Emission and Dry Deposition Characteristics of Metal Elements from Engineering Construction Sites

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In order to explore the emission characteristics of particulate and its particle-bound metal elements, eight construction sites in southern Taiwan were investigated during the period between Dec. 1996 and May 1997. Total suspended particulate (TSP) samples were collected with PS-1 samplers, and the dry deposition particles were sampled by dry deposition plates with smooth surfaces. The emission factors of particulate matter from construction sites were estimated using a dispersion model. Twenty elements, including Al, Ca, Fe, Mg, Na, Pb, Zn, Ni, V, Ba, Mn, Cr, Cu, Cd, Sr, Ag, Mo, Sb, As, and Ti, were analyzed in this study. The results indicated that dry deposition fluxes of TSP ranged between 762 and 3,760 mg/m^2-day with an average of 2,230 mg/m^2-day. The dry deposition velocities (V_d) of TSP varied in a narrow range between 2.63 to 5.55 cm/s with an average of 4.31 cm/s and a standard deviation of 1.21 cm/s. The major elemental components of particulate matter in the ambient air at construction sites were found to be crustal elements including Al, Ca, Fe, Mg and Na. These compositions were similar to those of road dust. Dry deposition fluxes of crustal metals were much higher than those measured at urban and suburban sites

Keywords: particulate, construction, metal elements, dry deposition, and emission factor

1. Introduction

Recently, considerable attention has been focused on the air quality degradation caused by the particulate matter. Many studies have shown that fugitive dust is the major source of TSP and/or PM_{10} [Chow et al., 1992; Watson et al., 1994]. Unpaved roads, agricultural tilling operations, aggregate storage piles, and heavy constructions contribute to fugitive dusts that are loaded with crustal elements [USEPA, 1996]. The ambient air concentration of particulate matter is universally high in developing areas because of higher road dust loading contributed from on-going construction activities.

PM_{10} can be easily transported through the upper respiratory tract into the bronchioles and alveoli of

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the lungs and cause direct health hazard. Most recent researchers focus their attentions on finer particulates such as $PM_{2.5}$ because of its ability to penetrate deep into the respiratory system. The effects of dust and deposits with large particles are both visible and tangible and are one of the main causes of complaint about air pollution [Hall et al., 1993]. The influences of coarse particles on the environment have been studied over the past decades [Steen, 1986; Noll et al, 1989; Noll et al., 1990]. Dry deposition is an important mechanism by which coarse particles are dispersed in the atmosphere to reach land surfaces. Some natural pollutants are also transported to the environment via the dry deposition process [Biddleman, 1988]. Particulate emission during construction is associated with land clearing, drilling and blasting, ground excavation, cut and fill operations, and the building of facilities itself. The particulate emission factors of these dust-generating activities are summarized in the USEPA's AP-42 manual. Application of numerical value suggested by the manual can yield uncertain emission estimates. There are recommendations for the reexamination of the manual [Venkatram, 2000].

The particulate matters emitted from construction sites are characterized by large particle sizes. Thus, the dry deposition phenomenon is significant. The particulates on the road and in construction areas are resuspended into the air by wind blow and mechanical disturbance. Johnson (1992) investigated the resuspension mechanisms of particulate matters from unpaved roads and found that one third of resuspended particulate matters (aerodynamic diameter greater than 10 μm) remained in the air after 40 seconds. That is, two thirds of particulate matters were deposited to the ground nearby. Nicholson (1992) investigated the relationship between resuspension and some parameters including time, wind speed, particle size, and particle shape by wind tunnel experiment. However, study on the characteristics of particulate and metal dry deposition at construction sites remains to be conducted. Many metals are hazardous to humans because they damage the nerve center, cause mental deficiency, induce heart diseases and even promote cancers [Nriagu and Pacyna, 1988; Paasivirta, 1991]. Metal pollution comes from industrial discharges and non-point sources of various kinds. Metals emitted from fugitive sources have been under-investigated. Fugitive sources emit large amounts of metal elements, especially crustal elements. In this study, twenty metal elements emitted from construction sites were measured. Particulate size distribution, particle-bound metal concentration, dry deposition flux and dry deposition velocity were evaluated.

2. Experiment

2.1. Sampling Programs

Eight large building construction sites (symbol as A-H) in Tainan city, Taiwan, were selected for this investigation. In Taiwan, construction activities are classified into building construction, road construction, zone development construction, bridge construction, pipe excavation construction and miscellanea for levying air pollution fees. Site E is a zone development construction and the other seven sites are all building construction. The area of zone development construction site E is 1,350,000 m^2 and the building construction sites are between 600 and 40,000 m^2 in area (Fig 1). The construction sites were selected with the following considerations: (1) The construction site is located in one open area without tall buildings nearby. (2) No other significant air pollution sources (especially of particulate matter) are identified near the sites. (3) On electricity supply, support from the site owner, and management security during the sampling are available. To enable comparison of upwind/ downwind data, multiple sampling spots were strategically situated around a construction site. One high volume sampler (General Metal

Table 1 Sample numbers and TSP concentrations at eight construction sites (A-H).

Sites	Sampling times (Number of sample)	Mean concentration ($\mu g/m^3$)	Range ($\mu g/m^3$)	RSD (%)
A	4 (16)	368	211-591	42.8
B	6 (24)	459	172-1150	49.1
C	4 (16)	1140	409-3990	83.4
D	3 (12)	633	190-2120	90.8
E	1 (2)	278	272-285	3.30
F	4 (16)	504	157-2530	112
G	2 (8)	1300	188-3240	93.7
H	2 (6)	122	107-233	39.9
Total	26 (100)	625	107-3990	

Work Co., GPS1 PUF sampler) and one set of dry deposition plate were set up at each sampling spot. The sampling campaigns were performed starting on Dec. 1996 through May 1997. The sampling durations were 6 hrs for PS-1 high volume sampler and dry deposition plate in order to collect enough particulate and metal elements for further elemental analysis. The sampling programs were performed at daytime (from 8:00 a.m. to 6:00 p.m.) when the construction work was active. A total of 100 particulate data and 100 dry deposition data for the whole sampling program were collected for analysis. All the sampling campaigns were performed from the beginning of the construction projects. The number of samples at each construction site is listed in the second column of Table 1.

2.2. Sampling Methods

Total Suspended Particulate (TSP)

TSP and metal elements were collected by using a high volume sampler (General Metal Works PS-1) equipped with a quartz filter (Whatman International Ltd., 2500QAT-upe). The diameter of the filter is 10.2 cm and the pore size is 0.8 μm. A quartz filter was weighed before and after sampling, the difference was accrued to the suspended particulate matter collected. The filter was then digested by acid for chemical analysis of metal elements.

Dry Deposition Plate

Dry deposition of particulates and metal elements were measured by a smooth surface plate with a sharp leading edge and the plate was mounted on a wind vane [Holsen et al.,1993]. The plate used in this study was similar to those used in wind tunnel studies [McCready, 1986]. It was made of polyvinyl chloride (PVC) and was 21.5 cm long, 8.0 cm wide, and 0.8 cm thick with a sharp leading edge (< 10-degree angle) pointing toward the wind direction. In order to minimize system errors during the experiments, 3 duplicate plate samples on a side- by-side basis were taken during each sampling period for averaging.

Each plate was covered with quartz strips (10 cm x 8 cm) coated with silicon grease (NO. 11025 silicon spray, Cling-surface CO., Inc., Angola, NY) to collect impacted particles (132 cm^2 of total exposed surface). The coating is hydrophobic and has a high molecular weight and low vapor pressure suitable for capturing the particulate and metal flux. The strips were placed on the plate and held down at the edge with a 0.03 cm thick stainless steel template, which was secured at each end by acrylic slats screwed into the plate. The plate was cut out so that it would slide onto a 3-cm diameter rod.

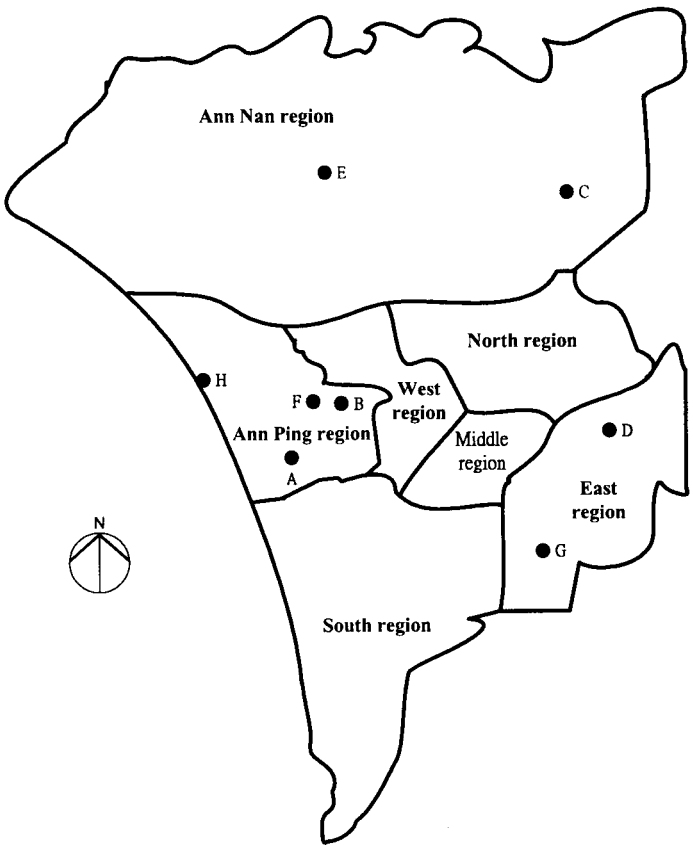

Fig. 1 Map of sampling sites. Area of construction sites are A: 12,900 m^2; B: 650 m^2; C: 19,300 m^2; D: 600 m^2; E: 1,350,000 m^2; F: 2,380 m^2; G: 9,300 m^2; H: 40,000 m^2. Site E is zone development construction and the others are all building construction sites.

Two screws were fastened through the plate to a wind vane, allowing the plate to swing freely into the wind direction. Each plate was separated by 55 cm (horizontally), which was shown experimentally to be sufficient to prevent sampling interference. The strips were weighed before and after sampling to determine the total mass of the particles collected. The strips were then digested and the solution was analyzed for metal elements.

Wind Direction and Wind Speed

Wind direction and wind speed at ground level height was measured for each sampling campaign. An anemometer (Davis Company, Model: Weather Monitor II) was used for this investigation.

Analysis of Elemental Composition

Twenty metal elements (Al, Ca, Fe, Mg, Na, Pb, Zn, Ni, V, Ba, Mn, Cr, Cu, Cd, Sr, Ag, Mo, Sb, As, and Ti) were analyzed in this study. Silicon (Si) was not resolved in this experiment due to its abundance in the quartz filter. The total suspended particulate and dry deposition particulate samples were first treated with pressurized digestion [Wang et al., 1989]. Polytetrafluoro-ethylene (PTFE), polyethylene and polypropylene containers were used. All chemicals used were supplied by Merck (pro analysis grade) and high-purity water (resistance > 10 MΩ) produced by reverse osmosis and demineralization was used. All stock solutions of the elements of interest (2000 μg/mL) were prepared from Titrisol concentrates (Merck) by diluting to volume with de-ionized water.

One fourth of Whatman 2500QAT-upe quartz filter loaded with airborne particulate matter was placed in a 25-mL PTFE container and a 5-mL mixture of HNO_3 and $HClO_4$ (3 + 7 V/V) was

Table 2 Blanks of quartz filter.

Metals	Wave length (nm)	Content (μg/g)
Al	396.152	0.22 ± 0.025
Ca	393.366	0.30 ± 0.027
Fe	238.204	0.19 ± 0.012
Mg	279.553	0.07 ± 0.006
Na	588.995	0.32 ± 0.029
Pb	220.353	0.01 ± 0.001
Zn	213.856	0.01 ± 0.002
Ni	221.647	0.04 ± 0.006
V	268.796	<0.018
Ba	455.403	0.00 ± 0.001
Mn	257.610	< 0.001
Cr	205.552	< 0.022
Cd	214.438	< 0.011
Ag	279.413	< 0.029
Cu	224.700	0.01 ± 0.002
Sr	421.552	< 0.014

added. The sealed container was then transferred into a pressure bomb (supplied by Berghof) and heated on a heating block at 170 °C for 5 hours to facilitate complete dissolution.

After cooling to room temperature, the solution was transferred into a 25-mL calibrated flask and diluted to volume with distilled water. The digested samples were then measured for the metal elements by using an inductively coupled plasma/atomic emission spectrometry (ICP/AES, Jobin-Yvon JY38 Plus).

Blank tests were performed. Quartz filters with no particulate matter were placed in PTFE containers and the digestion procedures were followed. The actual metal concentration was obtained by subtracting the blank concentration. The content of metal elements in the blank quartz filter are listed in Table 2. Spectral interferences due to the matrix effect and background shift were studied qualitatively by examining the standard additions and calibration graphs. The calibration graphs were constructed by measuring multi-element standards prepared in the laboratory.

3. Results and Discussion

3.1 TSP Concentration

TSP concentrations at the eight building construction sites are listed in Table 1. Except for sites E and H, TSP concentrations higher than 500μg/m^3 were observed at other sites. The concentration of 500 μg/m^3 is the regulation standard of TSP concentration at construction sites in Taiwan. Among these 100 samples, 34 samples did not satisfy the regulation standard. This showed that particulate matter emission from construction sites was serious. Levying air pollution fees on construction projects was started in Taiwan since 1997/7/1 (after our sampling campaign), and the particulate matter emission is expected to decrease. In this study, TSP concentrations were between 107 and 3,990, and averaged 625 μg/m^3. The relative standard deviation (RSD) of these eight construction sites was between 3.30 and 112 %. The high variation of particulate matter emission is one of the most important characteristics of construction sites. Particulate emissions at construction sites often vary substantially from day to day, depending on the wind speed, level of construction activity and the specificity of operations.

Table 3 The influence of wind direction and speed on TSP concentration at eight construction sites.

Sites	Sampling code	Wind speed (m/s)	Wind direction	Mean concentration (μg/m^3)	Concentration Ratio (Upwind/ Downwind)
A	A-1	4.8	N	553	0.99
	A-2	4.2	W	412	0.96
	A-3	4.5	E	277	0.98
	A-4	5.0	E	229	1.04
B	B-1	2.1	E	494	0.93
	B-2	3.6	E	504	0.90
	B-3	4.2	N	724	2.74
	B-4	1.9	S	391	0.40
	B-5	3.5	N	365	2.02
	B-6	2.9	N	366	1.05
C	C-1	2.1	W	976	0.31
	C-2	1.5	N	801	2.81
	C-3	3.1	N	1540	0.39
	C-4	2.1	N	1240	3.79
D	D-1	3.1	E	233	0.69
	D-2	2.7	N	956	0.59
	D-3	1.6	N	710	0.54
E	E-1	1.2	WS	278	0.95
F	F-1	2.0	N	451	3.42
	F-2	2.0	N	907	5.44
	F-3	2.7	S	329	0.60
	F-4	2.7	W	330	1.21
G	G-1	1.4	N	2330	0.85
	G-2	2.5	W	268	1.78
H	H-1	1.9	W	177	1.79
	H-2	2.1	S	147	0.63

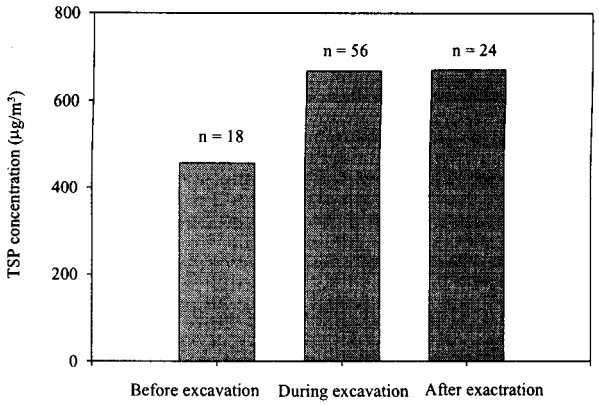

Fig. 2 The influence of excavation on TSP concentration.

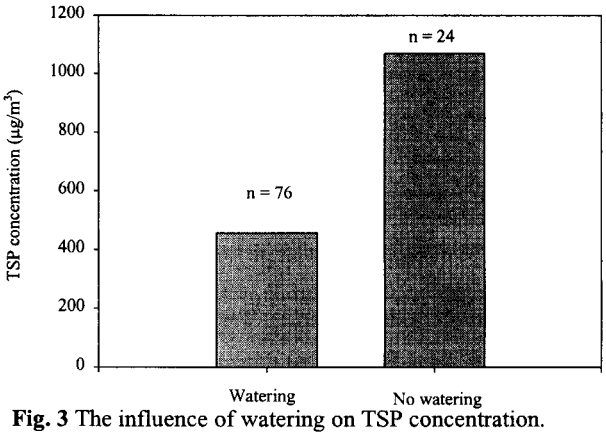

Fig. 3 The influence of watering on TSP concentration.

The factors affecting particle reentrainment include wind speed, particle size, humidity, and surface roughness [Matsusaka and Masuda, 1996]. Of these parameters, wind speed was proposed as an important factor that affects the emission of particulate matter from fugitive sources [USEPA, 1996]. The other previous studies showed reentrainment may occur at all wind speeds [Matsusaka and Masuda, 1996]. In this study, a ratio of TSP concentration at upwind divided by that at downwind was used to estimate the effect of wind speed on TSP concentration. The ratio less than 1.0 means that TSP concentration is higher on the downwind side, which is probably caused by reentrainment of particulate. In this field experiment of construction sites, however, TSP concentration was not significantly higher on the downwind side for wind speeds between 1.7 and 5.0 m/s (Table 3). Among the 26 sampling

Table 4 Input parameters for ISCST model and the estimated results.

Sampling code	Perimeter (m)	TSP conc. at downwind side (μg/m³)	Wind speed (m/s)	Wind direction	Stability	Ambient temperature (K)	Emission factor (kg/m²-month)	Average (kg/m²-month)
A-1	114	591	4.8	N	C	292	0.778	0.429
A-2		269	4.2	W	C	293	0.291	
A-3		230	4.5	E	C	294	0.311	
A-4		229	5.0	E	D	288	0.337	
B-1	23.7	467	2.1	E	B	288	0.671	0.768
B-2		529	3.6	E	B	288	1.35	
B-3		336	4.2	N	C	286	1.04	
B-4		425	1.9	S	B	287	0.555	
B-5		229	3.5	N	B	286	0.555	
B-6		244	2.9	N	C	287	0.544	
C-1	140	1500	2.1	W	B	287	1.09	0.686
C-2		1240	1.5	N	B	286	0.516	
C-3		491	3.1	N	B	287	0.645	
C-4		676	2.1	N	B	288	0.492	
D-1	24.5	272	3.1	E	C	289	0.591	0.886
D-2		830	2.7	N	B	287	1.48	
D-3		555	1.6	N	B	288	0.588	
E-1	200	285	1.2	WS	B	287	0.163	0.163
F-1	48.8	228	2.0	N	B	293	0.200	0.349
F-2		464	2.0	N	B	293	0.404	
F-3		345	2.7	S	B	293	0.404	
F-4		265	2.7	W	A	296	0.389	
G-1	96.5	3240	1.4	N	B	297	1.66	0.916
G-2		188	2.5	W	B	298	0.171	
H-1	200	107	1.9	W	A	299	0.152	0.197
H-2		356	2.1	S	A	301	0.242	
Overall							0.549 ± 0.303	

The perimeter of construction sites parallel to the wind direction (m)

campaigns, only 15 had higher TSP concentration at downwind. The anemometer installed in this study was not right at downwind side; therefore it is not certain whether the wind was parallel to the axis of upwind and downwind sites during TSP collection.

Some construction activities play a more important role in particulate emission than others. In this study, the effect of ground excavation and watering on TSP emission was investigated. TSP average concentrations before, during, and after ground excavation were 457, 668, and 670 μg/m^3, respectively (Fig. 2). This showed that before ground excavation, TSP concentration was

significantly lower. During ground excavation, a lot of dirt was resuspended into the air, which was enhanced by frequent truck flow. After ground excavation, various construction activities still caused high TSP emission. The influence of watering on TSP emission was shown in Fig. 3. Average TSP concentrations were 476 and 1,070 $\mu g/m^3$ for watering and no watering respectively. Watering reduced TSP concentration by 55.5% in this study.

3.2. Emission Factors of TSP

At present, three methods have been used to infer emissions from paved roads. These methods may be applicable to estimate the emission from construction sites [Venkatram, 2000]. The first is a mass balance calculation using the profiles of particulate concentrations [Cowherd and Englehart, 1984]; the second is a dispersion modeling using the concentration measurements [Claiborn et al., 1995]; the third is the tracer methods [Kantamaeni et al., 1996]. An ISCST dispersion model was utilized to estimate particulate emission factor in this study. Wind speed, wind direction, construction dimension, ambient temperature and stability conditions were the input parameters (Table 4). Particulate emission from these eight building construction sites was determined to be between 0.163 and 0.916 kg/m^2-month, and averaged 0.549 $\pm$ 0.303 kg/m^2-month. These values are very near the emission rates investigated by Chang et al. (1999).

3.3 Dry Deposition of TSP

Particulate dry deposition fluxes and dry deposition velocities at construction sites are listed in Table 5. Particulate dry deposition fluxes for these eight construction sites were between 678 and 3,760 mg/m^2-day. Noll et al. (1990) measured the particulate dry deposition flux of an urban environment (Chicago) by using the same type of dry deposition sample device. The mean dry deposition flux in Chicago is 175 mg/m^2-day. Lee (1991) and Lin et al. (1993) also investigated the dry deposition characteristics in Chicago and found the mean dry deposition fluxes are 172 and 163 mg/m^2- day, respectively. Sheu et al. (1996) found that the particulate dry deposition fluxes are 134 mg/m^2-day for urban and 361 mg/m^2-day for petrochemical-industry areas, respectively. Fang et al. (1997) found that the particulate dry deposition flux at slip roads in Taiwan is 323 mg/m^2-day. These studies showed that the particulate dry deposition fluxes in non-construction environments (urban environments, slip roads, and traffic interactions) are significantly lower than those at the construction sites of this study.

Table 5 Particulate dry deposition fluxes (mg/m^2-day) and dry deposition velocities (cm/s) at construction sites.

Sites	Location	Number	Particulate dry deposition flux	Mean	Particulate dry deposition velocity	Mean
A	E	4	712	1460	2.65	4.95
	W	4	1150		4.95	
	S	4	1950		6.70	
	N	4	2040		5.48	
B	E	6	2770	1780	5.28	4.30
	W	6	1710		4.82	
	S	6	888		3.46	
	N	6	1750		3.62	
C	E	4	3980	3760	2.13	3.43
	W	4	1240		2.36	
	S	4	1570		2.61	
	N	4	8240		6.62	
D	E	3	6920	3140	9.03	5.55
	W	3	1430		2.40	
	S	3	2850		6.93	
	N	3	1350		3.83	
E	EN	1	859	678	3.50	2.80
	WS	1	497		2.10	
F	E	4	2350	2180	8.45	5.55
	W	4	1260		4.85	
	S	4	1030		3.70	
	N	4	4060		5.18	
G	E	2	3260	3040	3.70	2.63
	W	2	2050		2.65	
	S	2	3680		2.75	
	N	2	3180		1.40	
H	E	2	464	762	3.75	5.25
	W	2	865		5.40	
	S	2	957		6.60	

The particulate dry deposition velocity has been estimated by the following equation [Noll et al., 1990]:

$$V_d = F/C \qquad (1)$$

Table 6 The influence of wind on particulate dry deposition flux

Sites	Sampling code	Wind speed (m/s)	Wind direction	Mean particulate dry deposition flux (mg/m^2-day)	Ratio (Upwind/Downwind)
A	A-1	4.8	N	1830	2.83
	A-2	4.2	W	1170	1.68
	A-3	4.5	E	919	0.49
	A-4	5.0	E	1920	0.49
B	B-1	2.1	E	1590	1.37
	B-2	3.6	E	1550	0.58
	B-3	4.2	N	3200	3.35
	B-4	1.9	S	1270	0.27
	B-5	3.5	N	1530	7.33
	B-6	2.9	N	1100	1.93
C	C-1	2.1	W	2030	0.52
	C-2	1.5	N	3440	9.93
	C-3	3.1	N	4490	1.28
	C-4	2.1	N	5100	10.0
D	D-1	3.1	E	430	1.46
	D-2	2.7	N	4760	0.58
	D-3	1.6	N	4950	0.14
E	E-1	1.2	WS	678	0.57
F	F-1	2.0	N	2000	2.70
	F-2	2.0	N	4540	4.55
	F-3	2.7	S	431	0.52
	F-4	2.7	W	1730	0.32
G	G-1	1.4	N	4040	10.5
	G-2	2.5	W	700	1.78
H	H-1	1.9	W	784	4.63
	H-2	2.1	S	741	0.84

Where

V_d : dry deposition velocity of particulate matter (cm/s).

F: dry deposition flux of particulate matter (mg/m^2-day);

C: measured ambient concentration of particulate matter ($\mu g/m^3$);

The estimated particulate dry deposition velocities of these eight construction sites are also listed in Table 5. The mean particulate dry deposition velocities for these eight construction sites were between 2.63 and 5.55 cm/s. These values are higher than the values measured at urban environments, slip roads, traffic interactions, and the ambient air [Noll et al., 1990; Lee, 1991; Lin et al., 1993; Fang et al., 1997]. The particulates generated from the construction sites were probably caused by wind blowing of road dust and sand pile, and mechanical disturbance of construction materials. These types of mechanisms generate

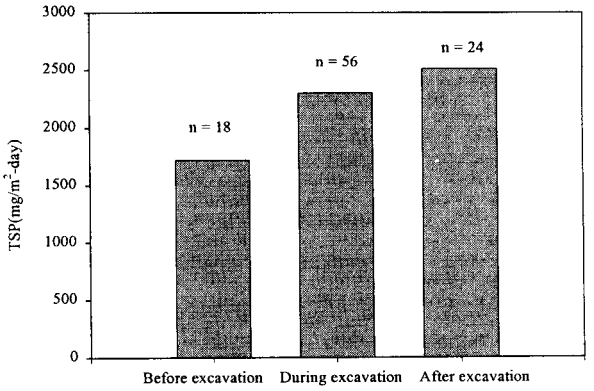

Fig. 4 The influence of excavation on particulate dry deposition flux.

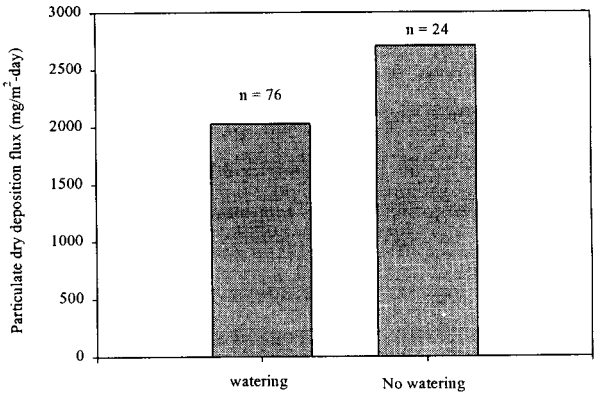

Fig. 5 The influence of watering on particulate dry deposition flux.

particles relatively large in size. Larger particles exhibit a high gravitational settling velocity that is tantamount to high dry deposition velocity at construction sites [Sheu et al., 1996].

The influence of wind on particulate dry deposition flux was also investigated. The ratio in Table 6 is the quotient of particulate dry deposition flux at upwind divided by at downwind. Similar to the TSP concentration, among the 26 sampling campaigns, only 11 sampling campaigns had a ratio lower than 1.0. Wind does not show as a significant factor for particulate dry deposition flux at building construction sites. The effects of ground excavation and watering on particulate dry deposition flux were also investigated. As Fig. 4 shows, particulate dry deposition fluxes before, during, and after ground excavation were 1,720, 2,300, and 2,510 mg /m^2-day, respectively. And

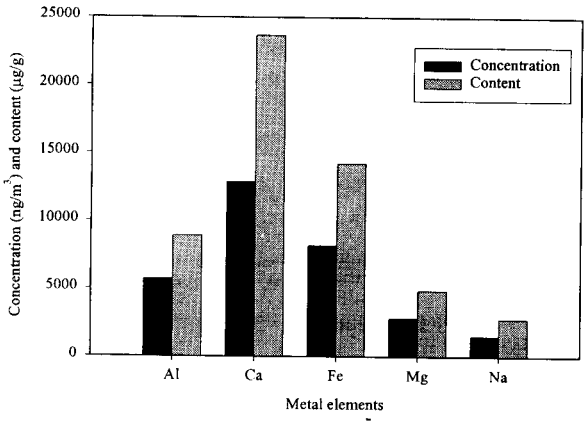

Fig. 6 Five major metal elements concentration and content at construction sites.

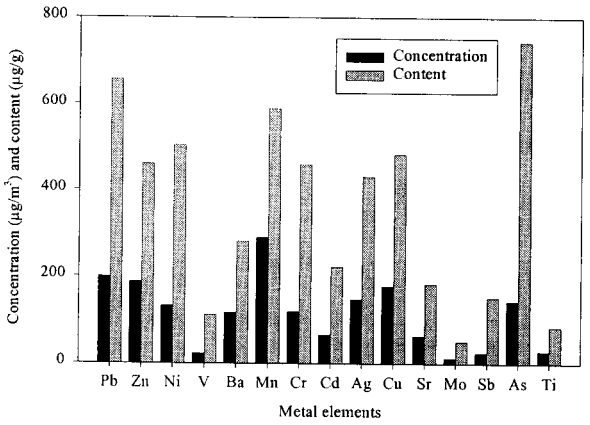

Fig. 7 Minor metal element concentration and content at construction sites.

as Fig. 5 shows, particulate dry deposition fluxes with and without watering were 2,030 and 2,710 mg/m^2-day, respectively. Similar to the effect on TSP concentration reduction, watering also reduced TSP dry deposition fluxes.

3.4 Emission of Metallic Elements at Construction Sites.

Twenty metal elements embedded in the particulates from construction sites were analyzed chemically. In terms of concentrations (ng/m^3) and contents (μg/g), the five top elements were Al, Ca, Fe, Mg, and Na. Fig. 6 shows the concentrations and contents of the major five while Fig. 7 shows the other elements. The mean concentrations of Al, Ca, Fe, and Mg at eight building construction sites were 5,720, 12,900, 8,210, and 2,860 ng/m^3, respectively. The mean contents of Al, Ca, Fe, and Mg were 8,930, 23,700, 14,200,and 4,870 μg/g, respectively. Na was also a major component, the content of Na in the particulate was 2,770 μg/g. Yang (1998) analyzed 16 ambient air metal element concentrations in southern Taiwan. The first five major metal elements were also Al, Ca, Fe, Mg, and Na. The fact that these metals are crustal elements shows that fugitive dust is a significant source of particulate in the ambient air. Of the other 15 metal elements, the variations of sampled concentrations among these eight building construction sites are small. These metal elements are not generated from mineral dust, and samplers at construction sites are far away from anthropogenic pollution sources, the concentrations of these metals are quite stable.

The concentrations of these 20 elements were further analyzed by performing linear regression analysis on the TSP concentrations. The R^2 values are 0.90, 0.80, 0.86, and 0.90 for Al, Ca, Fe, and Mg at the eight construction sites, respectively (Fig. 8). Except for Na ($R^2 = 0.80$), the R^2 values for the other metals are below 0.6. The results show that the concentrations of crustal elements are linear to the TSP concentrations.

3.5 Dry Deposition of Metallic Elements

Dry deposition flux and dry deposition velocity of the metal elements at construction sites have seldom been investigated. This study measured and evaluated the twenty metal dry deposition fluxes, and dry deposition velocities at eight building construction sites. Mean values of dry deposition fluxes and dry deposition velocities of Al, Ca, Fe, Mg, and Na are shown in Fig. 9 and Table 7. Similar to their showing the importance in concentrations, these five metals are also the major elements of dry deposition. The mean dry deposition fluxes of Al and Fe are 9.32 and 14.4 mg/m^2-day. These are higher than those observed in the Chicago urban environment of 3.25 and 5.14 mg/m^2-day [Noll et al., 1990] (Table 7).

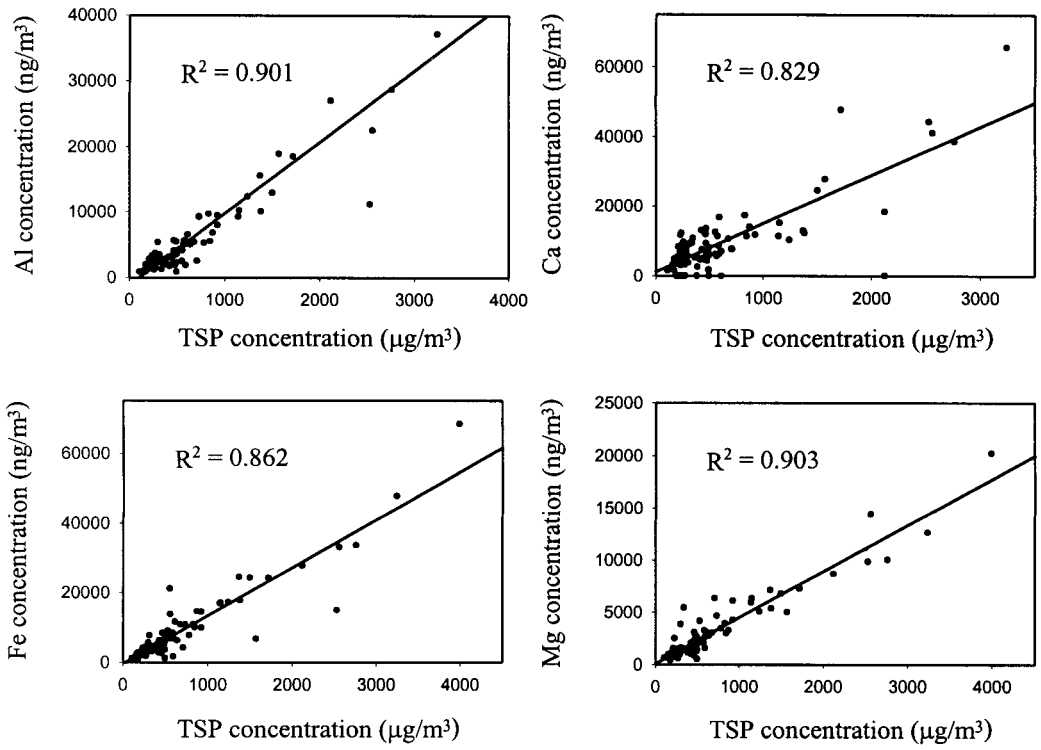

Fig. 8 Correlation between TSP and metal concentration for eight construction sites in this study

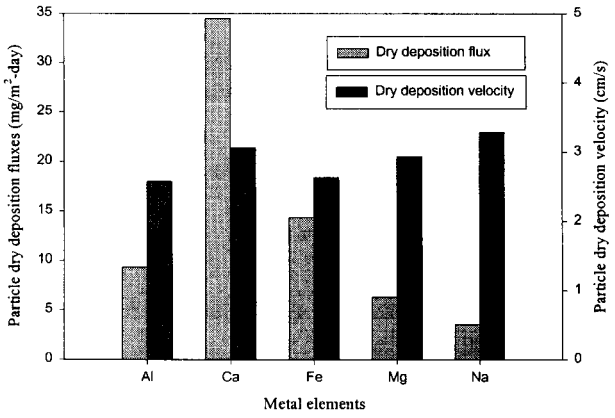

Fig. 9 Five major metal dry deposition fluxes and dry deposition velocities.

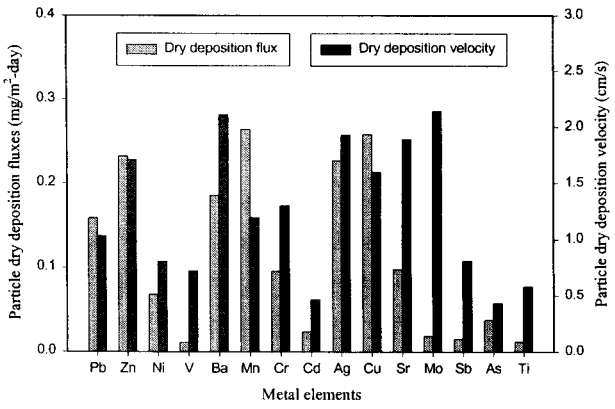

Fig. 10 Minor metal element dry deposition fluxes and dry deposition velocities.

In comparison with the studies in coastal areas, crustal elements dry deposition flux at construction sites is 1-10 order higher [Golomb et al., 1997; Rojas et al., 1993; Ottley and Harrison, 1993]. Except for the polluted city Chicago, the metal dry deposition fluxes were higher than coastal sites, but not significantly higher as major element (Table 7).

Similar to the particulate dry deposition velocity, metal dry deposition velocities were calculated from equation (1) and are shown in Figs. 9 and 10. Most previous studies focused on metal deposition to the sea and lakes. Ottley and Harrison (1993) found that the dry deposition velocities of Al, Fe, Pb, and Zn in the North Sea were 0.46, 0.45, 0.17, and 0.52 cm/s, respectively. Rojas et al. (1993) found that the dry deposition velocities of Pb and Zn in the North Sea were 0.25 and 0.35 cm/s. The dry deposition velocities of Pb and Ni at Ligurian Sea were 0.22 and 1.2 cm/s [Migon et al., 1997]. In our study, the dry deposition velocities of crustal metal elements (Al, Ca and Fe) are 2.6, 4.9 and 2.8 cm/s; these are higher than the findings of the previous studies. For other anthropogenic

Table 7 Dry deposition fluxes of metal elements in the literature ($\mu g/m^2$- day)

Metal	Noll et al (1990) Chicago	**Golomb et al (1997)** Massachusetts	Dedeuwaerder et al (1982) North Sea	Baeyens et al (1990) North Sea	Ottley and Harrison (1993) North Sea	Rojas et al (1993) North Sea	This study
Al	3249	34.0	N.D.	289	37.7	N.D.	9320
Ca	142733	N.D.	N.D.	N.D.	N.D.	N.D.	34500
Fe	5141	292	N.D.	224	28.4	N.D.	14400
Mg	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	6300
Na	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	3560
Pb	233	3.52	12.3	9.05	1.91	14.0	159
Zn	579	14.0	9.59	17.0	13.6	21.6	232
Ni	N.D.	2.48	N.D.	N.D.	N.D.	N.D.	68.0
V	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	11.0
Ba	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	186
Mn	104	7.26	N.D.	N.D.	N.D.	N.D.	264
Cr	N.D.	3.42	N.D.	N.D.	N.D.	N.D.	96.0
Cd	1.73	0.356	0.110	1.01	0.171	0.438	24.0
Ag	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	227
Cu	173	5.48	1.92	7.65	1.81	4.38	258
Sr	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	98.0
Mo	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	19.0
Sb	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	15.0
As	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	38.0
Ti	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	12.0

N.D.: No data.

elements, dry deposition velocities were not higher at construction sites than in the urban environment and coastal areas. Crustal metals are nonvolatile and most metals are bound with particulate. Thus, the higher particulate dry deposition velocity would result in a higher crustal metal dry deposition velocity.

4. Conclusions

Emission characteristics of twenty metal elements and particulate matter at eight construction sites were investigated for a period of 6 months from Dec. 1996 to May 1997. Ambient air TSP concentrations at the eight construction sites were between 107 and 3,990 $\mu g/m^3$ with an average of 625 $\mu g/m^3$. The relative standard deviations were between 3.30 and 112 %, which covered a wide range of variation. TSP concentrations before, during, and after ground excavation averaged 457, 668, and 670 $\mu g/m^3$, respectively. During ground excavation, a lot of dirt was scoured into the air. The intensity of pollution was enhanced by frequent truck flow. After ground excavation, various construction activities still caused high TSP emission. TSP concentrations averaged 476 and 1,070 $\mu g/m^3$ for watering and no watering. Watering reduced TSP by 55.5% concentration in this study. Particulate dry deposition fluxes for these eight construction sites were between 678 and 3,760 mg/m^2-day. The average of the particulate dry deposition fluxes before, during, and after ground excavation were 1,720, 2,300, and 2,510 mg/m^2-day, respectively. The averages of the particulate dry deposition fluxes with watering and without watering were 2,030 and 2,710 mg $/m^2$-day, respectively. Crustal elements (Al, Ca, Fe, and Mg) were found to be the major metal components in the atmospheric particulate at construction sites. The mean concentrations of Al, Ca, Fe, and Mg at these construction sites were 5,720, 12,900, 8,210, and 2,860 ng/m^3, respectively. Regression analysis showed that the concentrations of crustal elements and the TSP concentrations were linearly correlated ($R^2 \geq 0.8$). Finally, a dispersion model was employed to estimate particulate emission factor at construction sites. Particulate emissions from these eight building construction sites were between 0.163 and 0.916 kg/m^2-month with an average of 0.549 kg/m^2-month and a standard deviation of 0.303 kg/m^2- month.

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Received for review, May 25, 2000
Accepted, April 17, 2001
AAQR-2001-08