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Development of manufacturing method of simulated stormwater for indoor performance testing of nonpoint source pollution management facilities

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ABSTRACT

Performance evaluation of nonpoint source pollution management facilities prior to installation on site can provide consumers with guidelines on the ability of pollution removal and maintenance cost of facilities. Various test methods for demonstrating the performance of nonpoint source pollution management facilities exist, but in the case of standard test water for indoor testing, it is necessary to develop a test water manufacturing method that takes into account the characteristics of the stormwater runoff. In this study, we investigated and analyzed the particulate matter of the stormwater runoff flowing into the nonpoint source pollution management facility. Differences according to land use characteristics were analyzed for particle size, specific gravity, and organic matter content. Based on these findings, standards for manufacturing simulated stormwater were presented. The results showed that it is reasonable to simulate the particle size within a maximum of 190 μm, and specific gravity and organic matter content differed depending on the characteristics of land use. Although the results of this study were applied in Korea, this method can be applied in a variety of countries because it presents a method for selecting the criteria for soils required for manufacturing stormwater when evaluating nonpoint source pollution management facilities.

Keywords: Testing method; Simulated stormwater; Particle size distribution; Specific gravity; Organic contents

1. Introduction

Stormwater Management Technology (SMT) for reducing the impact of aquatic environment is undergoing continuous development within environmental industries [1–3]. In case of Korea, the United States (US), and Germany, SMTs are installed on site; thus, demonstrating the performance of water quality improvement efficiency is required. The background for the introduction of SMT demonstration are to contribute the improvement of water quality of rivers or reservoirs from nonpoint source (NPS) pollution by installing more than a certain level of stormwater technology on site and to support responsible use of stormwater technologies.

In Washington State (US), performance tests for nonpoint source pollution removal facilities are conducted through the Technology Assessment Protocol-Ecology (TAPE) [4] and the Technology Acceptance Reciprocity Partnership (TARP) in the state of California, Massachusetts, Maryland, New Jersey, Pennsylvania, and Virginia [5]. The Wisconsin Department of Natural Resources (DNR) also requires a performance test report for installation of a stormwater runoff sediment treatment facility. In Germany, decentralized Sustainable Urban Drainage System (SUDS) technology certification for stormwater runoff treatment is carried out by Deutsches Institut für Bautechnik (DIBt) [6]. In case of green SUDS, it is possible to install an on-site system without certification, but in case of technical SUDS, performance testing results are required for on-site installation.

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The Ministry of Environment, Korea has recently introduced a performance testing system for stormwater management technologies and treatment facilities through the revision of the Water Environment Protection Act, and is developing and improving test methods. Currently, the indoor test method applied in Korea is producing simulated stormwater and testing the Suspended Solid (SS) removal efficiency and head loss considering only particulate matter distribution and SS concentration. According to this system, the distribution range of particulate matter is 70%–80% of the total volume under 64 μm and 20%–30% of the total volume under 200 μm. The SS concentration ranges from 150 to 350 mg/L. This method is described in the Non-Point Pollution Management Facility Performance Test manual of the Ministry of the Environment (NPPT manual), Korea [7].

In the case of testing stormwater management facilities, TAPE and Wisconsin DNR in USA, and DIBt in Germany use silica [4–6]. Silica for the performance test has already been used to demonstrate the SMT. Such demonstration can be applicable to testing on land-based facilities that reduce NPS pollution from the surface. However, it may not be suitable for demonstration of stormwater management facilities buried underground in which stormwater runoff flows through storm drains because the particles in the stormwater contain many kinds of organics and nutrients. Particle size distribution and specific gravity of the particles in stormwater can significantly affect the removal performance of stormwater management facility [8–10]. Particularly, the specific gravity of particulate matter in stormwater can be affected by the content of organic matter, and the content of organic matter can be affected by land use characteristics in the drainage area. This finding indicates that for the manufacture of simulated stormwater for the test of SMT, it is necessary to select or manufacture the soil or materials required for simulated stormwater manufacturing by analyzing the characteristics of the stormwater runoff discharged from the drainage area. Therefore, the objectives of this study were to determine the manufacturing criteria of simulated stormwater considering the stormwater runoff characteristics from the urban drainage area.

2. Materials and methods

2.1. Field experiment and particles collection

Eight field experiments were conducted between July and September 2019 (Table 1). Sampling sites were selected in accordance with different land uses such as road, industrial, and residential areas in Gwangju, Yeongam, and Gangjin, Korea. More than 300 L of stormwater for gathering particles were collected at the inlet of technical best management practices (BMP) device installed at the outlet of stormwater drainage chamber. The ranges of rainfall depth ranged from 15.0 to 104.0 mm and antecedent dry days (ADDs) ranged from 1 to 8 d. Rainfall intensities ranged from 1.25 to 6.93. The reason for monitoring various rainfall events was to determine the physical properties of the soil after considering the stormwater runoff from various rainfall.

To collect particles in stormwater, all collected samples were settled for 48 h at room temperature. The supernatant was then collected further through 1.2 μm glass fiber filter paper. The precipitated sediments and the filtered particulate matters were heated at 110°C for 6 h and analyzed for particle size distribution, true specific gravity, and soil organic matter content.

2.2. Selection of representative factors affecting the simulated stormwater

Particle size distribution, specific gravity, and organic matter were selected to manufacture the stormwater. Particle size distribution is widely recognized as the characteristics of the sources from urban runoff [11–13]. In addition, the sizes of particulate matter are related to the distribution of organic matter, indicating that it is related to the specific gravity of soil [14]. In this regard, many studies have revealed that suspended solids, which have organic-rich characteristics that tend to have relatively low specific gravity [15,16]. Specific gravity is highly correlated with the content of organic matter in the soil. In the relationship between specific gravity and organic matter, the higher the organic content, the lower the specific gravity. That is, since the soil deposited on the road may contain a large amount of organic matter, it is necessary to consider the content of the organic matter together with specific gravity when producing simulated stormwater.

2.3. Analysis of particle size distribution

Particle size distribution in stormwater particles were analyzed using the QICPIC particle size analyzer (LIXELL, QICPIC, produced by Sympatec GmbH, Clausthal-Zellerfeld, Germany). This instrument can measure particles from 1 to 2,000 μm; its main method of particle size analysis is laser diffraction. The laser diffraction method measures particle distribution by measuring the variation in the light scattered angle when the laser beam passes through the water sample. Large particles scatter light at smaller angle, while small particles scatter light at larger angles. The particle size distribution measured in this way results in a volume equivalent sphere diameter.

2.4. Measuring the specific gravity

The true specific gravity of the collected sediments from stormwater were measured using an instrument called as AccuPyc II 1340 (produced by Micromeritics, GA, USA). ASTM D5550-14 is a standard test method for measuring specific gravity of soil solid using a gas pycnometer to measure the true specific gravity of stormwater sediments. All samples were dried for 3 h at 110°C in the dry oven and allowed to cool for 30 min in a desiccator. In order to measure the specific gravity of the pre-treated samples, helium was used as the inert gas, and the temperature was maintained at 25°C ± 2°C during measurement. The gas injection flow rate was 0.005 psig/min, and the specific gravity was calculated by measuring the pressure change due to the volume reduction of the adsorbed gas by adsorbing the sample to be measured with helium or nitrogen gas close to the ideal gas to calculate the volume and true density of the sample.

2.5. Measuring soil organic matter contents

To measure the organic matter contents of the stormwater sediments, the loss on ignition (LOI) method was used in this study. LOI is widely used to measure the organic contents in soil or sediments [17,18]. To burn organic matter contained in all samples, an electric muffle furnace (Model: FTMF-702, produced by Vision Scientific Co., Ltd., Republic of Korea) was used. All sediment samples were exposed to high temperature (550°C) for 2 h due to the prevention of the overestimation for organic matter [19]. After drying all samples, the weights were obtained by electronic scale.

The LOI is calculated according to Eq. (1):

$$\mathrm{LOI}_{550} = \frac{\mathrm{DW}_{105} - \mathrm{DW}_{550}}{\mathrm{DW}_{105}} \times 100 \tag{1}$$

in which LOI_{550} represents LOI at 550°C, DW_{105} represents the dry weight of each sample before the combustion and DW_{550} represents the dry weight of each sample after heating at 550°C.

2.6. Analysis of mineral components in samples

To identify the minerals composition of particulate matters contained in the stormwater, X-ray fluorescence (XRF) analysis was carried out on eight samples using XRF-1800 (Shimadzu, Japan). After the particulate matter was collected from stormwater and dried, the powdery state of particulate matter was used to contain these powdered samples and molded with a press. XRF analysis was performed on the samples subject to this pretreatment.

3. Results and discussion

3.1. Particle size distribution of particles in stormwater

Fig. 1 shows the particle size distributions (PSD) for nine field tests. PSD D_{90}, D_{50}, and D_{10} correspond to 90%, 50%, and 10% of particulate matter. D_{90}, D_{50}, and D_{10} mean that the portion of particles with diameters smaller than the value are 90%, 50%, and 10%, respectively. As a result of particle size analysis based on the samples obtained through a total of nine field tests, there was a difference based on rainfall event and land uses, but the maximum particle size was measured to be 190 μm. As shown in Fig. 1, D_{90}, D_{50}, and D_{10} were 130, 47, and 19 μm, respectively. After considering the standard deviation for each particle size, the upper and lower limits were in the range of 100 to 150 μm for D_{90}, 40 to 55 μm for D_{50}, and 16 to 21 μm for D_{10}. The range of this particle size is similar to that of the current NPPT manual, and the maximum particle size was 10 μm smaller than the current particle size. In the Wisconsin DNR, soil particles are composed of up to 250 μm, and soil that was 60 μm larger than the results in this study was used for the production of test water. The difference in particle size was based on initial rainfall runoff simulation was the surface runoff in two cases, whereas in this study, the runoff was simulated to a nonpoint pollution reduction facility. Therefore, the size of the particle may be smaller than that of simulating surface runoff. That is, in order to simulate the stormwater, it is necessary to manufacture simulated stormwater within the range of the particle sizes mentioned above. However, because the characteristics of stormwater runoff can be different for each drainage area, it is necessary to estimate the range of particle size distribution through additional field tests in the case of nonpoint pollution management facilities for specific drainage areas.

3.2. Specific gravity (Gs) of particles in stormwater

The average specific gravity value through analysis of eight samples was 2.48 on average and ranged from a minimum of 2.2 to a maximum of 2.62. As shown in Table 2, the specific gravity values of particulate matters contained in stormwater was different according to the characteristics of land use. Daebul Industrial Complex was built in 1988 with shipbuilding equipment and steel-related companies and shows the characteristics of industrial structures mainly composed of iron. The results of the XRF analysis demonstrated that the Fe_2O_3 content of particulate matter contained in the stormwater in Daebul Industrial Complex was the highest compared to other regions (Fig. 2). Due to these results, the specific gravity of Daebul Industrial Complex was relatively high at 2.62. Cheomdan Industrial Complex is an industrial complex that was built in 1990 and consists of companies related to electrical and electronics and machinery. Although it had a relatively low weight compared to Daebul Industrial Complex, it had a high level of weight compared to other land use areas (Fig. 2). Hanam Industrial Complex consists of companies in the chemical and mechanical industries. As a result of analyzing the specific gravity by collecting the particles from stormwater, it showed the lowest mean value of 2.53 among the three industrial complexes. Gangjin Industrial Complex, on the other hand, is a relatively new industrial complex that was completed in 2012. The site of the empty factory was covered with loess with high organic content, resulting in the loss of loess during rainfall, which resulted in an average specific gravity of 2.2. The residential and urban traffic areas had a specific gravity value of 2.5, which was somewhat lower than the industrial complex.

Although there was a difference in specific gravity for each type of land use, the average specific gravity of the eight samples was 2.49, and the standard deviation was 0.16. Considering these values, it may be reasonable to use soil with a specific gravity of 2.33 to 2.65 for manufacturing simulated stormwater.

3.3. Organic matter contents of particles in stormwater

The results of the LOI experiment conducted on the particulate matter collected to measure the organic matter content showed an average organic matter content of 7.55% ± 0.92%. Gangjin Industrial Complex showed a high organic content of 9.2% due to the effect of loess outflow, while Daebul Industrial Complex showed 7.7%. The place with the lowest organic content was Hanam Industrial Complex with 5.9%. Pearson's correlation showed a negative correlation (−0.694; $p < 0.05$) between organic matter and specific gravity. (In other words, the higher the organic content, the lower the specific gravity). This finding

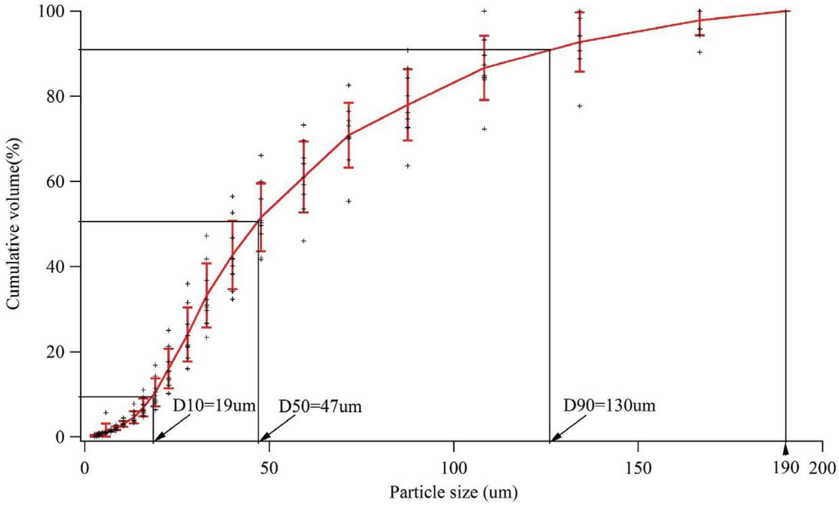

Fig. 1. Particle size distributions for eight samples from stormwater in different types of land use. D_{10}, D_{50}, and D_{90} indicates that the portion of particles with diameters smaller than the value are 90%, 50%, and 10%, respectively.

Table 1
Features of sampling sites and rainfall events for eight field studies

Sampling date	Site	Land use	Rainfall depth (mm)	Rainfall duration (h)	Rainfall intensity (mm/h)	Antecedent dry days (d)
July 27, 2019	Shandong bridge	Road	44.5	21	2.12	1
August 12, 2019	Hanam	Industrial area	35	18	1.94	3
August 21, 2019	Hanam	Industrial area	104	15	6.93	8
August 21, 2019	Cheomdan	Industrial area	104	15	6.93	8
August 21, 2019	Sangmu	Residential area	27.5	19	1.45	8
August 27, 2019	Sangmu	Residential area	15	12	1.25	5
August 27, 2019	Gangjin	Industrial area	33.5	11	3.05	5
September 3, 2019	Yeongam	Industrial area	34.5	13	2.65	1

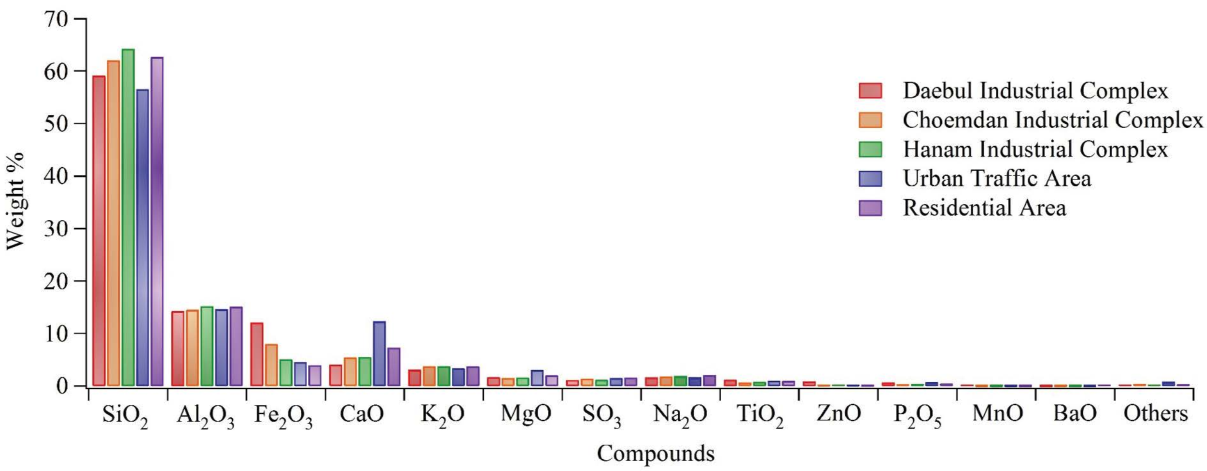

Fig. 2. Mineral compounds of particles collected from stormwater by the X-ray fluorescence spectroscopy. Each color bar represents a monitoring point, and the sum of the weights of each compound is 100%.

Table 2
Specific gravity values for particles of the stormwater in the industrial complex and traffic and residential areas

Sampling date	Site	Mean	Standard deviation	Coefficient of variation	Run		
					1	2	3
July 27, 2019	Urban traffic area	2.5316	0.0009	0.04	2.5309	2.5313	2.5326
August 12, 2019	Hanam Industrial Complex	2.5548	0.0005	0.02	2.5543	2.5550	2.5552
August 21, 2019	Hanam Industrial Complex	2.5016	0.0002	0.01	2.5014	2.5016	2.5017
August 21, 2019	Cheomdan Industrial Complex	2.6185	0.0018	0.07	2.6168	2.6184	2.6203
August 21, 2019	Residential area	2.5910	0.0009	0.03	2.5902	2.5910	2.5919
August 27, 2019	Residential area	2.2756	0.0005	0.02	2.2752	2.2754	2.2762
August 27, 2019	Gangjin Industrial Complex	2.1969	0.0033	0.15	2.1935	2.1970	2.2001
September 3, 2019	Daebul Industrial Complex	2.6152	0.0003	0.01	2.6149	2.6152	2.6155

shows results similar to those from several previous studies. Therefore, considering the mean and standard deviation, it may be reasonable to select soils with an organic content range of 6.63–8.47 when manufacturing simulated stormwater.

4. Conclusions

Based on these results and the discussions, we present several conclusions:

- For indoor testing of nonpoint source pollution management facilities, the stormwater should be simulated, and manufacturing should derive the characteristics required for manufacturing through analysis of stormwater collected in the field.
- The particle size ranges of the particulate matter derived through this experiment were 100–150 μm for D_{90}, 40–55 μm for D_{50}, and 16–21 μm for D_{10}.
- The specific gravity range should be 2.33–2.65, and the organic content range should preferably be 6.63–8.47.
- These results are the results of experiments in urban areas, including industrial, roads, and residential areas in Korea, and different results may be derived depending on the characteristics of climate, land use, and bedrock.

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