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Particulate Behavior in Subway Airspace

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ABSTRACT

The most pivotal approach to improve subway indoor air quality (IAQ) is to examine the emission sources and particulate behavior. Therefore, the main objective of this study is to investigate the particulate behavior in the subway. In order to examine IAQ in the subway, a sampling and measurement campaign was carried out for 35 sites during the summer and winter seasons from May, 2005 to February, 2006. In case of 24 hour measurement, the mean concentrations (PM_{10}-24 hr) of platform and waiting room were 156.18±53.79 μg/m^3 and 111.00±53.31 μg/m^3. Besides, as a result of 20 hour measurement, the mean concentrations (PM_{10}-20 hr) of platform and waiting room were 146.09±53.71 μg/m^3 and 99.08±42.77 μg/m^3, respectively. In general, PM_{10}-24 hr was higher than PM_{10}-20 hr, and both PM concentrations showed a high correlation coefficient ($r = 0.803$). It was found that the $PM_{2.5}$ concentration (109.56±28.24 μg/m^3) in winter was higher than that (83.66±57.82 μg/m^3) in summer.

Key words: Particulate, Subway, $PM_{2.5}$, Indoor Air Quality

1. INTRODUCTION

Seoul, a metropolitan city, has been using more energy than any other areas in South Korea due to the high density of population; therefore, reveals very high emissions of air pollutants. The air pollution intensity in the city is 1.7 to 3.5 times more serious than that of advanced countries. This environmental air quality is closely associated with indoor air quality (IAQ) depending upon air pollutants. That is to say, most of the people in urban areas, who stay indoors most of their time, are threatened because of outdoor dirty air infiltrated into indoor airspace through a ventilation system. US EPA (Environment Protection Agency) reported that the residential time in indoors was 21 hr, the outdoor one 1.5 hr, and the duration in the vehicles 1.3 hr, on the other hand, GerES II of Germany reported that the durations were 20, 3, 0.9 hr, respectively. Especially, urban people in modern society are spending most of their time in indoor airspace such as houses, buildings, schools and vehicles, however, these people are sometimes endangered by exposure to a contaminated environment; therefore, IAQ has been more recognized as a significant factor in determinating our health and welfare. Our indoor environment has been increasingly airtight in order to cut down energy and its efficiency. Also, various air pollutants generated physically, chemically, and biologically are emitted from mixed emission sources unlikely with atmospheric environment. Indoor air quality is not only serious in buildings, but also in underground communities and public transportation systems such as an underground subway and market. Government and local autonomous entity have been pursuing a measure for IAQ improvement as well as outdoor air quality for the metropolitan areas including Seoul; however, there was no distinct improvement of air quality due to its high population density and busy economic activities. This infavorable circumstance is, also, the same as in indoor environment including a subway. Especially, a part of subway systems in the Seoul metropolitan area is expected to have the prospect that different species of hazardous pollutants may remain cumulated indoor due to too old ventilation and accessory systems (Kim *et al.*, 2007). This subway system is serviced as lines 1 to 8 in the city, and occupies more than 34.1% among all means of transportation. It is estimated that approximately six million to ten million citizens in Seoul use the subway. However, the problem of indoor particulate matters has been more serious because the subway airspace is a sort of enclosed system. Therefore, particulate levels on the subway were 3-8 times higher than those on the ground (Adams *et al.*, 2001). In

Table 1. Sampling date and construction status in subway stations.

Line	Summer			Winter		
	Site	Date	Construction condition	Site	Date	Construction condition
A line	A-1	05/18/05		A-1	12/13/05	o
	A-2	05/19/05		A-2	12/12/05	
	A-3	05/23/05		A-3	12/09/05	
	A-4	05/24/05		A-4	12/08/05	
	A-5	05/26/05		A-5	12/06/05	
	A-6	05/30/05		A-6	12/05/05	
	A-7	05/31/05	o	A-7	12/02/05	
	A-8	07/19/05		A-8	12/01/05	
B line	B-1	06/02/05	o	B-1	12/19/05	o
	B-2	06/07/05	o	B-2	12/20/05	o
	B-3	–		B-3	12/21/05	
	B-4	06/09/05		B-4	12/22/05	o
	B-5	06/20/05	o	B-5	12/13/05	
	B-6	06/21/05		B-6	12/14/05	o
	B-7	07/11/05		B-7	12/23/05	o
	B-8	07/12/05		B-8	12/26/05	o
	B-9	07/13/05		B-9	12/27/05	o
	B-10	07/14/05		B-10	12/28/05	
	B-11	07/18/05		B-11	12/14/05	
C line	C-1	06/22/05		C-1	12/29/05	o
	C-2	06/23/05		C-2	12/30/05	
	C-3	06/27/05		C-3	01/02/06	
	C-4	06/28/05		C-4	01/03/06	
	C-5	06/29/05	o	C-5	01/04/06	o
	C-6	06/30/05		C-6	01/05/06	o
	C-7	07/04/05		C-7	01/06/06	
	C-8	07/05/05		C-8	01/09/06	
	C-9	07/06/05		C-9	01/10/06	
	C-10	07/07/05		C-10	01/11/06	
D line	D-1	05/09/05		D-1	01/19/06	
	D-2	05/10/05		D-2	01/18/06	o
	D-3	05/11/05		D-3	01/17/06	
	D-4	05/12/05		D-4	01/16/06	o
	D-5	05/16/05		D-5	01/13/06	
	D-6	05/17/05		D-6	01/12/06	

addition, measurements showed that the average exposure concentration of $PM_{2.5}$ and TSP was 8 and 12 times higher for people traveling by the underground as compared to taxi drivers (Johansson, 2003). The recent studies have focused both PM_{10} and $PM_{2.5}$ (Park and Ha, 2008; Kim *et al.*, 2007; Nieuwenhuijsen *et al.*, 2007; Johansson, 2003; Chow *et al.*, 2002; Harrison *et al.*, 1997). However, most previous studies in Korea have a tendency to concentrate on PM_{10} concentration distribution. Korea Ministry of Environment established IAQ Act to control five major pollutants in indoor environment. IAQ standard for PM_{10} concentration was set to 150 $\mu g/m^3$ to protect public health.

The most pivotal approach to improve subway IAQ is to examine the emission sources and particulate behavior. Therefore, the main objective of this study is to investigate the particulate behavior in the subway.

2. EXPERIMENTAL METHODS

2.1 Sampling Site

In this study, in order to examine indoor air quality in the subway, a sampling and measurement campaign was carried out for 35 sites during the summer and winter seasons from May, 2005 to February, 2006. Sampling date and construction status are summarized in Table 1. Particulate sampling was conducted continuously for 20 and 24 hr. Hence, twenty hour sampling depicts that subway stop duration (i.e., 4 hrs)

Table 2. PM distributions with respect to sampling durations and sites on subway stations.

Sampling duration	Site	N	Mean	STD	Min.	Max.	p-Value
PM_{10}-24 hr ($\mu g/m^3$)	Platform	60	156.18	53.79	40.28	256.67	<0.05
	Waiting room	67	111.00	55.31	16.67	290.56	
	All	127	132.35	57.93	16.67	290.56	
PM_{10}-20 hr ($\mu g/m^3$)	Platform	66	146.09	53.71	26.67	258.33	<0.05
	Waiting room	63	99.08	42.77	18.98	222.33	
	All	129	123.13	53.92	18.98	258.89	

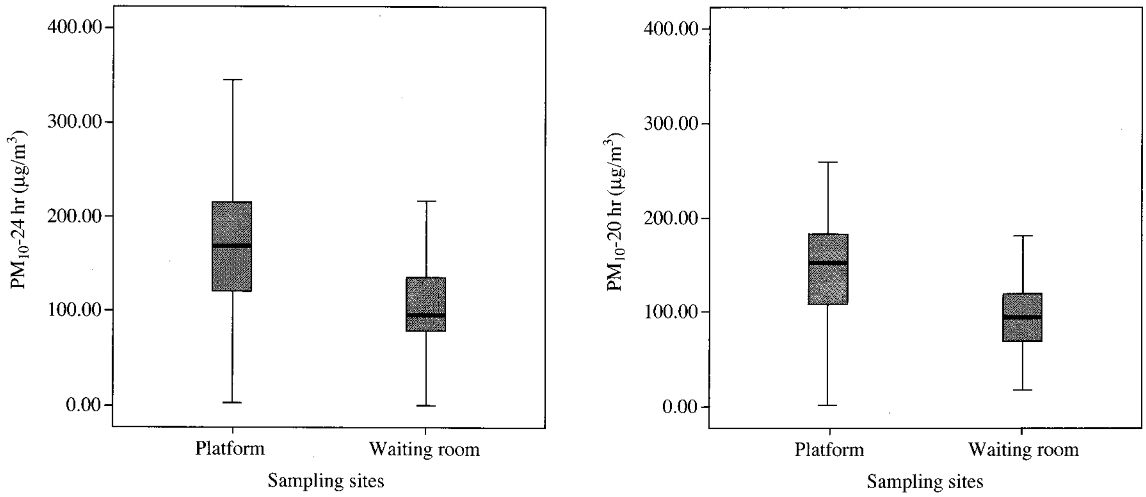

Fig. 1. PM_{10} concentration distribution by sampling site.

was excluded.

2.2 Methods

PM_{10} sampling and analysis were carried out based on the standard method of Korean IAQ. In this study, mini-volume air samplers (Model 4.1, Airmetrics Co,. USA) were used to measure PM_{10} from the subway airspace of concern, when the sampling flow rate was 5 L/min and the filter type used was MCE (Mixed Cellulose Ester, 0.45 µm pore size, ψ 47 mm, MFS. Inc). After sampling was conducted, the filter was kept in a desiccator for more than 48 hours, then its mass was measured using a chemical balance with a minimum sensitivity of 0.001 mg.

3. RESULTS AND DISCUSSION

3.1 Measurement Sites

It has been reported that the source of particulate matter (PM) which affects the IAQ of the subway could be associated with complicated conditions, such as movement of passengers, operating process of subway, outside air for ventilation. The concentrations of PM obtained from platform and waiting room are presented in Table 2. In case of 24 hour measurement, the mean concentrations of platform and waiting room were 156.18 ± 53.79 $\mu g/m^3$ and 111.00 ± 53.31 $\mu g/m^3$ ($p < 0.05$). Besides, as a result of 20 hour measurement, the mean concentrations of platform and waiting room were 146.09 ± 53.71 $\mu g/m^3$ and 99.08 ± 42.77 $\mu g/m^3$, respectively, and it was also found that concentrations in platform with respect to the two different sampling durations were higher than those of waiting room most of the time as shown in Fig. 1. Kim *et al.* (2008) who worked on concentrations of PM_{10} in the Seoul Metropolitan Subway reported that PM_{10} concentration levels at platforms (359.0 $\mu g/m^3$) were higher than those at the station precincts (182.1 $\mu g/m^3$).

3.2 Variations of PM by Season

In order to find out seasonal characteristics of PM in the subway during summer and winter seasons, a seasonal comparison study was performed. As a result, PM concentration (PM_{10}-24 hr) measured for 24

Table 3. concentration distributions of PM by season.

Sampling duration	Season	Site	N	Mean	STD	Min.	Max.	p-Value	
PM_{10}-24 hr ($\mu g/m^3$)	Summer	Platform	31	141.79	43.82	40.28	215.28	<0.05	<0.05
		Waiting room	33	96.05	53.41	16.67	230.56		
		All	64	118.20	53.80	16.67	230.56		
	Winter	Platform	29	171.57	59.70	58.33	256.67	<0.05	
		Waiting room	34	125.51	49.77	59.26	290.56		
		All	63	146.71	58.85	31.67	290.56		
	All	127		132.35	57.93	16.67	290.56		
PM_{10}-20 hr ($\mu g/m^3$)	Summer	Platform	33	150.84	54.46	26.67	211.11	<0.05	>0.05
		Waiting room	29	98.41	45.93	21.67	228.33		
		All	62	126.31	56.74	21.67	228.33		
	Winter	Platform	33	141.34	53.36	51.39	248.61	<0.05	
		Waiting room	34	99.65	40.58	18.98	223.61		
		All	67	120.18	51.43	18.98	248.61		
	All	129		123.13	53.92	18.98	258.98		

hr in winter was 146.71±58.85 $\mu g/m^3$, which was higher than a summer value, 118.20±53.80 $\mu g/m^3$ ($p<0.05$). On the other hand, a particulate level (PM_{10}-20 hr) measured for 20 hr in summer was 126.31±56.74 $\mu g/m^3$, which was similar to a winter value, 120.18±51.43 $\mu g/m^3$ ($p>0.05$). In addition, PM concentration distribution with respect to sampling locations and seasons is revealed in Table 3. As a result of PM_{10}-24 hr measurement, PM concentrations in platform were higher than in waiting room during summer and winter seasons ($p<0.05$). In case of PM_{10}-20 hr measurement, PM concentrations in platform were also higher than in waiting room during the two seasons ($p<0.05$); however, it was observed that those in winter was higher than in summer ($p>0.05$).

3. 3 Statistical Analysis with Reference to Sampling Time

The difference of the PM_{10} concentration by sampling time is shown in Table 4, which was obtained from t-test. It should be statistically concluded that PM_{10}-24 hr was the same as that for PM_{10}-20 hr during summer months for all sampling locations because p value was greater than 0.05. It was found that PM_{10}-24 hr was higher than PM_{10}-20 hr in both platform and waiting room during winter months ($p<0.01$). Also, it was observed that PM_{10}-24 hr and PM_{10}-20 hr in winter had a high correlation ($r = 0.836$). In general, PM_{10}-24 hr was higher than PM_{10}-20 hr ($p<0.01$), and both PM concentrations showed a high correlation coefficient ($r=0.803$). This result implies that PM_{10} should be suspended in underground stations for 4 hr when the train was not run.

3. 4 Characteristics of $PM_{2.5}$

In this study, the difference of $PM_{2.5}$ concentration at all sampling sites could not be observed since only platform measurement was conducted, and it was found that the $PM_{2.5}$ concentration (109.56±28.24 $\mu g/m^3$) in winter was higher than that (83.66±57.82 $\mu g/m^3$) in summer. On the other hand, Adams (2001) reported that the $PM_{2.5}$ concentration (247.2 $\mu m/m^3$) in summer was much higher than that (157.3 $\mu g/m^3$) in winter based on the data obtained from London subway using high flow personal samplers.

$PM_{2.5}$ is assumed to be one of the most significant factors of PM_{10} increase in the subway; therefore, the correlation analysis between the two concentration levels was carried out. Correlation coefficients between PM_{10} and $PM_{2.5}$ in the subway are shown in Table 5. In case of underground subway stations, correlation coefficient between PM_{10} and $PM_{2.5}$ was 0.487 and positive ($p<0.01$).

Johansson *et al.* (2003) and Park *et al.* (2008) also reported that the correlation coefficients from their works were 0.95 and 0.88, respectively, which were even higher than those values obtained from this study.

3. 5 Characteristics of Particulate Behavior

Additional experiments were performed at 5 platforms of subway stations in line A so as to find out the characteristics of particulate behavior according to particle size distributions. This result revealed that the highest PM_{10} concentration, 162.2 $\mu g/m^3$, appeared at station II. The mean PM_{10} and $PM_{2.5}$ concentrations in the stations of concern were 85.4-190 $\mu g/m^3$ and 51.4-113.2 $\mu g/m^3$, respectively. These concen-

Table 4. Comparison between PM_{10}-24 hr and PM_{10}-20 hr.

Season	Sampling location and duration		N	Mean	STD	r	p-Value
Summer	Platform	24 hr	24	158.08	31.72	0.617**	>0.05
		20 hr	24	152.31	33.81		
	Waiting room	24 hr	22	104.37	47.09	0.732**	>0.05
		20 hr	22	101.67	36.72		
	Total	24 hr	46	132.39	47.8	0.785**	>0.05
		20 hr	46	128.09	43.22		
Winter	Platform	24 hr	27	175.76	57.68	0.825**	<0.01
		20 hr	27	148.11	54.36		
	Waiting room	24 hr	29	124.45	47.78	0.76**	<0.01
		20 hr	29	103.86	38.69		
	Total	24 hr	56	149.19	58.34	0.836**	<0.01
		20 hr	56	125.2	51.54		
Total		24 hr	102	141.61	54.24	0.803**	<0.01
		20 hr	102	126.5	47.76		

*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

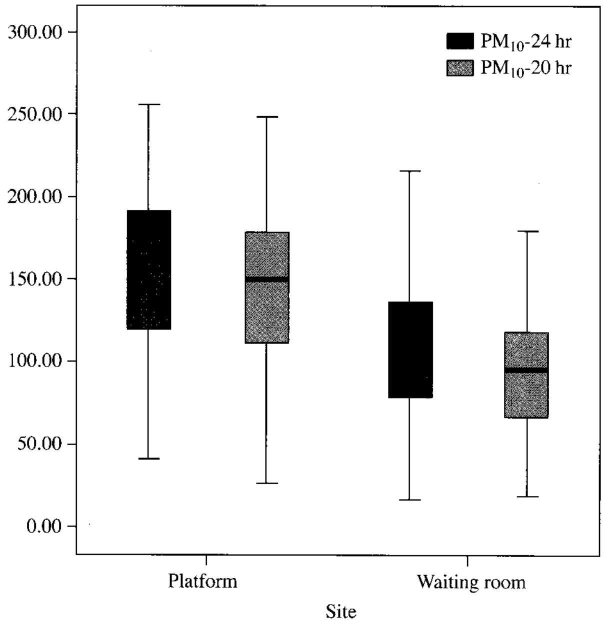

Fig. 2. PM_{10} concentration distributions with respect to sampling time.

Table 5. Correlation analysis of PM_{10} and $PM_{2.5}$.

Site	Pollutant	$PM_{2.5}$	PM_{10}
Subway station	$PM_{2.5}$	1	
	PM_{10}	0.487**	1

**Correlation is significant at the 0.01 level (2-tailed).

Table 6. Distribution characteristics of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$.

A line	Subway station with PSD		Subway station without PSD		
	I	II	III	IV	V
PM_{10}	85.4	162.2	190	188.6	131.2
$PM_{2.5}$	51.4	50.4	113.2	96.8	78.0
$PM_{1.0}$	42.8	34.2	82.2	72.6	59.4
$PM_{2.5}/PM_{10}$ (%)	60.2	31.1	60.0	51.3	59.5

tration distributions were very different depending upon the installation of platform screen door (PSD), ventilation rates, and characteristics of outdoor air quality and the structure of the subway. In this study, however, it was found that the ratio of $PM_{2.5}$ to PM_{10} was higher than 50% except for station II. Chan (2002) revealed that $PM_{2.5}$ to PM_{10} ratios in the Guangzhou subway trains of China was very high ranging from 74% to 85%. Besides, Park *et al.* (2006) also reported that the particulate ratios in a platform and inside trains were 80.7% and 79.9%, respectively.

4. CONCLUSION

This study is to investigate the particulate behavior in the subway. A sampling and measurement campaign was carried out for 35 sites during the summer and winter seasons. The concentration of PM_{10} and $PM_{2.5}$ in platforms were observed to be higher than those measured waiting room. PM concentration (PM_{10}-24 hr) measured for 24 hr in winter was higher than that in summer. On the other hand, a particulate level (PM_{10}-20 hr) measured for 20 hr in summer was similar to a winter value. PM_{10}-24 hr was higher than PM_{10} -20 hr, and both PM concentrations showed a high correlation coefficient. In case of underground subway stations, correlation coefficient between PM_{10} and $PM_{2.5}$ was 0.487 and positive. Therefore, in general, $PM_{2.5}$ to PM_{10} concentration ratio seems to be significant in the subway stations concerned.

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