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Characteristics and Reducing Methods of Urban Particulate Matter

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ABSTRACT

Purpose: Modern-day cities are experiencing various problems that have not been experienced before. For instance, abnormal climate in various areas accompanied by climate change is regarded as a representative urban problem, and it causes other issues. Recently, particulate matter (PM) is emerging as a major urban problem. Particulate matter is a complex result of many factors and is closely related to abnormal climate. Therefore, in this study, we aim to identify the characteristics of the PM generated and active in cities from the perspective of urban planning. In addition, we seek to draw the possibility and implications for reducing urban PM through case analysis. **Method:** This study consists of theoretical and case studies. Based on preceding studies, the conceptual definition of 'urban PM' was established. Moreover, the main factors affecting the generation and activity of PM in the city were identified. In the case study, we analyzed the cases focusing on 'reduction' as a way to solve the urban PM problem. **Result:** Urban PM is influenced by urban functions structures and components, climate and nature. In order to cope with PM, urban spaces can be conceptually divided into 'road', a hot spot that generates PM, and 'open space' and 'building', where the particulate matter moves and spreads. The ways to solve urban PM problem can be divided into 'prevention', which minimizes the impact in advance in response to the causes of PM, and 'reduction', which minimizes the damage to the generated PM. 'Prevention' consists of legal and institutional regulations, spatial unit management, measurement, forecasting and warning systems. 'Reduction' includes ecological, physical and chemical solutions.

KEYWORD

미세먼지
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1. Introduction

1.1. Research Background and Purpose

In the 21st century, various cities have various problems that have not been experienced before and confronted with challenges that are difficult to cope with by using traditional ways. In particular, abnormal climate accompanied by climate change is regarded as a representative urban problem, and it leads to other issues[1]. Recently, particulate matter (PM) problem is a serious threat to the lives and health of urban residents. PM is a complex result of numerous factors that have not yet been identified, including urban systems operated by fossil fuels and structures centered on automobiles[2]. It is also known to be closely related to abnormal weather, such as heat waves and heat island phenomena[3].

PM is a fine dust with a diameter of 10㎛ or less. Therefore, the particles can penetrate the alveoli and have a fatal effect on human health[4]. In 2013, the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) designated PM as a group 1 carcinogen. PM can also occur in ordinary living environment of urban areas, and there is a risk of staying in a specific space for a long time depending on the structure of the city or microclimate. In cities, the ratio of secondary PM (i.e., generated by chemical reaction of pollutants, such as NH_3, NO_x, and SO_x in the atmosphere) is high[5]. Appropriate measures should be taken since it could have a more serious effect on the human body. Therefore, it is necessary to identify the characteristics of particulate matters generated and active in the cities.

1.2. Scope and Method

To identify characteristics of PM, this study classifies urban areas into roads, open spaces and buildings. Moreover, it explores the methods to reduce the exposure of PM generated in urban areas. This study follows two parts, which are theoretical review and case analysis. By reviewing previous studies, we identify the concept of PM and major factors affecting the generation and activity of PM in urban areas. We then analyzed cases adopting ecological, physical and chemical solutions to mitigate the PM in various cities.

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2. Concept and Characteristics of PM

2.1. Concept of PM

Dust is a complex mixture of organic and inorganic substances, with a diameter ranging from 0.1㎛ to 100㎛[6]. Basically, it can be classified according to the particle size. A dust of diameter of 50 to 100㎛ is called total suspended particles (TSP). Particulate matter (PM) refers to particles with a diameter of 10㎛ or less. It is divided into PM10 (10㎛ or less) and PM2.5 (2.5㎛ or less)). PM floats in the air for a long time and contains pollutants, such as NO_x, SO_x, CO, lead and ozone, etc.[4].

PM could increase the prevalence and premature mortality of asthma and lung diseases because it is not filtered through the nasal mucosa, but directly penetrates into the alveoli upon inhalation[7]. Increase of PM concentration by 10㎛/m3 grows the rate of hospitalization and mortality of chronic obstructive pulmonary diseases by 2.7% and 1.1%, respectively[8]. In the case of PM2.5, the incidence of lung cancer increases by 9% when its concentration increases by 10㎛/m^3, and the mortality rate of ischemic heart disease increases by 30~80% after prolonged exposure. In addition, it is reported that PM affects depression (40%), suicide (24%), and stress (20%)[9].

2.2. Characteristics of PM in Urban Areas

Urban PM refers to fine dust generated and active in urban areas. This includes primary particulates emitted directly from the sources and secondary particulates that are produced by chemical reactions with atmospheric substances in the urban spaces[10]. Major sources of urban PM are mobile pollutants, such as automobiles, local and household energy. In most large cities, more than 40% of the particulate matters are generated from automobiles. This is due to the large amount of secondary PM generated by NOx components of exhaust gas and direct emission from the operation of engines and tire wear[10].

The PM concentration in cities vary in a city and a small area depending on the surrounding environmental elements and urban spatial structures. Urban PM concentrations are highly correlated with urban functions, structures and components, and natural and climatic conditions[10]. Thus, in order to maximize the effects of reducing PM in urban areas, it is necessary to grasp the characteristics of urban areas.

Table 1. Major factors affecting urban PM

Factor	Contents
Urban Functions and Structure	• Function (residential, commercial, industrial, etc.), layout and shape of building
Urban Components	• Roads (walkways, driveways, intersections, etc.), materials, parks and green spaces, roadside trees, etc.
Nature and Climate	• Wind, terrain, temperature, humidity, etc.

1) Urban Function and Structure

The function and structure (layout and shape) of a city is one of the factors that greatly influence PM concentration. Areas adjacent industrial facilities are at higher risk of exposure to PM. Commercial districts and residential complexes with high population densities tend to have high concentrations of NO_x (which cause secondary PM) due to the relatively high traffic volume. The layout and shape of a building can also affect the flow of air, with the inclusion of particulate matter. In high-density areas where skyscrapers are located, PM is likely to accumulate or stagnate because the wind flow is not constant. On the other hand, fresh air can be introduced into the city in the region where wind paths are established through spatial planning.

2) Urban Components

Spatial elements that make up a city (e.g., vegetation, tunnels, intersections and road pavement) could directly and indirectly affect urban particulate matter. Green-blue infrastructures, such as neighborhood parks, buffered green spaces, roadside trees and water spaces, can play a role in suppressing and reducing particulate matter activities. This could also introduce air flow by evaporative action creating a difference in temperature in urban spaces. On the other hand, impermeable pavement or tunnels cause urban heat island phenomenon and prevent fresh air from entering the city. This accumulates particulate matter in a specific space that increases the exposure risk.

3) Nature and Climate

Urban temperatures, humidity, wind speed and direction have a direct impact on particulate matter activity. The reversal of temperature accompanied by urbanization causes air flow to stall and expose residents to high levels of particulate matter. Moreover, in areas with high humidity, water vapor particles are combined with atmospheric pollutants, such as ozone and ammonia, causing secondary PM generation in a city. The effects of natural and climatic conditions make it difficult to predict particulate matter concentrations as well as increase damage.

3. The Ways to Reduce Urban PM

In urban areas, roads are the main spaces where considerable amounts of PM are generated by exhaust gas, tire wear, etc. Therefore, it is necessary to find a way to reduce PM by dividing the urban space around the road (hot spot).

Urban space can be divided into road, open space and building [10]. This is a conceptual division of the cross-sectional area from road to block. Here, the building does not mean the interior space of the building, but the solid that constitutes the block in the urban space. Conceptually, roads are main spaces where particulate matter is generated. The PM generated in roads should be reduced in advance so that it does not spread to the space where urban activities take place. Open space and buildings are spaces in which particulate matter moves and spreads. These are spaces where residents can be exposed to particulate matter for a long time due to walking and outdoor activities. Thus, it is needed to prevent PM diffusion in open spaces and buildings.

In order to solve the urban PM problem, solution ways can be divided into 'prevention', which minimizes the impact in response to the causes of PM, and 'reduction', which minimizes the damage to the generated PM. Specifically, 'prevention' consists of legal and institutional regulations, spatial unit management, measurement, forecasting and warning in an effort to reduce the PM generation in advance at national and city levels. On the other hand, 'reduction' consists of ecological, physical and chemical approaches in an effort to control the urban structure and environment, thus minimizing the negative effects by the generated PM.

3.1. Prevention

1) Establishment and Reinforcement of Standards

Standards for action need to be established or strengthened to curb PM emissions. In 1990, Korea began to manage air pollutants separately for air quality management. PM is registered and managed as an environmental reference substance under the 「Air Conservation Act」. In addition, the 「Special Act on the Improvement of the Metropolitan Air Environment」, which is the ground law for the management of particulate matter, was established in 2003[11].

In Korea, the environmental standard for PM10 (10㎍/m^3 or less) was established in 1993. The PM2.5 criteria was introduced in 2015, much later than in the US (2006), EU (2010), Japan (2009) and China (2012). Moreover, the daily and annual averages for the PM2.5 concentrations were below those of the major countries as well as the WHO recommendations at the time. Since March 2018, the daily and annual average standards have been strengthened to 35㎍/m^3 and 15㎍/m^3, respectively. Since particulate matter has a great impact on human health, it is necessary to continue to strengthen domestic standards in consideration of international recommendations.

2) Spatial Unit Management

Spatial unit management is a way to manage the spaces where urban residents work around the roads, under the premise that urban PM emitted or generated by road movement pollutants is relatively high. There are ways to designate a zone that restricts entry of vehicles at certain times or parking.

A representative example is the German environmental zone (Umweltzonen). It was implemented since 2005 in accordance with the German Federal Environmental Pollution Act (BImSchG). As of April 2017, only vehicles with the green sticker (Euro 4) are allowed to access 55 areas in Germany[12]. This has resulted in a reduction in the share of traffic from PM10 sources in urban areas from 23% (1998) to 15% (2013)[13]. Low Emissions Zone (LEZ) is not only operating in Germany but also in other European countries, such as Italy, UK, Netherlands and Sweden. In the UK, the LEZ has been implemented since 2008. Recently, the LEZ has further been reinforced, and Ultra LEZ (ULEZ) will be introduced in 2020 in central London, which permits only the Euro 6 level. This aims to reduce PM and NOx by about 45% in road transport emissions by 2020[14].

3) Measurement and System for Forecasting and Alarming

Accurate measurement and information are very important ways to cope with emitted PM. Microclimatic conditions of the space in which people live and breathe in a city varies depending on the location and shape of buildings, and PM may be congested in a specific space. In addition, the particulate matter measurement at the top may be less accurate. This is because the PM density tends to be lower at the higher levels from the ground due to the spreading by wind. Therefore, PM concentrations in cities need to be measured and managed within the sources of emissions, in particular around roads.

Moreover, it is essential to provide and manage information on primary and secondary PM generation as well as those on the number of times exceeding environmental standards. The information should be provided in real-time at places that are easily accessible to urban residents. Moreover, it should be provided with accurate numerical values rather than ambiguous phrases, such as 'good', 'bad', 'very bad', etc.

3.2. Reduction

1) Ecological Solutions

Ecological solutions (i.e., greening in the city) are the most sustainable methods to reduce PM. Plants are basically capable of absorbing and adsorbing PM. Since the ability to absorb and adsorb PM differs depending on the plant species, it is necessary to select plants that are effective in reducing particulate matter and to make a list for them. In addition, the location, shape and structure of planting should consider the characteristics of space.

In general, the more the planting area is secured, the better it is to reduce PM. Therefore, the existing greening should be maintained and preserved. Moreover, the space for additional greening should be considered as much as possible. For example, building facades, roofs and fences can be used. Modularization and weight lightening are required for high variability and applicability of additional greening with easy and simple installation.

Urban greening needs to consider new plans and designs, or the application of facilities or equipment. However, it may be a good idea to utilize the existing infrastructure because areas that are already densely populated with elements of the city are not enough to secure new facilities or space. Green infrastructure needs to be actively utilized because its basic function contribute to the improvement of the quality of life as well as reducing urban PM.

2) Physical Solutions

Physical solutions to reduce particulate matter include filter and electrical precipitators. The filter refers to a filter medium for removing small solids in the gas or liquid phases. Fiber filters mainly used to control the PM are very effective for separating particulate contaminants from gases[15]. The principle of the filter is a combination mechanism of inertia, blocking, diffusion and gravity. It is possible to collect various types of particulate matter by manipulating the filter structure and handling capacities according to the design scale[16]. Furthermore, it can be operated under various resistance conditions and has the advantage of being cheaper.

An electrical precipitator is a device that collects PM by moving them to the surface of the collecting electrode after being charged by a corona discharge[17]. Since PM is collected by an electrostatic force, it is effective to remove particles having small diameters and has the advantage of being able to operate for a long time[18]. The principle of electrical precipitator is a combination mechanism of electric and inertial forces, and gravity. In the electric force, the most important action consists of charging of particles, movement of charged particles and collection.

3) Chemical Solutions

Chemical solutions to reduce PM include the use of photo-catalysts and CMA (calcium magnesium acetate). Photocatalyst refers to a substance that decomposes various bacteria and contaminants by promoting the catalytic reaction (oxidation-reduction) with light as an energy source[19]. In particular, TiO_2 can be used as the most common photocatalyst because it can be used semi-permanently, and it can oxidize all organic materials and decompose them into CO_2 and water. The TiO_2 may be coated on the road or surface of buildings and infrastructures to remove PM precursors, such as NOx. Recently, photocatalysts have been introduced to reduce PM in crosswalks, pedestrian sidewalk blocks, subway entrances, apartment walls and tunnels, etc.[20].

CMA is widely used as an environmentally friendly antacid to prevent freezing of road surfaces in winter[21]. CMA was recently highlighted as an economical chemical binder that has an excellent effect of adsorbing PM[22]. Moreover, it is biodegradable, non-corrosive and harmless, so it does not affect the ecology and human health. Various projects are under way to reduce PM in cities in EU countries, such as Austria, Italy and Germany. In the near future, it is expected that CMA could be applied to diverse urban spaces to effectively reduce particulate matter and prevent road freezing.

4. Case Analysis

4.1. Outlines

In this chapter, the case analysis was conducted focusing on the ‘reduction’ perspective to solve the urban PM problem. Five cases were selected with literature or internet data, and analyzed based on method, urban space, application area, applied technology and features, and expected effectiveness. In particular, the expected effectiveness was collected according to the performance data of cases that relevant organizations presented.

In the case of ecological methods, they were selected by subdividing the application location of various plants (i.e., ‘City tree’ as a mobile system case, ‘Enka®-Moss’ as a flat surface greening case, and ‘Via Verde’ as a vertical greening case). ‘Filter cube Ⅲ’ was selected as the case for physical solution and ‘Torre de Especialidades’ was chosen as that for chemical solution, respectively.

4.2. Cases for Ecological, Physical, and Chemical Solutions

1) Ecological Solutions

The ecological solutions selected in this study aimed to reduce particulate matter by using plants with various techniques. All three cases are applicable to roads, which are ‘hot spots’ of PM. City tree has the advantages of mobile systems. Therefore, it can also be applied to open spaces, such as parks and plazas. Enka®-Moss is known as a pilot project based on the proven results of moss absorption and adsorption effects. The case of ‘Via Verde’, designed to utilize reclaimed rainwater, is an additional idea that increases the sustainability of ecological measures.

It was confirmed that ivy or moss was selected for all the cases. This is because they are classified as plants having excellent ability to adsorb and adsorb particulate matter in Europe. In addition, in two cases except Enka®-Moss, plant pockets were developed or pots were used to make room for plants to absorb their basic nutrients and root. The system was automated, monitored and remotely controlled.

City tree is meaningful in that it combines the functions of street furniture to secure a new greening area. The other two cases are significant in that they have obtained additional greening area from existing infrastructure.

2) Physical Solutions

A representative case of the physical solution is the 'Filter Cubes Ⅲ' pilot project. This is a fixed standalone installation unlike the movable 'City tree'. It is planned to be applied adjacent to roads where NOx or particulate matters are highly generated.

'Filter Cubes Ⅲ' is 3.6m high and consists of three cubes. It is equipped with a PM collecting filter and energy efficient fans. In addition, the control unit can adjust the operation of the filter according to the real-time air quality. Integrated sensors can record atmospheric and weather data, and upload it to cloud services for analysis[28].

3) Chemical Solutions

A representative case of the chemical solution is the 'Torre de Especialidades' hospital using TiO_2 on the facade of a building that forms a vertical plane in an urban space.

The tile on the building's surface is coated with TiO_2, which uses ultraviolet light to break down pollutants into non-toxic chemicals (e.g., CO_2 and water)[29][30]. The facade of the building is designed in a honeycomb geometric tile network structure and applied in the form of a double skin to make a higher surface area (2,500㎡)[31]. This structure doubles the surface area compared to the planar form[31].

5. Conclusion

Until now, in order to cope with the particulate matter problem, it has been mainly taken by the macroscopic approach at the government level. This study emphasizes the need for a microscopic approach to mitigate PM generated and active in the spaces where urban residents live from the perspective of urban planning and design. Therefore, we identified the characteristics of PM generated in cities from the perspective of urban planning and design. In addition, we attempted to derive the possibility and implications for the reduction of urban PM, based on the case analysis.

It has been revealed that the major factors affecting PM in cities are urban function, structure and components, and nature and climate. To cope with urban particulate matter, the space could be divided into 'road', a hotspot for generating PM, and 'open space' and 'building', where particulate matter moves and spreads. The methods to solve the urban PM problem were classified as 'prevention' and 'reduction.' The case analysis was conducted to suggest specific solutions focusing on 'reduction'. PM is the result of a combination of various factors, and it is difficult to clearly identify the causes that influence PM generation and movement. Accordingly, foreign cities were attempting to gradually solve PM problems in terms of urban planning and design by implementing pilot projects, based on R&D results from various sectors.

For the urban planning and design approach, it is very important to select the technology and technique suitable for the space characteristics and to design it in the appropriate size and

Table 2. Case analysis

Project	Via Verde	Enka®-Moss	City tree	Filter cube Ⅲ	Torre de Especialidades
Location	Mexico city, Mexico	Bonn, Germany	Dresden, Germany	Stuttgart, Germany	Mexico city, Mexico
Method	Ecological	Ecological	Ecological	Physical	Chemical
Urban space	Road	Road	Road and Open space	Road	Building
Application year	2017	2007	2014	2018	2013
Application area	Underpass where the overpass and normal roads are overlapped	Median strip of highway	Parks and plazas showing high concentrations of PM	Road junction where exceeds NOx limit values	Building facade
Applied technology and features	· Vertical greening (ivy, foxtail and aralia etc.) on 700~1,000 of concrete columns (about 60,000㎡) · Integration of planting, remote monitoring and automatic irrigation	· Flat surface greening · Moss planting	· Mobile green wall (height: 4m; width: 3m) · Integration of planting, IoT, and automatic irrigation	· Column filter installation · PM free filter, energy efficient fan, and sensor for air and weather data collection	· TiO_2 coated tiles · High surface area with double skin (2,500㎡ area)
Expected effectiveness	· Filtering of toxic gases (27,000ton/yr) · Capturing of PM (about 5,000kg) · Removal of heavy metals (about 10,000kg)	· Removal of PM by absorbing 13~20g/m² per day	· Reduction of NOx by 10~15% · Reduction of PM by 20~25%	· Reduction of PM by 10~30%	· Purification of air pollutants emitted from 1,000 of vehicles
References	[23], [24]	[25], [26]	[27]	[28]	[29], [30], [31]

shape. In addition, the solution should be derived through the linkage of diverse sectors, as there are various causes of urban PM.

In particular, ecological solutions, such as green infrastructure, contribute in the improvement of the quality of life, including PM reduction as well as greenhouse gas reduction, ecosystem services, climate adaptation and crisis management, education and culture, and health and activities. Therefore, the active use of ecological solutions is expected to be very advantageous to solve urban PM problems in terms of urban sustainability.

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