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Concentrations of particulate matter ($PM_{2.5}$) and contributions of tire wear particle to $PM_{2.5}$ in an indoor parking garage: Comparison with the outside and the differences according to the sampling sites

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ABSTRACT

Particulate matter (PM) is increasingly affecting the social-economic development of countries. An increase in $PM_{2.5}$ concentration increases susceptibility to cardiovascular and respiratory diseases and cancer. Tire wear particles (TWP) contribute to airborne PM. In the present work, we investigated the variation in the concentration of TWP of <2.5 μm in aerodynamic diameter ($TWP_{2.5}$) in an indoor parking garage depending on the sampling sites. $PM_{2.5}$ samples were collected at four sites in an indoor parking garage of a college campus: the entrance of the parking garage (Ent), the second floor toward the third floor (2F), the front of the parking zone on the second floor (2FP), and the third floor toward the fourth floor (3F). Each $PM_{2.5}$ sampling was performed for 4 days during the fall season. The $PM_{2.5}$ concentrations at the 2F and 2FP were similar to the outside $PM_{2.5}$ concentrations, whereas those at the Ent and 3F were higher than the outside $PM_{2.5}$ concentrations. The $TWP_{2.5}$ concentrations in the indoor parking garage were 0.61–0.73 μg/m^3. The differences in the $TWP_{2.5}$ concentrations depending on the sampling sites were due to the differences in traffic volumes. The $TWP_{2.5}$ concentration at the 2FP was higher than those at the other sampling sites owing to air stagnation and TWPs produced by the high friction when parking and exiting a car in the parking zone. The contributions of $TWP_{2.5}$ to the $PM_{2.5}$ concentrations were 3.9–11.7%, in the order of 2FP ≫ Ent > 3F > 2F. A good air ventilation system can be recommended to reduce $TWP_{2.5}$ concentrations in indoor parking garages.

1. Introduction

Air pollution affects the environment and can cause cardiovascular and respiratory diseases and lung cancer [1,2]. According to the World Health Organization (WHO), outdoor air contains fine particulate matter ($PM_{2.5}$) which affects air quality and is a Group I human carcinogen [3]. Traffic-related non-exhaust emissions, including tire, road, and brake wear and road dust resuspension, contribute to airborne PM [4–7]. Tire wear particles (TWPs) are generated by friction between the road surface and tire, and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) is widely used to identify and quantify TWPs in environmental samples [8–11]. TWP concentrations in PM samples collected near roads were analyzed, and the concentrations of TWP in $PM_{2.5}$ and PM_{10} were 0.002–0.052 μg/m^3 and 0.03–0.95 μg/m^3, respectively [7,12–14].

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Parking lots can contain high concentrations of traffic-related air pollutants because of the high vehicle activity and limited fresh air exchange [15,16]. Some studies determined the concentrations of PM, CO, volatile organic compounds, polycyclic aromatic hydrocarbons (PAHs), and elements in parking garage [15–17]. Relatively high PM_{10} concentrations were observed in underground garages and semi-enclosed parking lots [15]. A previous study analyzed the concentrations of air pollutants in parking lots used by local hospitals and college commuters, and revealed that the concentrations of CO and particle-bound PAHs during weekdays were higher than those on weekends owing to high traffic [16]. In another study, PM_{10} measured at the exit of an underground parking lot in a public complex in Wuhan, China exceeded the indoor air quality standard [17].

Previous studies on air pollutants in parking garages have showed that pollution is aggravated by traffic activity, owing to vehicle movement and braking on parking ramps when moving up and down slopes [18,19]. Additionally, the rotational section is included and the slip angle increases, which is a condition under which tire wear can occur more easily. It is expected that some TWPs are found in parking garages; however, few studies have been performed on TWP concentrations in indoor parking lots. The present study investigated the variation in the concentration of TWP of <2.5 μm in aerodynamic diameter ($TWP_{2.5}$) in an indoor parking garage. $PM_{2.5}$ samples were collected during the fall season in an indoor parking garage of a college campus. $PM_{2.5}$ sampling was performed at four different sites in the parking garage; the entrance of the parking garage, the second floor toward the third floor, the front of the parking zone in the second floor, and the third floor toward the fourth floor. The $PM_{2.5}$ sampling sites were selected to examine the difference in air quality considering the outside and inside, the floors, and the passage and parking zone. Quantitative analysis of the TWP contents in the $PM_{2.5}$ samples was carried out using Py-GC/MS. The analysis results are explained by the traffic volumes and TWPs produced when parking and exiting a car in the parking zone.

Fig. 1. $PM_{2.5}$ sampling sites in the indoor parking garage.

2. Materials and methods

2.1. $PM_{2.5}$ sampling

$PM_{2.5}$ samples were collected in a 4-story parking garage of a college campus of Sejong University, Seoul, Republic of Korea. The $PM_{2.5}$ sampling was carried out using a low volume particulate sampler of KMS-4200 (Kemik Co., Republic of Korea) and a PM collection filter with a diameter of 47 mm. The sample names were described according to the sampling sites. PM sampling was performed at four different sites in the parking garage (Fig. 1 and Table 1); (1) the entrance of the parking garage (sample name: Ent), (2) the second floor toward the third floor (sample name: 2F), (3) the front of the parking zone in the second floor (sample name: 2FP), and (4) the third floor toward the fourth floor (sample name: 3F).

The $PM_{2.5}$ sampling was performed for 12 h per day from 8 a.m. to 8 p.m. for 4 days at each site. The total $PM_{2.5}$ sampling time was 48 h. The $PM_{2.5}$ samples were collected on weekdays during the fall season, 2022; on September 19–22 (Monday-Thursday), 2022 at the Ent, on September 26–29 (Monday-Thursday), 2022 at the 2F, on October 04–07 (Tuesday-Friday), 2022 at the 2FP, and on October 11–14 (Tuesday-Friday), 2022 at the 3F. The $PM_{2.5}$ sampling rate was 1.0 m^3/h, and total sampling volume was 48 m^3 at one site. Outside weather conditions for the $PM_{2.5}$ sampling dates are summarized in Table 2. The numbers of vehicles parked in the parking garage were checked twice per day at 10 a.m. and 4 p.m. The average numbers of vehicles parked in the parking garage during the $PM_{2.5}$ sampling are listed in Table 3.

2.2. Pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS)

Quantitative analysis of rubber components in the $PM_{2.5}$ samples was performed using Py-GC/MS. Py-GC/MS analysis was carried out using a JCI-55 Curie-point pyrolyzer (Japan Analytical Industry Co., Japan) coupled to an Agilent 6890 gas chromatograph equipped with a 5973 mass spectrometer (Agilent Technology Inc., USA). All samples were pyrolyzed using a pyrofoil of 590 °C Curie temperature for 10 s in helium (He) atmosphere. A DB-5MS capillary column (30 m × 0.32 mm, 0.25 μm film thickness, Agilent Technology Inc., USA) was used. The injector temperature was 250 °C. GC oven temperature program was used as follows: 30 °C (held for 3 min) to 50 °C (held for 3 min) at 10 °C/min, then to 180 °C (held for 1 min) at 10 °C/min, and raised up to 250 °C (held for 3 min) at 10 °C/min again. The interface temperature of GC to MS was 250 °C. The electron ionization (70 eV) was used to ionize the pyrolysis products. The MS source temperature was 230 °C.

2.3. Conversion of rubber to TWP

Rubber components in the $PM_{2.5}$ samples were identified using principal pyrolysis products formed from rubbers used in tire tread compounds. Isoprene and dipentene were detected in the Py-GC/MS chromatograms of the $PM_{2.5}$ samples and were the key pyrolysis products of natural rubber (NR). The weights of rubber in the $PM_{2.5}$ samples were determined using the calibration curve built by dipentene. Tire tread rubber compounds of vehicles are composed of rubbers, fillers, and additives including crosslinking agents, antidegradants, and processing aids [20–22]. Therefore, the weight of the rubber must be converted into that of the tire tread compound. The fraction of rubber in tire tread rubber compounds is generally 50% [23–25]. The conversion factor from rubber to TWP was 2.0.

3. Results and discussion

3.1. Comparison of $PM_{2.5}$ concentrations between the indoor parking garage and outside

The amounts of $PM_{2.5}$(Ent), $PM_{2.5}$(2F), $PM_{2.5}$(2FP), and $PM_{2.5}$(3F) samples were 0.5, 0.8, 0.3, and 0.7 mg, respectively, and the order was $PM_{2.5}$(2F) > $PM_{2.5}$(3F) > $PM_{2.5}$(Ent) > $PM_{2.5}$(2FP). They were approximately proportional to the outside $PM_{2.5}$ concentrations (Table 2); the order of the outside $PM_{2.5}$ concentration was the same to that of the amount of $PM_{2.5}$ sample. However, the amount of $PM_{2.5}$(Ent) sample was higher than that of $PM_{2.5}$(2FP) sample, although the outside $PM_{2.5}$ concentrations for the sampling dates at the Ent and 2FP were similar. This may be because of the difference in traffic volumes. All vehicles using the parking garage passed through the entrance point (the sampling site of Ent); however, vehicles parked on the first floor were not included in the 2FP. The amount of $PM_{2.5}$(3F) sample was exceptionally high even when considering the traffic volume and the outside $PM_{2.5}$ concentration. The outside $PM_{2.5}$ concentration during the $PM_{2.5}$(3F) sampling was much lower than that during the $PM_{2.5}$(2F) sampling: however, the amount of $PM_{2.5}$(3F) sample was marginally lower than that of $PM_{2.5}$(2F) sample. Traffic volume at the 3F was lower than

Table 1
$PM_{2.5}$ sampling sites in the indoor parking garage and the sample names.

Sample name	Sampling site
Ent, $PM_{2.5}$(Ent)	Entrance of the parking garage
2F, $PM_{2.5}$(2F)	The second floor toward the third floor
2FP, $PM_{2.5}$(2FP)	Front of the parking zone in the second floor
3F, $PM_{2.5}$(3F)	The third floor toward the fourth floor

Table 2
Outside weather conditions during $PM_{2.5}$ sampling. Values in the parentheses are the ranges.*

Sampling date	Sep. 19–22, 2022	Sep. 26–29, 2022	Oct. 04–07, 2022	Oct. 11–14, 2022
Temperature (°C)	20.9 (13.0–29.6)	20.4 (14.0–27.9)	16.2 (11.1–23.1)	14.5 (6.5–29.8)
Wind velocity (m/s)[(a)]	2.4/6.6	1.6/3.5	2.4/5.7	1.8/4.7
$PM_{2.5}$ concentration (μg/m^3)	6.0 (1–16)	17.5 (5–54)	5.6 (1–17)	10.3 (5–14)
Corresponding sample name	$PM_{2.5}$(Ent)	$PM_{2.5}$(2F)	$PM_{2.5}$(2FP)	$PM_{2.5}$(3F)

(a) Wind velocity: average/maximum values.
* Data were obtained from the regional meteorological office in Gwangjin-gu, Seoul, Republic of Korea.

Table 3
Average numbers of vehicles parked in the indoor parking garage.

Sampling date	Sample	1F	2F	3F	4F
Sep. 19-22	$PM_{2.5}$(Ent)	218	156	81	14
Sep. 26-29	$PM_{2.5}$(2F)	224	151	90	17
Oct. 04-07	$PM_{2.5}$(2FP)	209	142	48	11
Oct. 11-14	$PM_{2.5}$(3F)	209	166	128	38

those at the other sampling sites. The unusual amount of the $PM_{2.5}$(3F) sample may have been because of dust scattering from the lower floors.

The $PM_{2.5}$ concentrations in the indoor parking garage were compared with those outside. The $PM_{2.5}$ concentrations in the indoor parking garage were obtained by dividing the weight of the $PM_{2.5}$ sample by the collection volume (48 m^3), whereas the outside concentrations were regional $PM_{2.5}$ concentrations obtained from the regional meteorological office listed in Table 2. Except for the 2F, the $PM_{2.5}$ concentrations in the indoor parking garage were higher than those on the outside, as shown in Fig. 2. This may be because of increase in PM due to dust resuspension and abrasion of the tires and pavements by driving vehicles. Since an indoor parking garage has limited fresh air exchange, the air quality is likely to be worse than outdoors. The $PM_{2.5}$ concentration at the 2F was marginally lower than that on the outside (the difference was 0.8 μg/m^3 and 5%), which may be because the outside $PM_{2.5}$ concentrations at the time were high (17.5 μg/m^3). The $PM_{2.5}$ concentration at the ENT was much higher than that on the outside (the difference was 4.4 μg/m^3 and 73%), owing to dust resuspension resulting from the entry and exit of traffic. The $PM_{2.5}$ concentration at the 3F was also higher than the outside $PM_{2.5}$ concentration (the difference was 4.3 μg/m^3 and 42%), owing to dust dispersing from the first and second floors toward the third floor. The $PM_{2.5}$ concentration at the 2FP was marginally higher than the outside $PM_{2.5}$ concentration (the difference was 0.7 μg/m^3 and 13%), owing to low dust dispersion because of low traffic volume at this parking zone and vehicles moving at a low speed.

3.2. Amounts of TWP in the $PM_{2.5}$ samples

The weights of rubber in the $PM_{2.5}$ samples obtained through the calibration curve are listed in Table 4. The amounts of TWP in the

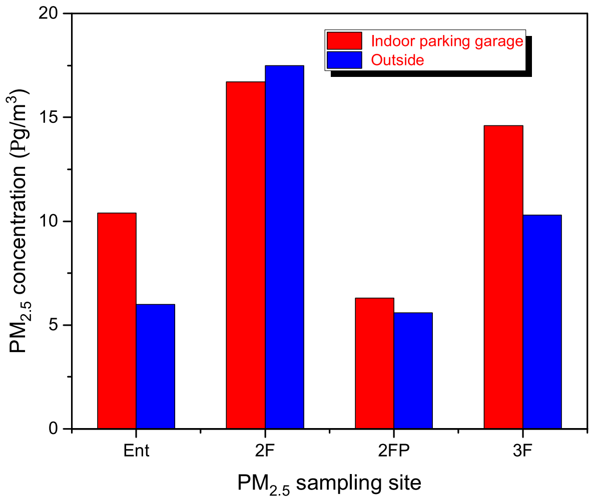

Fig. 2. Variations of the $PM_{2.5}$ concentration in the indoor parking garage and the outside $PM_{2.5}$ concentration with the sampling site. The outside $PM_{2.5}$ concentrations were obtained from the regional meteorological office in Gwangjin-gu, Seoul, Republic of Korea (Table 2) on the sampling dates.

$PM_{2.5}$ samples were obtained by applying the conversion factor of 2.0, and the results are listed in Table 2. The weight of TWP in the $PM_{2.5}$(Ent) sample was greater than those in the $PM_{2.5}$(2F) and $PM_{2.5}$(3F) samples, whereas that in the $PM_{2.5}$(2F) sample was greater than that in the $PM_{2.5}$(3F) sample. This is because of the differences in traffic volumes. The amount of TWP in the $PM_{2.5}$(2FP) sample was higher than those in the other samples, owing to air stagnation and high friction between the tire tread and the parking lot surface when a car is parking and exiting the parking zone. Drivers must turn 90° corners to park and exit from a parking zone because parking lanes are generally rectangular. A high tire slip angle results in a high abrasion of the tire tread [26–28]. Furthermore, air stagnates in the parking zone of an indoor parking garage because of the limitation of fresh air exchange.

3.3. *$TWP_{2.5}$ concentrations in the indoor parking garage*

The $TWP_{2.5}$ concentration in the parking garage was calculated by dividing the TWP weight in the $PM_{2.5}$ sample by the collection volume of 48 m^3. The $TWP_{2.5}$ concentrations in the parking garage were 0.70, 0.64, 0.73, and 0.61 μg/m^3 at the Ent, 2F, 2FP, and 3F sampling sites, respectively (Fig. 3). The difference in the $TWP_{2.5}$ concentrations was not large with the largest difference being >20%. This is noteworthy because the traffic volumes and $PM_{2.5}$ concentrations among the four sampling sites were different. The differences in the $TWP_{2.5}$ concentrations among the three $PM_{2.5}$ sampling sites of Ent, 2F, and 3F can be explained by their differences in traffic volumes. The order of $TWP_{2.5}$ concentration and traffic volume at the $PM_{2.5}$ sampling sites was Ent > 2F > 3F.

The $TWP_{2.5}$ concentration in the 2FP was higher than those in the other sampling sites. Sources of $TWP_{2.5}$ collected at the 2FP were vehicles passing via the second floor and those parked in the parking zone. The high $TWP_{2.5}$ concentration at the 2FP can also be explained by air stagnation and the increasing abrasion rate of the tire tread by the high friction between the tire tread and the parking lot surface as discussed above. The high $TWP_{2.5}$ concentration at the 2FP indicates that the $TWP_{2.5}$ concentration in the parking zone can be higher than those in the passage roads between floors.

Contributions of $TWP_{2.5}$ to the $PM_{2.5}$ concentrations in the indoor parking garage were obtained by dividing the weights of $TWP_{2.5}$ by those of $PM_{2.5}$ collected at the sampling sites (Fig. 4). The contributions of $TWP_{2.5}$ in the $PM_{2.5}$ concentrations were 3.9–11.7%, and the order was 2FP ≫ Ent > 3F > 2F. The order of Ent > 3F > 2F was probably owing to the differences in traffic volumes, and the traffic volume had the following order: Ent > 3F > 2F. The $TWP_{2.5}$ contribution at the 2FP was much greater than those at the other sites. This is because the amount of $PM_{2.5}$(2FP) sample was lower than those of the other samples, and the TWP weight of the $PM_{2.5}$(2FP) sample was greater than those of the other samples. The $TWP_{2.5}$ contributions were inversely proportional to the amounts of $PM_{2.5}$ samples. The unusually high contribution of $TWP_{2.5}$ at the 2FP can be explained by air stagnation and an increased abrasion rate due to the high friction between the tire tread and parking lot surface, as elaborated above. Therefore, a good air ventilation system can be recommended to reduce the $TWP_{2.5}$ concentrations in indoor parking garages.

4. Conclusion

The $PM_{2.5}$ concentrations in the indoor parking garage were 6–17 μg/m^3, and their order, considering the sampling sites, was 2F > 3F > Ent > 2FP. The $PM_{2.5}$ concentrations at the 2F and 2FP were similar to the outside $PM_{2.5}$ concentrations, whereas those at the Ent and 3F were higher than the outside $PM_{2.5}$ concentrations by approximately 50%. The higher $PM_{2.5}$ concentration at the Ent was because of the high traffic volume. The $TWP_{2.5}$ concentrations in the parking garage were 0.61–0.73 μg/m^3, and its order was 2FP > Ent > 2F > 3F. The order of the $TWP_{2.5}$ concentrations at the Ent, 2F, and 3F was possibly owing to the differences in traffic volumes. The high $TWP_{2.5}$ concentration at the 2FP may be because of air stagnation and the increased abrasion rate of the tire tread due to the high friction. The $TWP_{2.5}$ contributions in the $PM_{2.5}$ concentrations were 3.9–11.7%, and its order was 2FP ≫ Ent > 3F > 2F. The unusually high contribution at the 2FP was also because of air stagnation and an increase in the abrasion rate of the tire tread. A good air ventilation system is required to reduce $TWP_{2.5}$ concentrations in indoor parking garages.

Data availability statement

Data will be made available on request.

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Table 4
Weights of rubber in the $PM_{2.5}$ samples and converted TWP weights.

Sample	$PM_{2.5}$(Ent)	$PM_{2.5}$(2F)	$PM_{2.5}$(2FP)	$PM_{2.5}$(3F)
Weights of rubber in the $PM_{2.5}$ samples (μg)				
	16.8	15.4	17.6	14.7
Weights of TWP in the $PM_{2.5}$ samples (μg)				
	33.6	30.8	35.2	29.4

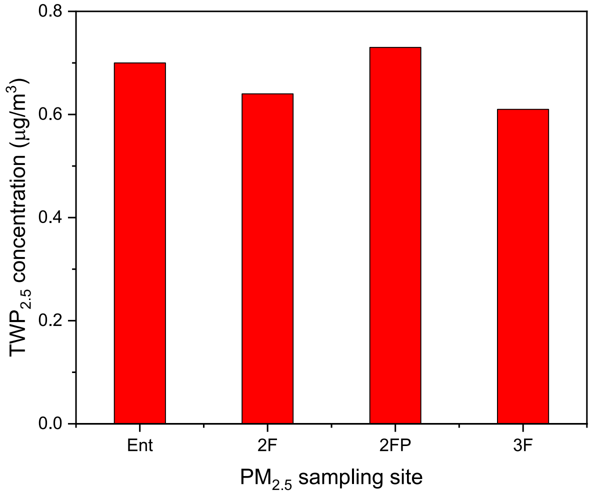

Fig. 3. Variation of the $TWP_{2.5}$ concentration in the indoor parking garage with the sampling site.

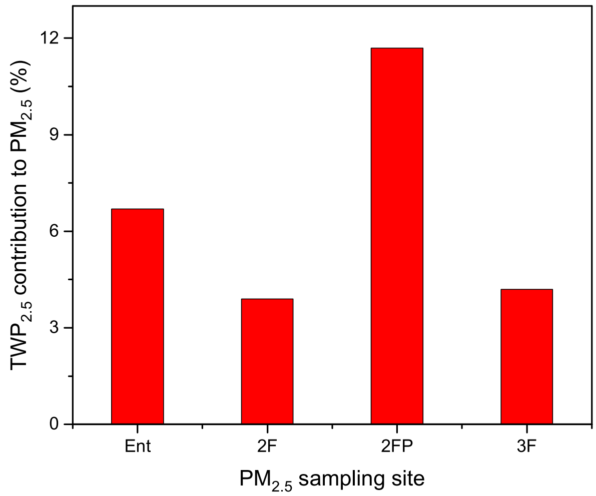

Fig. 4. Variation in the contribution of $TWP_{2.5}$ to the $PM_{2.5}$ concentration with the sampling site.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Eunji Chae: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Sung-Seen Choi:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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