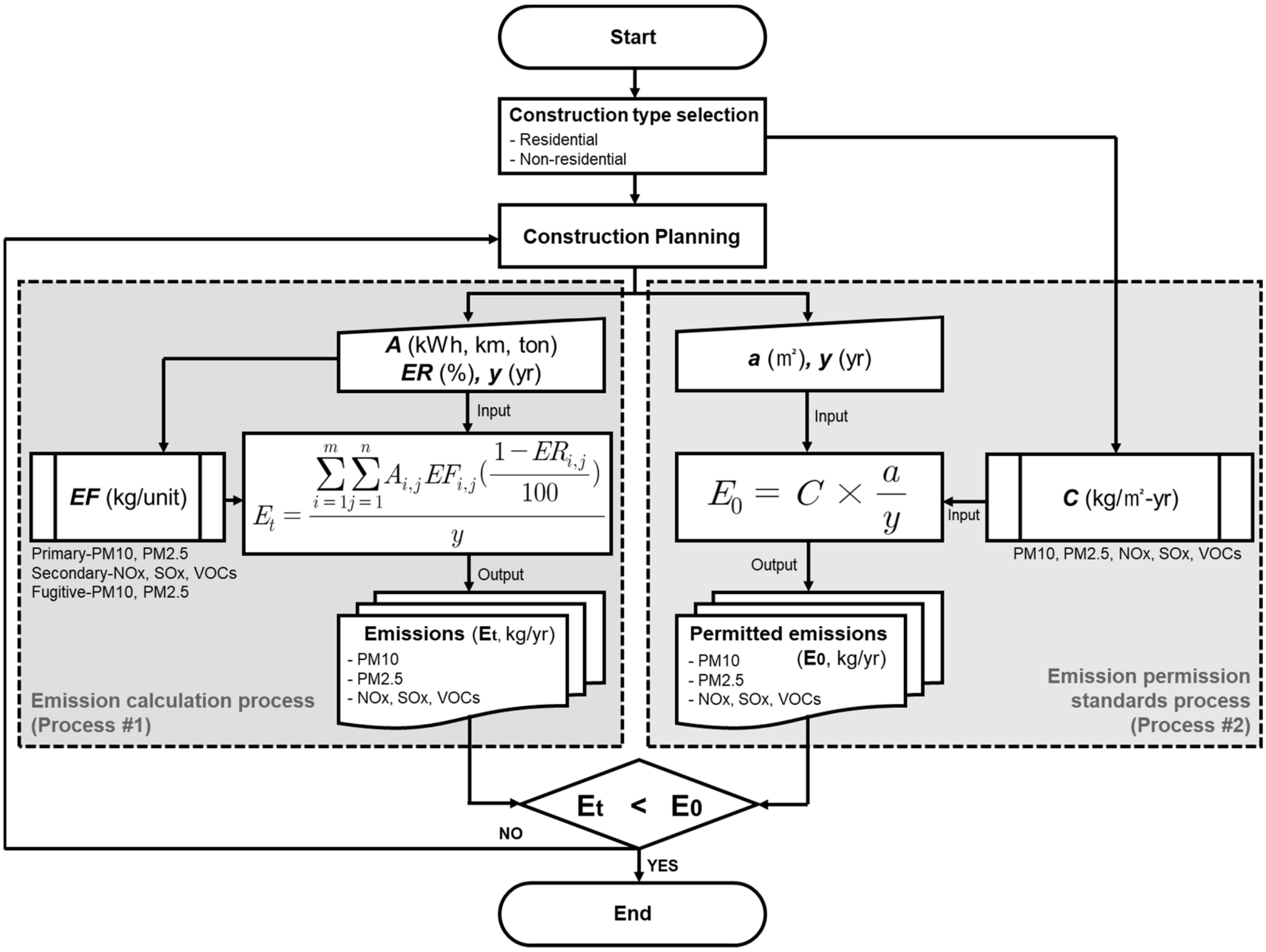

Figure 3. Algorithm of the construction site PM emissions evaluation system model.

5. Examination of the PM Emissions Evaluation Model for Construction Sites

The emission factors and emission calculation methods for the emission calculation process (Process #1) and the emission permission standards process (Process #2) were compared to verify the appropriateness of the proposed model. In addition, future improvements were derived by comparing the results of the two processes through a case study.

5.1. Emission Factors and Emission Calculation Methods

In Process #2, standards were set based on the national air pollutant emissions statistics data, which verified that the direct and secondary emission factors and emission calculation method for each piece of construction equipment used in the statistical analysis was equal to the emission factor and emission calculation method used in Process #1. However, in the case of fugitive emissions in Process #1, emission factors and emissions for each piece of equipment were calculated based on AP-42, whereas in Process #2, emissions were calculated using Equation (5) and the emission factors in Table 6.

$$E = \sum A \times P \times EF \tag{5}$$

where E denotes the total fugitive emissions (kg/yr), A denotes the annual construction area (m^2), P denotes the annual construction period (month/yr), and EF denotes emission factor (kg/m^2/month).

Table 6. Emission factors (kg/m^2/month) for Equation (5). [31].

Construction Type		PM10	PM2.5
Residential	House	0.0072	0.00072
	Apartment	0.0247	0.00247
Non-residential		0.0426	0.00426
Road construction		0.0941	0.00941

These emission factors were derived from NIER research to select the most suitable factor for construction sites among the emission factors developed by the US EPA and MRI. To achieve this, the fugitive emission factors for each piece of construction equipment were calculated using AP-42 as in Process #1 of this study [32]. However, the NIER study considered only a limited number of construction equipment and activities compared with that considered in Process #1. Accordingly, Process #1, derived from this study, was deemed more precise in terms of fugitive emission calculation than Process #2; as a result, the statistics on the amount of fugitive emissions from construction sites derived using the fugitive emission calculation method of Process #1 should be equally applied to Process #2 in future studies. Table 7 shows the comparison of the fugitive emission factor calculation method between the NIER research and Process #1 of this study.

Table 7. Comparison of the fugitive emission factor calculation method.

Equipment	Activities	A. NIER, 2008 (Process #2)	B. This Study (Process #1)	Notes
Bulldozer	Bulldozing	PM10 $EF = 0.45\frac{s^{1.5}}{M^{1.4}}$	PM10 $EF = 0.75 \times 0.45\frac{s^{1.5}}{M^{1.4}}$ PM2.5 $EF = 0.105 \times 2.6\frac{s^{1.2}}{M^{1.3}}$	a
Loader	Loading	N/A	$EF = k(0.0016)\frac{\left(\frac{U}{2.2}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}}$	b
Excavator	Dragline	$EF = \frac{0.0029h^{0.7}}{M^{0.3}}$	$EF = \frac{0.0029h^{0.7}}{M^{0.3}}$	-
	Loading	N/A	$EF = k(0.0016)\frac{\left(\frac{U}{2.2}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}}$	b
Crane	Lifting	N/A	N/A	c
	Travel	N/C	$EF = 1.5\left(\frac{s}{12}\right)^{0.9}\left(\frac{W}{3}\right)^{0.45}\frac{365-p}{365} \times 0.2819$	-
Concrete pump	Pumping	N/A	N/A	c
Roller	Compacting	$EF = K(0.10)\frac{s}{1.5}\frac{d}{235}$	$EF = K(0.10)\frac{s}{1.5}\frac{d}{235}$	-
Compressor	Compressing	N/A	N/A	c
Boring machine	Drilling	N/C	$EF = k \times 0.59$	-
Fork lift	Lifting	N/A	N/A	c
	Travel	N/C	$EF = 1.5\left(\frac{s}{12}\right)^{0.9}\left(\frac{W}{3}\right)^{0.45}\frac{365-p}{365} \times 0.2819$	-
Concrete mixer truck	Travel	N/C	$EF = 1.5\left(\frac{s}{12}\right)^{0.9}\left(\frac{W}{3}\right)^{0.45}\frac{365-p}{365} \times 0.2819$	-
Dump Truck, Trailer	Travel	$EF = 1.5\left(\frac{s}{12}\right)^{0.9}\left(\frac{W}{3}\right)^{0.45}\frac{365-p}{365} \times 0.2819$	$EF = 1.5\left(\frac{s}{12}\right)^{0.9}\left(\frac{W}{3}\right)^{0.45}\frac{365-p}{365} \times 0.2819$	-

EF: emission factor (kg/unit); s: silt content (%); M: moisture content (%); k: scaling factors for PM10 or PM2.5 (constant); U: mean wind speed (m/s); h: drop height (m); W: mean weight (ton); p: number of days in a year with at least 0.254 mm of precipitation (days); K: activity factor (Constant); N/A: not available; N/C: not considered. [a] In A, the PM15 emission factor of Bulldozing presented in AP-42 was applied as the PM10 emission factor, and the PM2.5 emission was calculated by collectively applying the PM2.5/PM10 fraction to 0.1. Contrastively, the bulldozing emission factor calculation method of AP-42 is used in B. [b] In A, the aggregate storage piles emission factor of AP-42 was collectively applied to the entire earth quantity of the construction site, and in B, it was applied separately for each construction equipment. [c] Categories that do not generate fugitive emissions.

5.2. Case Study

To compare the results of Process #1 and Process #2, a case study for a commercial building with RC structure, which is a representative non-residential building type in Korea with a total floor area of 17,226 m^2, was evaluated. Emissions (Process #1) and emission permission standards (Process #2) were then derived, as shown in Table 8.

Table 8. Case study results.

Emission Methods	Process	PM2.5	PM10	NOx	SOx	VOCs
				(kg/yr)		
Direct Emission	#1	1.54×10^{0}	1.68×10^{0}	-	-	-
	#2	6.04×10^{2}	6.56×10^{2}	-	-	-
Secondary Emission	#1	-	-	7.78×10^{1}	7.32×10^{1}	7.28×10^{0}
	#2	-	-	1.30×10^{4}	7.78×10^{0}	1.54×10^{3}
Fugitive Emission	#1	2.01×10^{2}	1.98×10^{3}	-	-	-
	#2	2.41×10^{2}	2.16×10^{3}	-	-	-
Total	#1 (Et)	2.02×10^{2}	1.98×10^{3}	7.78×10^{1}	7.32×10^{-1}	7.28×10^{0}
	#2 (E0)	8.44×10^{2}	2.82×10^{3}	1.30×10^{4}	7.78×10^{0}	1.54×10^{3}

Through the case study, it was found that the PM2.5, PM10, NOx, SOx, and VOCs emissions (Process #1) of the target construction site satisfy the total emission permission standards (Process #2). The results of the two processes appeared in a similar range in the case of fugitive emissions. However, in the case of direct emissions and secondary emissions, a large difference was detected in the results between the two processes due to the difference in the basic source used for calculations; that is, in the case of Process #1, emissions were limited to the building construction site of the case study, whereas for air pollutant emission statistics used in Process #2, the emission statistics were calculated based on the total annual equipment operating hours, which include the operation time for building construction, but also the operation time for other construction activities. Therefore, the standard for Process #2 was excessively calculated, as the total emission (E-latest of Equation (4)) was overestimated. Accordingly, it is necessary to develop an annual emission statistics database specialized for building construction for Process #2.

6. Discussion

Various PM concentration regulation policies are being implemented in Asia with the rising threat of PM to human health and the environment. However, concentration-oriented policies only regulate the additional generation of PM based on the PM in the air and, thus, have limitations associated with quantitatively reducing the amount of PM generated from their sources. Particularly, in South Korea, which is suffering from serious damage due to various PM generated from construction sites, preemptive efforts to prevent damage by quantitatively evaluating PM should be made to ensure the safety of local residents and construction site workers.

This study proposed a system model for calculating the amount of PM generated at construction sites and for evaluating the appropriateness of the calculated PM amount by referring to the total volume control of air pollutants in businesses in South Korea. The emission factors database and emissions calculation method derived in this study can be used to predict the PM emissions generated at domestic construction sites, and the permitted emissions standards will be used to regulate PM at construction sites to appropriate levels. Ultimately, the proposed model is expected to contribute to the safety of residents and site workers by encouraging the active reduction of PM from the construction planning stage.

However, the differences in basic materials used for the emission calculation process and emission permission standard process may cause the final evaluation to be inaccurate.

Therefore, in future studies, emissions from various construction sites will be calculated using the emission calculation process presented in this study, and the results of the case studies will be used as statistical data for the emission permission standards process.

The results of this study are expected to be highly useful as basic data for PM emissions evaluation to establish the total PM emissions control, seasonal management, and emissions trading systems for construction sites currently under discussion in South Korea. However, the emission factors for each piece of construction equipment and activity proposed in this study are limited, and the effects of emissions according to the application of emissions reduction technology (ER) have not been suggested. To complement these limitations, the emission factors database must be updated continuously in the future, and field experiments should be conducted to derive the PM emissions reduction rate of each emissions reduction technology, which should then be reflected in the proposed model. We plan to conduct further research to hone the precision of the evaluation system for PM emissions from construction sites and reflect these results in establishing various fine dust management policies.

7. Conclusions

This study aimed to develop a model for construction site PM emissions evaluation systems as part of promoting national health. This was achieved by proposing an emissions evaluation method to be used to establish policies to control PM emissions from construction sites in South Korea. The primary findings of this study are as follows:

1. The PM emission methods for construction sites were classified into primary, secondary, and fugitive emissions. Among the non-road-mobile pollution sources and road-mobile pollution sources presented by the NIER, the PM10, PM2.5, NOx, Sox, and VOCs emission factors of each emission method were calculated for the types of construction equipment causing PM, and a database of the emission factors was constructed.
2. A total emissions calculation method for construction sites according to the movement and work volume of each type of construction equipment was proposed using the derived emission factors database based on the general equation for calculating emissions suggested by the US EPA.
3. This study derived a method for calculating the PM10, PM2.5, NOx, SOx, and VOCs emission permission standards for residential and non-residential construction sites using the recent construction PM statistics of South Korea.
4. An evaluation method was derived to measure the appropriateness of the total emissions of PM10, PM2.5, NOx, SOx, and VOC in construction sites during the design and planning phase of construction projects, and an algorithm model for this method was proposed.
5. Considering the possibility that the final evaluation result may not be accurate due to differences in the basic materials used for the emission calculation process and emission permission standards process, the basic material data for calculating the emission standards should be revised in future studies.

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