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On-site Evaluation of NOx Removal Efficiency on Photocatalytic Pavements and Analysis of Environmental Variables

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ABSTRACT

The objective of this study was to identify the correlation between NOx concentration and envi-ronmental variables at photocatalytic concrete pavements containing TiO_2 by direct monitoring in field. In order to confirm the NOx concentration according to various environmental variables of the photocatalytic concrete pavements, humidity, temperature, light intensity, and NOx concen-tration were measured continuously for 3 days at photocatalytic pavement, concrete pavement, and atmospheric conditions, respectively. We identified the NOx concentration at all measurement sites and calcu-lated the NOx removal efficiency of the photocatalytic pavements. As a result, the NOx concentration of the photocatalytic pavement was 0.086 ppm on the 1st day, 0.125 ppm on the 2nd day, and 0.106 ppm on the 3rd day, which was mostly lower than that of the concrete pavement and the atmospheric conditions. When the NOx removal efficiency of the photocatalytic pavement on days 1–3 was examined by time, the NOx removal efficiency was evidently higher in the order of 0–6 h > 18–24 h or 6–12 h > 12–18 h for all three measurement days. In addition, the relationship between NOx removal ef-ficiency and environmental variables was analyzed. As a result of corre-lation analysis between NOx removal efficiency and environmental variables of the site, relative hu-midity showed a positive (+) correlation, while temperature and light intensity showed a negative (-) correlation. Based on our results, we summarize some considerations for evaluating the NOx removal performance of photocatalytic pavements applied in the field.

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INTRODUCTION

Airborne particulate matter (PM) is a main pollutant of environmental concern (Kim et al., 2015; Valavanidis et al., 2008) and plays an important role in human health because of its adverse effect (Choi et al., 2012). Especially, long-term exposure to PM was associated with the increased incidence of respiratory and cardiovascular disease (Dockery et al., 1993; Du et al., 2016; Schwartz et al., 2002). The International Agency for Research on Cancer (IARC) has classified PM in outdoor air pollution as carcinogenic to humans, based on sufficient evidence of carcinogenicity in humans (Loomis et al., 2014). As public interest in health and safety grows, Korean government has established the air quality standards of Fine particulate matter ($PM_{2.5}$) in 2015 to control. In addition, strengthened the standard of daily average of $PM_{2.5}$ from 50 $\mu g/m^3$ to 35 $\mu g/m^3$, annual average from 25 $\mu g/m^3$ to 15 $\mu g/m^3$ in 2018, along with the environmental

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quality standards of United States and Japan.

$PM_{2.5}$ is generated through chemical reactions with various air pollutants, such as nitrogen oxide (NOx), sulfur oxide (SOx), Volatile organic compound (VOCs), and ammonia (NH_3). Photocatalysts are considered to inhibit the generation of $PM_{2.5}$ by removing pollutants in advance (Yue et al., 2020). Based on the application of this function, photocatalytic products have recently been applied to various overseas sites, including road and road facilities (Bocci et al., 2016; Chen and Chu, 2011; Wang et al., 2017), pavements (Active, 2009; Ballari and Brouwers, 2013; Boonen and Beeldens, 2014; Folli et al., 2015; Hassan et al., 2013), tunnels (Gallus et al., 2015; Guerrini, 2012) and building exterior walls (Maggos et al., 2008). In South Korea, NOx has been decomposed using construction materials or photocatalytic coatings containing TiO_2 photocatalysts on roads to reduce PM. In particular, photocatalytic coating is being applied onto the exterior walls of apartments, or photocatalytic pavements are installed.

The NOx removal efficiency of photocatalytic products should be quantitatively evaluated (Beeldens, 2008; Hassan et al., 2013; Sikkema, 2013). However, such evaluations are mostly performed by setting and limiting certain conditions (e.g., radiation source, light intensity, temperature, humidity, flow rate, and flow velocity) in laboratories, considering the difficulty in measuring the accurate efficiency in field site due to effect of environmental variables such as changing NOx concentration, temperature, humidity, and light intensity (Bocci et al., 2016; Wang et al., 2017). The NOx removal performance can be evaluated in laboratories using photoreactors after collecting specimens from the field (Wang et al., 2017; Yue et al., 2020), or it can be indirectly evaluated by measuring the byproducts generated during the photoreaction process (Hassan et al., 2013). In addition, when the NOx removal efficiency is directly evaluated in the field, the NOx concentration is measured using a NOx analyzer within a short period (Beeldens, 2008) or a mobile photoreactor (Boonen and Beeldens, 2014). Thus, NOx reduction performance of photocatalytic products is evaluated typically using various methods because of the absence of a standardized evaluation method that can directly measure in field.

Therefore, this study aims to comprehensively evaluate the NOx concentration and removal efficiency of photocatalytic pavements by continuously monitoring environmental variables that may affect NOx removal efficiency by directly measuring the NOx concentration at a photocatalytic pavement site. In addition, based on the analysis of the characteristics of various environmental variables through continuous monitoring and their correlations with NOx removal efficiency, an attempt is made to summarize the factors that should be considered for the quantitative verification of the NOx removal performance of photocatalytic products that are applied in the field.

MATERIAL AND METHODS

A site in Seoul with photocatalytic pavements was selected as the target area to identify the characteristics of environmental variables, including NOx concentration. Table 1 and Figure 1 present detailed information about on-site measurements.

Environmental variables were measured at the following three sites: a site with photocatalytic pavement, a site with concrete pavement, and a site with atmospheric conditions. Measurements were performed at sites with photocatalytic and concrete pavements to examine the variations in environmental variables with the presence or absence of photocatalysts; measurements were conducted at sites with atmospheric conditions to identify the atmospheric condition of the target area. Among the sites where measurements were possible, those that were less affected by vehicle traffic and walking pedestrians were selected as the measurement sites. The three measurement sites were located within a radius of 5 m to minimize the influence of different measurement locations.

Among the factors that affect photocatalytic activity, the initial NOx concentration,

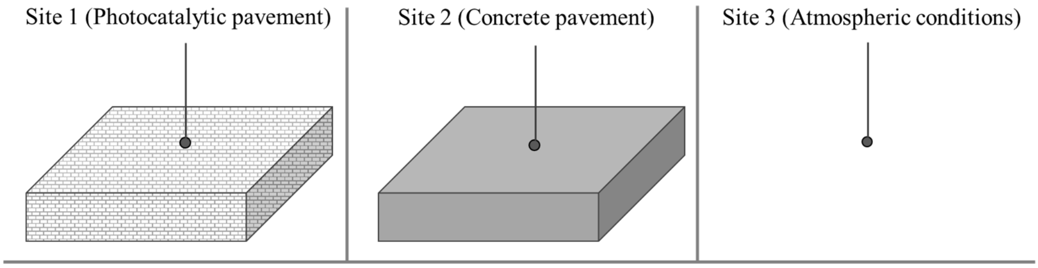


Fig. 1. Schematic of measurement site in field.

Table 1. Information about on-site measurements.

Measurements site	Monitoring time	Measured Parameters
Site 1: Photocatalytic pavement Site 2: Concrete pavement Site 3: Atmospheric conditions	24 h	NOx concentration, Temperature, Humidity, Light intensity

temperature, humidity, and light intensity were selected as measurement environmental variables (Chen et al., 2012; Guo et al., 2017; Maggos et al., 2007; Nguyen et al., 2018).

For the continuous monitoring of NOx concentration in the atmosphere, the NOx concentration was measured using Serinus 40 (ECOTECH, Australia) and 200E (Teledyne, USA) based on the chemiluminescence measurement method. The Tygon tube connected to the NOx analyzer was installed in contact with the pavement surface. According to a previous study, there was no significant difference in NOx concentration depending on the measurement position when NOx measurement positions were set to 30 and 100 cm (Sikkema, 2013). NOx concentration was monitored by keeping the Tygon tube in maximum contact with the pavement surface to minimize external influence. In addition, the temperature, humidity, and light intensity were measured by selecting representative points within a radius of 5 m from the NOx analysis point. SK-L200THIIa (SATO, Japan) was used for the continuous monitoring of temperature and humidity, and HD2102.2 (Delta OHM, Italy) was used for measuring the light intensity.

The NOx removal efficiency at the photocatalytic pavement application site was identified by calculating the removal efficiency using the NOx concentrations on the photocatalytic and concrete pavements. The calculation formula used in a previous study was used (Dylla et al., 2010).

$$\text{NOx removal efficiency}(\%) = \frac{\text{NOx conc. of Concrete pavement} - \text{NOx conc. of Photocatalytic pavement}}{\text{NOx conc. of Concrete pavement}} \times 100 \qquad (1)$$

The average NOx removal efficiency was analyzed by dividing a day by a 6-h unit to examine the difference in the NOx removal efficiency of the photocatalytic pavement depending on the presence or absence of light.

RESULT AND DISCUSSION

The NOx concentration was measured at three measurement sites comprising photocatalytic pavement (site 1), concrete pavement (site 2), and atmospheric conditions (site 3) on days

1–3 (November 24 to 26), 2020. The measurement results of average NOx concentration are presented in Figure 2 and Table 2.

Comparing the average NOx concentrations at each site for each measurement day (days 1–3), the concrete pavement exhibited the highest average value, followed by the photocatalytic pavement and atmospheric conditions. Over the three measurement days, the average NOx concentrations for the photocatalytic pavement were 0.086, 0.125, and 0.106 ppm on days 1, 2, and 3, respectively, resulting in a total average of 0.106 ppm. The average NOx concentrations for the concrete pavement were 0.101, 0.148, and 0.128 ppm, on days 1, 2, and 3, respectively, resulting in a total average of 0.126 ppm. For the atmospheric conditions, the average NOx concentrations were 0.088, 0.125, and 0.102 ppm, on days 1, 2, and 3, respectively, resulting in a total average of 0.105 ppm. Figure 2 shows that the NOx concentrations ranged from 0–0.4 ppm for sites one to three, and some outliers were observed. The maximum NOx concentrations were 1.020 ppm for the photocatalytic pavement (site 1), 1.284 ppm for the concrete pavement (site 2), and 1.813 ppm for the atmospheric conditions (site 3), showing that the maximum value exceeded 1 ppm for all three measurement sites.

NOx concentration values were summarized with respect to time to examine the variations in NOx concentration depending on the presence or absence of light (Table 2). The analysis of NOx concentration on the photocatalytic pavement (site 1) with respect to time revealed that there was no significant reduction in NOx concentration during the daytime when photoreactions could easily occur. First, on day 3, the average NOx concentration on the photocatalytic pavement was the lowest (0.073 ppm) in the 12–18 h period when light was present and highest (0.132 ppm) in the 18–24 h period when light was absent. However, on day 1, the average NOx concentration was lowest (0.052 ppm) in the early morning period (0–6 h) when photoreactions barely occurred due to insufficient light. Similarly, the lowest NOx concentration was also measured in the early

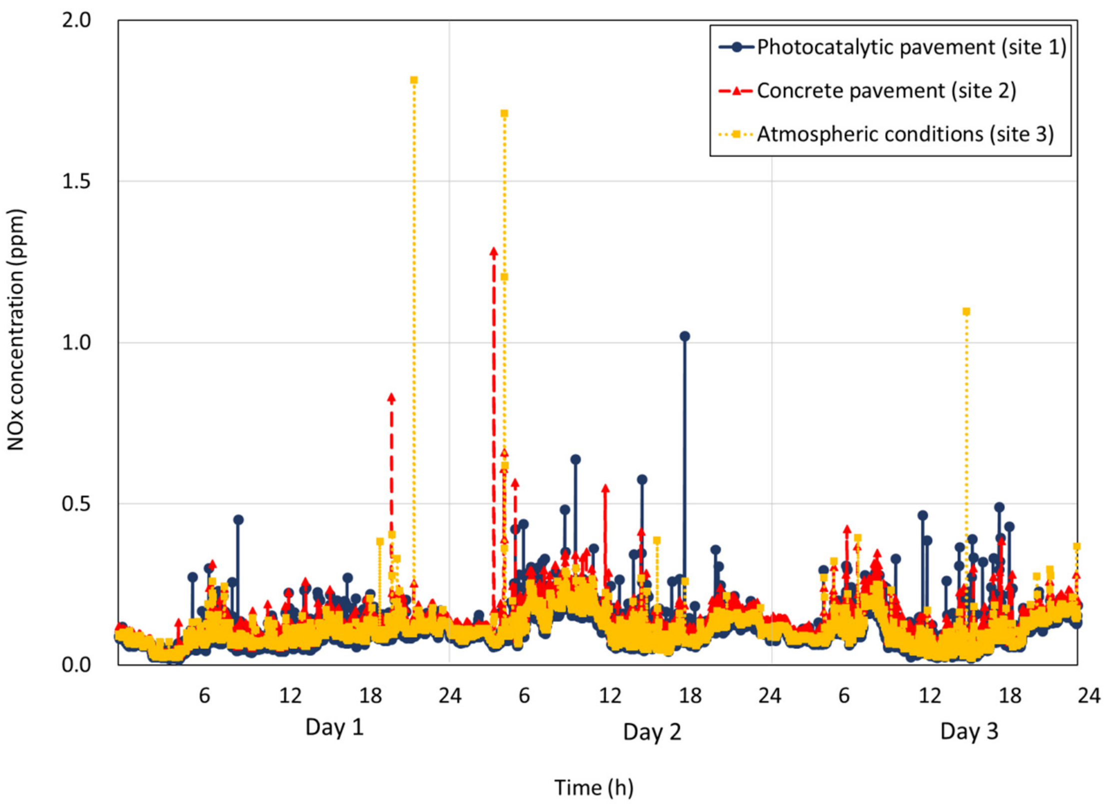


Fig. 2. Real-time monitoring of NOx concentrations at each site.

Table 2. Summary of NOx concentrations measured at each site.

Site	Type	Day	NOx conc. (ppm)	Time (h)				Total
				0–6	6–12	12–18	18-24	
Site 1	Photocatalytic pavement	Day 1	Avg	0.052	0.084	0.094	0.112	0.086
			Range	0.017–0.271	0.038–0.452	0.042–0.271	0.063–0.219	0.017–0.452
		Day 2	Avg	0.094	0.185	0.098	0.124	0.125
			Range	0.056–0.422	0.087–0.639	0.042–0.575	0.055–1.020	0.042–1.020
		Day 3	Avg	0.092	0.126	0.073	0.132	0.106
			Range	0.063–0.293	0.025–0.329	0.020–0.465	0.055–0.490	0.020–0.490
Site 2	Concrete pavement	Day 1	Avg	0.067	0.096	0.105	0.135	0.101
			Range	0.029–0.131	0.055–0.313	0.054–0.259	0.086–0.831	0.029–0.831
		Day 2	Avg	0.127	0.211	0.110	0.146	0.148
			Range	0.078–1.284	0.117–0.349	0.055–0.549	0.079–0.240	0.055–1.284
		Day 3	Avg	0.123	0.151	0.079	0.158	0.128
			Range	0.092–0.303	0.051–0.422	0.038–0.299	0.072–0.384	0.038–0.422
Site 3	Atmospheric conditions	Day 1	Avg	0.059	0.085	0.090	0.120	0.088
			Range	0.022–0.134	0.055–0.258	0.053–0.171	0.074–1.813	0.022–1.813
		Day 2	Avg	0.110	0.182	0.091	0.119	0.125
			Range	0.062–1.711	0.066–0.300	0.040–0.388	0.059–0.259	0.040–1.711
		Day 3	Avg	0.098	0.118	0.062	0.132	0.102
			Range	0.068–0.320	0.041–0.394	0.020–1.096	0.053–0.368	0.020–1.096

morning hours (0–6 h) on day 2. Contrastingly, the highest average NOx concentration (0.185 ppm) was recorded during the morning period (6–12 h) when active photoreactions may easily occur due to the presence of light. Therefore, there were limitations in deriving consistent results regarding the increase and decrease in NOx concentration on the photocatalytic pavement depending on the presence or absence of light.

The analysis of average NOx concentrations at each site on the day of measurement revealed that the photocatalytic pavement exhibited the lowest average NOx concentration in all periods, except for the 12–18 h period on day 1 (Table 2). However, the photocatalytic pavement exhibited the lowest average NOx concentration for the 0–6h periods on day 2 and day 3. This confirmed that the photocatalytic pavement did not exhibit the lowest NOx concentration value for overall measurement day (day 1–3) consistently.

According to previous studies, the NOx removal efficiency of photocatalytic pavement was higher than that of concrete pavement in laboratory measurements, but the NOx removal efficiency of concrete pavement was higher than that of photocatalytic pavement in field measurement (Beeldens, 2008; Sikkema, 2013).

To examine the NOx reduction effect of the photocatalytic pavement, the NOx removal efficiency by time was calculated using the difference in NOx concentration between the photocatalytic (site 1) and concrete pavements (site 2). The results are shown in Figure 3. When the NOx reduction effect was examined based on the NOx concentration measurements on days 1–3, the average NOx removal efficiency was found to be 14.56%, 15.21%, and 17.28%, respectively (day 1: 10.80–15.21%, day 2: 10.02–22.26%, and day 3: 11.21–25.48% range). For all

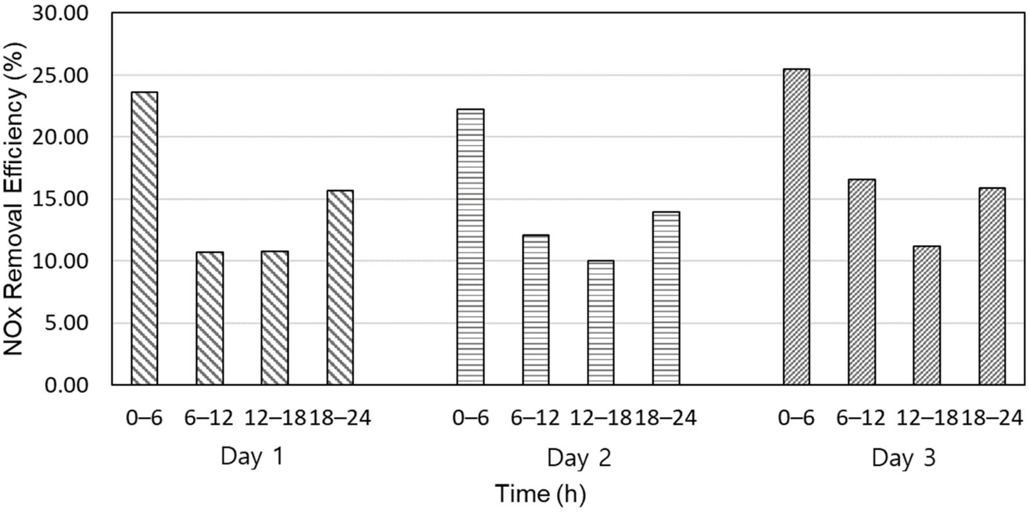


Fig. 3. Results of NOx removal efficiency of photocatalytic blocks by day.

three measurement days, the average NOx removal efficiency was <20%.

According to a previous study, the light conditions including radiation source (Guo et al., 2017; Hüsken et al., 2009; Yu and Brouwers, 2009) and light intensity (de Melo and Trichês, 2012; Guo et al., 2017; Hüsken et al., 2009; Nguyen et al., 2018; Yu and Brouwers, 2009) are an important factor for the NOx reduction reaction by photocatalysts. The removal efficiency during daytime is different from that during nighttime because there are differences in light exposure time and intensity (Chen et al., 2012). Measurement results of NOx removal efficiency on days 1–3 by time, the NOx removal efficiency was evidently higher in the order of 0–6 h > 18–24 h or 6–12 h > 12–18 h for all three measurement days. Higher NOx removal efficiency was observed in the 0–6 h period for days 1–3, although photoreactions were difficult due to insufficient light. The NOx removal efficiency during 0–6 h period was 23.62% on day 1, 22.26% on day 2, and 25.48% on day 3. In the 18–24 h period, the NOx removal efficiency was high at 15.68% on day 1, 13.94% on day 2, and 15.87% on day 3. For the 6–12 and 12–18 h periods on days 1–3, low NOx removal efficiency was observed despite the prolonged presence of light in the morning and afternoon hours. In the 6–12 h period, in morning, the NOx removal efficiency was 10.74% on day 1, 12.10% on day 2, and 16.56% on day 3. In the 12–18 h period, in afternoon, the NOx removal efficiency was also low at 10.80% for day 1, 10.02% for day 2, and 11.21% for day 3, resulting in low removal efficiency compared to the night time.

Based on the results of previous studies, several reasons can be derived for the low NOx removal efficiency of the photocatalytic pavement observed in the morning and afternoon hours in the presence of light. The light intensity and the presence play an important role in the photocatalytic activity (Guo et al., 2017). In case of the measurement period is winter, the light intensity that promotes photoreactions might have been insufficient compared to summer (Chen et al., 2012). Related to light source (radiation source), this study was conducted under the solar light condition in field site. According to previous study, both anatase and rutile phases of TiO_2 reflect the visible light and are not absorbed in visible light spectrum (Lan et al., 2013). As the photocatalyst varies depending on the type of light source and usually photocatalytic activity showed higher efficiency under the UV lamp than solar light (Guo et al., 2017; Hüsken et al., 2009; Yu and Brouwers, 2009).

In addition, because the measurement positions of sites 1–3 were located near the roadside with the heavy traffic of people and vehicles, the initial concentrations of air pollutants, including NOx, may have increased due to the emissions from vehicles, which could affect the NOx reduction (Guo et al., 2017). In general, in laboratory, measurement and evaluation of NOx removal efficiency was conducted under the limited conditions. On the contrary, on-site measurement was differ from the results of laboratory due to the influence of various environmental variables (e.g., radiation source, light intensity, temperature, humidity, flow rate, and flow velocity) (Beeldens, 2008).

The photocatalytic activity and corresponding reaction may vary depending on various factors, such as the light source intensity (Dylla et al., 2010; Guo et al., 2017; Nguyen et al., 2018), initial NOx concentrations (Dylla et al., 2010; Guo et al., 2017; Nguyen et al., 2018), and relative humidity (de Melo and Trichês, 2012; Guo et al., 2017; Maggos et al., 2007; Nguyen et al., 2018). Depending on the correlations between these influencing factors, the pollutant removal efficiency can be positive (+) or negative (-) conflicting results have been obtained depending on each experimental conditions and locations. Based on the measurement results at sites 1–3, the changes in the NOx removal efficiency of photocatalysts due to the environmental variables are summarized in Table 3 and Figure 4.

Figure 4(a) shows the correlation between the average NOx removal efficiency of the photocatalytic pavement and the relative humidity (%) over time for measurement days 1–3 (November 24 to 26). The average relative humidity was the highest (approximately 55.12%) in the 0–6 h period. It decreased to approximately 52.27% in the 6–12 h period, reached the lowest value of 39.30% in the 12–18 h period, and slightly increased to 49.18% in the 18–24 h

Table 3. Parameters of measurement and NOx removal efficiency over time.

Measuring time (h)	0–6	6–12	12–18	18–24
NOx Removal Efficiency (%)	23.79	13.13	10.68	15.16
(a) Light Intensity (Lux)	1.75	6,226	11,581	2.84
(b) Temperature (°C)	5.26	6.21	10.93	8.69
(c) Humidity (%)	55.12	52.27	39.30	49.18
(d) NOx concentration (ppm)	0.08	0.13	0.09	0.12

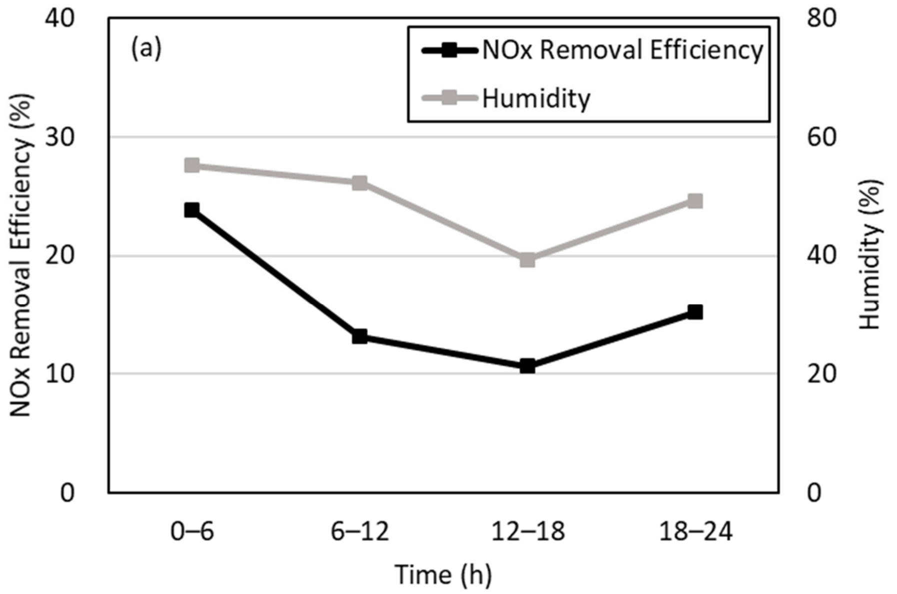
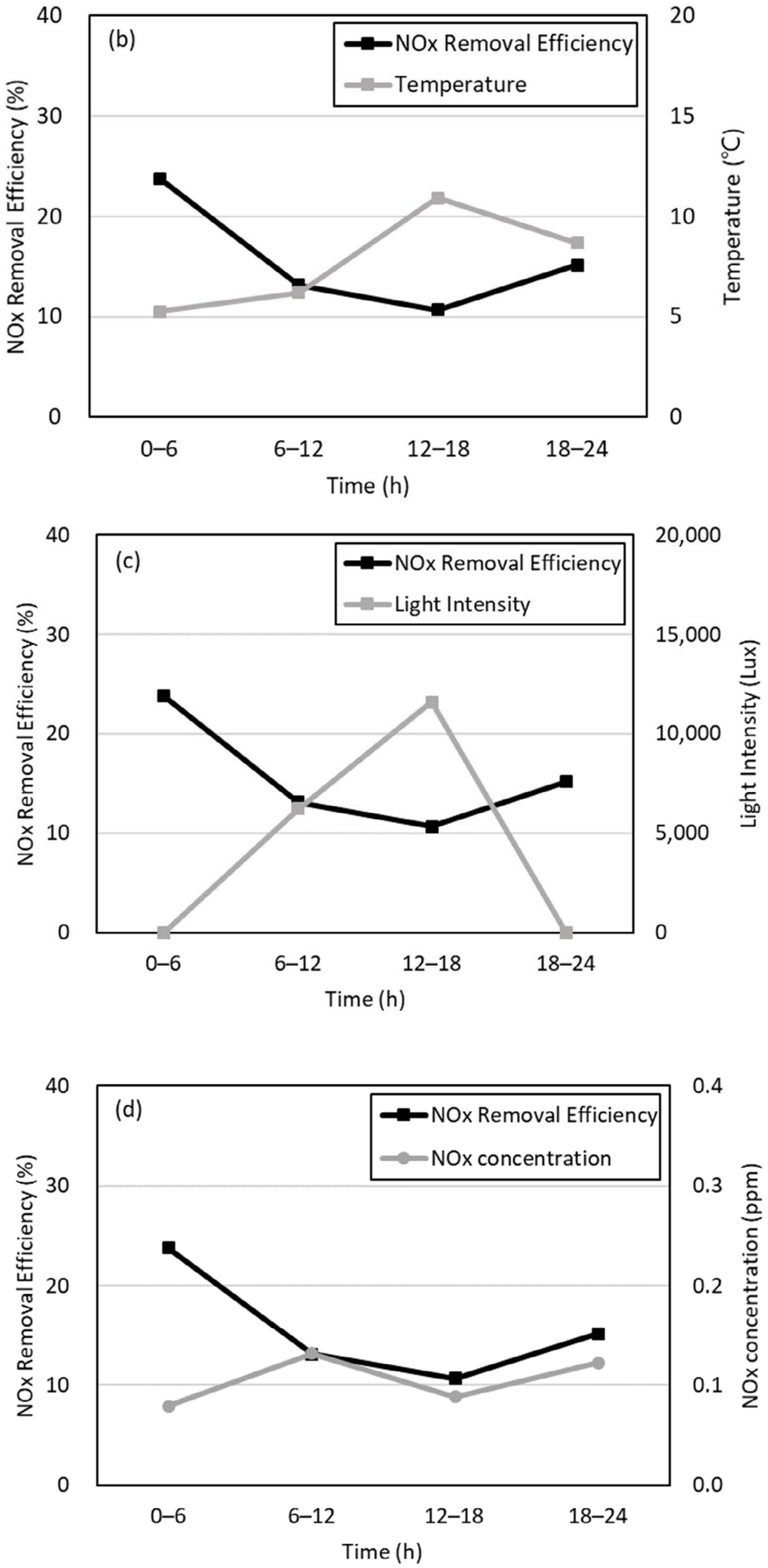


Fig. 4. Relationship between NOx removal efficiency and various parameters of on-site measurements: (a) humidity; (b) temperature; (c) light intensity; and (d) NOx concentration.



Continued Fig. 4. Relationship between NOx removal efficiency and various parameters of on-site measurements: (a) humidity; (b) temperature; (c) light intensity; and (d) NOx concentration.

period. In this study, the relative humidity and NOx removal efficiency exhibited similar trends. Both the relative humidity and NOx removal efficiency exhibited a tendency to decrease in the 0–18 h period and increased in the 18–24 h period. Humidity has been reported to represent both positive and negative effects on photocatalytic oxidation (Guo et al., 2017; Nguyen et al., 2018). In general, it is reported that under the high relative humidity conditions, water vapor is adsorbed on the surface of the photocatalyst, preventing the adsorption of contaminants (Yu and Brouwers, 2009). According to previous studies, the photocatalytic activity was highest when the humidity ranged from 20–40%, and the activity exhibited a tendency to decrease when the humidity was higher (Guo et al., 2017; Nguyen et al., 2018). However, there were also cases where high removal efficiency was observed with relative humidity of approximately 50% (de Melo and Trichês, 2012; Maggos et al., 2007). In our study, the relative humidity measured ranged from 39–55%, having a positive (+) correlation with NOx reduction efficiency.

Figure 4(b) shows the correlation between the average NOx removal efficiency and the temperature (°C) over time for measurement days 1–3 (November 24 to 26). For all the measurement days, the average temperature was low because of the characteristics of winter. Between dawn and the morning, the temperature ranged from 5–6 °C. It increased to approximately 11 °C in the afternoon and decreased again to 9 °C at night. In this study, the temperature and NOx removal efficiencies exhibited the opposite tendencies. The temperature tended to increase in the 0–18 h period and decreased in the 18–24 h period (0–6 h: 5.26 °C, 6–12 h: 6.21 °C, 12–18 h: 10.93 °C, and 18–24 h: 8.69 °C). However, the NOx removal efficiency exhibited a decreasing tendency in the 0–18 h period and increase in the 18–24 h period. Generally, most of the previous studies were conducted in 20–25 °C range (de Melo and Trichês, 2012; Guo et al., 2017; Hüsken et al., 2009; Nguyen et al., 2018; Yu and Brouwers, 2009) due to the purpose of the study was to evaluate the NOx removal efficiency of photocatalyst under the ambient condition (about 25 °C). This study was conducted in 5–10 °C range, which is the winter temperature in Korea and showed a negative (-) correlation with NOx removal efficiency under the winter temperature conditions.

Figure 4(c) shows the correlation between the average NOx removal efficiency and the light intensity over time for measurement days 1–3 (November 24 to 26). The average light intensity was low (1.75 lux) in the 0–6 h period. It increased to approximately 6,226 lux in the 6–12 h period, reached the maximum value of 11,581 lux in the 12–18 h period, and decreased again to 2.84 lux in the 18–24 h period. In most previous studies, an increase in the light source intensity led to an increase in the NOx removal efficiency (de Melo and Trichês, 2012; Guo et al., 2017; Hüsken et al., 2009; Nguyen et al., 2018; Yu and Brouwers, 2009). However, the NOx removal efficiency exhibited a tendency to decrease (0–6 h: 23.79%, 6–12 h: 13.13%, 12–18 h: 10.68%, and 18–24 h: 15.16%) in the 6–12 and 12–18 h periods when the light source intensity increased. This may be because the light source intensity was not sufficient to promote photoactivity (Guo et al., 2017) or the influence of factors other than the light source intensity was stronger. According to previous study, the measurement of the NOx reduction showed lower activity in winter compared to summer due to light intensity (Chen et al., 2012). In addition, in visible light spectrum which is included in the solar spectrum, both anatase and rutile phases of TiO_2 reflect the visible light and are not absorbed in the visible light region (Lan et al., 2013).

Figure 4(d) shows the correlation between the average NOx removal efficiency and NOx concentration over time for measurement days 1–3 (November 24 to 26). The average NOx concentration was low (0.08 ppm) during the 0–6 h period. It increased to 0.13 ppm in the 6–12 h period, decreased to 0.09 ppm in the 12–18 h period, before increasing again to 0.12 ppm in the 18–24 h period. In the 6–12 h period, the NOx removal efficiency decreased as the NOx concentration increased, thereby exhibiting a negative (-) correlation. A positive (+) correlation, was observed in the 12–18 h period when the removal efficiency decreased with the decrease in NOx concentration and in the 18–24 h period when the removal efficiency increased with the increase in NOx concentration. Studies between initial NOx concentrations and NOx removal efficiency showed not similar tendencies at all. In lower initial concentration (0.1–2.0 ppm range), the inverse relationship between the initial concentration and the NOx removal efficiency was observed (Guo et al., 2017; Hüsken et al., 2009). As the initial concentration of NOx increased, the removal efficiency decreased. On the contrary, in other study, the correlation changed at specific initial concentration point. NOx removal efficiency was increased when the initial concentrations were 0.2–0.35 ppm range but decreased when the initial concentrations were 0.45–1.0 ppm range (Nguyen et al., 2018). Similarly, in our results, it seemed to be no significant correlation between initial NOx concentration and NOx removal efficiency in 0.08–0.13 ppm range.

Photocatalyst has become a one of the main technology for degradation of NOx which is a precursor of PM in advance. Based on the function of photocatalyst, laboratory tests were conducted to measure the removal efficiency and photocatalytic products have been applied to various field including road, pavements, tunnels and building. Due to the absence of a standardized evaluation method that can directly measure in field, NOx reduction performance of photocatalytic products is evaluated typically using various methods. Therefore, it is difficult to quantitative verify the NOx removal performance of photocatalytic products which applied in the field. In addition, previous study had limitations to certify the correlations between the environmental variables and NOx removal efficiency as most of measurements were conducted in short-term at field.

We evaluated the NOx removal efficiency of the photocatalytic pavement by continuously monitoring environmental variables that could affect the NOx removal efficiency for 3 days at the photocatalytic pavement site. The average NOx removal efficiency of the photocatalytic pavement over time for the three measurement days ranged from 11–24%. Higher efficiency was observed in many previous studies which evaluated the NOx removal efficiency of photocatalyst products in laboratories. However, a previous study revealed a low removal efficiency of <2% when the NOx removal efficiency was evaluated at sites in winter, consistent with this study (Gallus et al., 2015). Based on the present results, several reasons can be summarized for the low photocatalytic activity. From November 24 to 26, the measurement conditions exhibited strong seasonal characteristics of winter, including low temperature, weak light intensity, strong wind, and high wind speed. According to previous studies, lower activity was observed in winter than in summer when the NOx removal efficiency was measured seasonally (Chen et al., 2012). The NOx conversion rate was also low in winter because the light source intensity was weak (Guo et al., 2017). In addition, as the wind speed increased, the residence time decreased, and a low decomposition rate was observed because the polluted air passed through the photocatalyst surface at high speed (Sikkema, 2013).

Comprehensively, it is difficult to verify the 'field efficiency' of photocatalytic pavement and to understand the correlation between various environmental variables and photocatalytic efficiency in the field. In laboratory, test of photocatalyst performance was conducted under the optimum environmental variables for promote the photocatalytic activations by maximum. Where as in actual field measurement site, environmental variables could not be control and different with the best conditions for photocatalytic activations definitely. In our results from on-site measurements, the range of light intensity was 3~11581 lux, the temperature was 5~11 °C, the humidity 39~55%, and the initial concentration of NOx was 0.08~0.13 ppm. With this range of environmental variables, the average NOx removal efficiency was <20% due to the factors that affecting the photocatalytic pavements. Environmental variables that could affect the NOx removal efficiency were differed from the optimum conditions for activating photocatalyst by far.

Throughout our study, we found that it is difficult to verify the 'on-site efficiency' of photocatalytic pavement with environmental variables and it is difficult to determine the correlation with environmental variables including light intensity, temperature, humidity, and initial NOx concentrations. However, we confirmed that the NOx removal efficiency of photocatalytic pavement was higher than that of concrete pavement, which can be presented by the characteristics of TiO_2, such as atmospheric purification, surface adsorption and self-cleaning (Boonen and Beeldens, 2014; Gallus et al., 2015). Through our study, we suggested the scientific and theoretical evidence that further study should be performed to verify the 'on-site efficiency' of photocatalytic pavement and study on evaluation methods should be developed to monitor the removal effectiveness of applied photocatalytic products.

In addition, we propose the following requirements to evaluate the NOx removal efficiency at the application site of the photocatalytic pavement through this result. Although on-site measurements were performed for three days in winter, it is necessary to predict the tendencies of environmental variables and photocatalytic activity in spring, summer, and autumn. This will help in analyzing the maximum, minimum and average levels as well as the characteristics of influencing factors by season, month, day, and time. Moreover, based on this analysis results, photocatalytic activity under the conditions of each scenario due to the changes in influencing factors can be predicted. It is also necessary to consider the influencing factors, such as the number of vehicles, air pollutant emissions from vehicles, wind direction, and wind speed, which were not considered in this study. To identify the accurate and objective NOx removal efficiency of photocatalyst products that can be applied in the field, it is essential to consider various factors in the field and predict photocatalytic activity due to the changes in these factors. Considering the factors that may affect NOx removal efficiency in field, quantitative evaluation method of NOx removal performance for photocatalytic products could be derived.

CONCLUSIONS

In this study, a few environmental variables (NOx concentration, temperature, humidity, and light intensity) were continuously monitored for 24 h at a photocatalytic pavement application site for three days to identify the variations in these variables affecting photocatalysts performance. In addition, the correlations between the NOx removal efficiency of the photocatalytic pavement and environmental variables were analyzed. As a result, the NOx concentration of the photocatalytic pavement was mostly lower than of the concrete pavement and the atmospheric conditions. Correlation analysis results between the NOx removal efficiency and the environmental variables of the site revealed that the relative humidity exhibited a positive (+) correlation, whereas the temperature and light intensity exhibited a negative (-) correlation. We inferred that on-site direct measurement to confirm the NOx reduction effect did not show a significant correlation between NOx reduction efficiency and environmental variables because the range of changes in environmental variables is not extreme in the actual field. We proposed considerations and requirements for evaluating the NOx removal efficiency of photocatalytic pavement sites through the results of this study, and future studies should be performed to evaluate the effect of vehicle air pollutants, wind direction, wind speed, etc., with long-term monitoring in photocatalytic pavement.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. Additionally, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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