Characterization of PM_{10} and $PM_{2.5}$ source profiles for fugitive dust in Hong Kong

K.F. Ho[a], S.C. Lee[a,*], Judith C. Chow[b], John G. Watson[b]

[a] *Department of Civil and Structural Engineering, Research Centre for Urban Environmental Technology and Management, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

[b] *Division of Atmospheric Sciences, Desert Research Institute, 2215 Raggio, Parkway, P.O. Box 60220, Reno, NV 89506, USA*

Abstract

PM_{10} and $PM_{2.5}$ chemical source profiles from Hong Kong were investigated for paved road dust and soil. These profiles are needed for urban-scale speciated emissions inventories and for source apportionment by receptor modeling. Five urban soil and five paved road dust samples were collected, dried and sieved, resuspended in a laboratory chamber, air drawn through PM_{10} and $PM_{2.5}$ inlet onto Teflon and quartz filters. The filter samples were submitted for both gravimetric and chemical analyses. Chemical analyses included X-ray fluorescence for elemental composition, ion chromatography for water soluble chloride, nitrate, sulfate, atomic absorption spectrophotometry for water soluble sodium and potassium, automated colorimetric analysis for ammonium and thermal/optical reflectance analysis for carbon species. The $PM_{2.5}$ constituted 11–30% of the PM_{10} in all geological samples. Al, Si and organic carbon (OC) are abundant constituents in all paved road dust and soil samples. The chemical abundances of $PM_{2.5}$ and PM_{10} for a given source type were similar for most species. In addition, results from resuspended soil (three sets), paved road dust (five sets), aggregate (three sets) and cement (two sets) were obtained from Hong Kong Environmental Protection Department (HKEPD) for comparison as well as mass closure analysis.
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1. Introduction

Fugitive dust from paved and unpaved roads, construction and demolition and bare ground sites are important contributors to PM_{10} and $PM_{2.5}$ in many urban areas (Watson et al., 1989; Chow et al., 1993a; Chow and Watson, 2002). In Hong Kong, no PM_{10} and $PM_{2.5}$ chemical source profiles for fugitive dust have previously been performed. Soil and road dust surveys have been conducted to study the current conditions of heavy metals contamination (Li et al., 2001). Our previous studies found that, TSP exceeded the annual average of the Hong Kong Air Quality Objective (HKAQO) by a factor of 1.53, while PM_{10} exceeded by 1.39. The annual average concentration of $PM_{2.5}$ exceeded the Unit States National Ambient Air Quality Standard (NAAQS) annual average of $15 \, \mu g/m^3$ by a factor of 3.8 at the Hong Kong Polytechnic monitoring station (Chan et al., 2001). Aerosol particles emissions (motor vehicle exhausts, lubricating oil residues, tire and brake lining wear, street surface weathering, etc.) are emitted into the atmosphere and redeposited (Manoli et al., 2002). Other pollutants can accumulate in topsoil from atmospheric deposition by sedimentation, impaction and interception. Urban soils near heavy traffic are easily polluted by vehicular exhaust (Culbard et al., 1988; Wong and Mak, 1997). Fugitive dust emission rates for these sources are difficult to measure or

*Corresponding author. Tel.: + 852-276-66011; fax: + 852-2334-6389.

E-mail address: ceslee@polyu.edu.hk (S.C. Lee).

estimate (Cowherd and Grelinger, 1992; Fryrear, 1992; Watson et al., 2000). Although most of the sources of $PM_{2.5}$ and PM_{10} in Hong Kong originate from fuel combustion and secondary aerosol formation, a substantial fraction is still contributed by fugitive dust from roads and construction. According to reconstructed chemical composition, using Al as a tracer material of crustal element, crustal matter accounted for 11% of PM_{10} and 6% for $PM_{2.5}$ in Hong Kong (Ho et al, 2002). Several studies have identified mass concentrations (Chan et al., 2001; Chan and Kwok, 2001) and chemical composition for atmospheric aerosols in Hong Kong (Cheng et al., 2000; Zhuang et al., 1999a; Qin et al., 1997; Fung and Wong, 1995). There is limited information on source emissions, however, especially the chemical compositions in $PM_{2.5}$ size fractions. The most important use of these source profiles is for source apportionment using receptor models that quantify contributions from different source types to chemically speciated ambient samples (Chow et al., 1993a, 1999; Chow and Watson, 1994a; Watson et al., 1994). This is the first study on chemical source profiles of several fugitive dust emitters in Hong Kong. The objective was to develop profiles that could be used for receptor modeling.

2. Methodology

2.1. Study area

Hong Kong consists of three geographical areas, namely the Hong Kong Island, the Kowloon Peninsula and the New Territories. Most of the commercial and residential areas are located in the northern part of Hong Kong Island and the Kowloon Peninsula. As shown in Fig. 1, ten geological samples (five urban soil samples and five road dust samples) were collected during 2001 in Hong Kong. These included the urban area of PolyU (PU), Kwun Tong (KT), Cheung Sha Wan (CSW) and Tuen Mun (TM) as well as the non-urban area of Hok Tsui (HT). PU, CSW, TM are classified as heavy traffic area and KT is mixed residential and industrial area. HT situated at the tip of southern Hong Kong, where the least anthropogenic pollution is expected. Also 13 set of resuspension data for soil (three sets from country park), paved road dust (five sets) aggregate (three sets) and cement (two sets) were obtained from HKEPD for data analysis (Fig. 1). The descriptions of sampling locations for fugitive source profile are shown in Table 1.
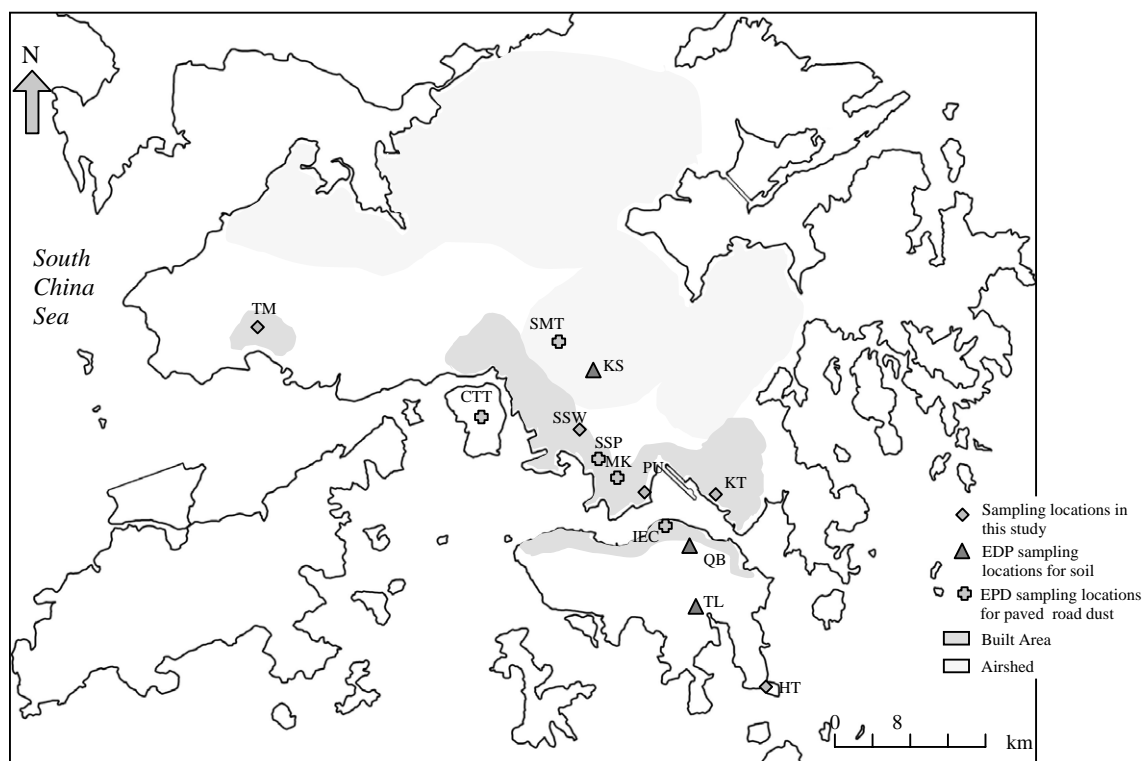

Fig. 1. The sampling locations of soil and paved road dust in Hong Kong (CSW = Cheung Sha Wan; HT = Hok Tsui; KT = Kwun Tong; PU = PolyU; Tuen Mun = TM; KS = Kam Shan Country Park; QB = Quarry Bay Country Park; TL = Tai Lam Country Park; CTT = Cheung Tsing Tunnel; IEC = Island East Corridor; MK = Mongkok; SMT = Shing Mun Tunnel; SSP = Shamshuipo).

Table 1
Descriptions of sampling locations for fugitive source profile

Profile name	Description
Country park soil	Composite of three soil samples collected in country park (Kam Shan Country Park, Quarry Bay Country Park, Tai Lam Country Park)
Urban soil	Composite of five soils samples collected in urban or near roadside areas
Paved road dust	Composite of 10 paved road dust samples collected in highways, commercial/residential areas and tunnels
Cement	Composite of 2 cement samples
Aggregate	Composite of 2 aggregate samples

3. Sampling and analysis

A portion of the surface dusts and soils were swept from representative portions of the ground surface using a plastic brush and tray. The samples collected were stored in labeled polyethylene bags prior to analysis. Samples were oven-dried at about 50°C for more than 24 h to remove moisture while minimizing losses of volatile compounds such as nitrate and organic carbon (Vega et al., 2001). Samples from different locations within a given source type were thoroughly mixed and sieved for approximately 1 h through Tyler 30, 50, 100, 200, and 400 mesh sieves to obtain ~5 g of material (nominal geometric diameter <38 μm for the 400 mesh sieve). The sieved material was suspended in a chamber and sampled through size-selective inlets onto filters for analyses (Chow et al., 1994b). Approximately 100 g of sieved material was placed in a 250 ml side-arm vacuum flask sealed with a rubber stopper. Air puffs into the flask introduced dust into the chamber where it was sampled until 0.5–5 mg deposits were obtained on $PM_{2.5}$ and PM_{10} filters. Clean, filtered laboratory air was drawn into the chamber by the sample flow of 10 l/min through each filter. Filters for both $PM_{2.5}$ and PM_{10} were periodically weighed during the resuspension process to monitor loading. Teflon-membrane filters (#R2PJ047) of 47 mm in diameter (Gelman Scientific, Ann Arbor, MI) with 2 μm pore size collected samples for mass and subsequent elemental analysis (40 elements from Na to U). Quartz-fiber filters (Whatman Corp., Hillsboro, OR; QM/A) collected samples on parallel channels for water-soluble anions (Cl^-, NO^{3-}, SO_4^{2-}) and cations (Na^+, K^+, NH_4^+), organic carbon and elemental carbon analyses. The Teflon-membrane filters were equilibrated in a relative humidity (~30%) and temperature (21.5 ± 0.5°C) controlled environment before gravimetric analysis to minimize particle volatilization and aerosol liquid water bias. Filters were exposed to a low-level radioactive source (500 pCi of polonium210) prior to and during sample weighing to remove static charge. Filters were weighed before and after sampling with a microbalance. The balance sensitivity is ± 0.001 mg, although up to a ± 0.010 mg is allowed on periodic re-weights before all filters were submitted for re-weighing. Chemical analyses of the filters included X-ray fluorescence for Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Y, Zr, Mo, Pd, Ag, Cd, In, Sn, Sb, Ba, La, Au, Hg, Tl, Pb, and U (Watson et al., 1999), ion chromatography (Chow and Watson, 1999) for water soluble Cl^-, NO_3^-, SO_4^{2-}, atomic absorption spectrophotometry for water-soluble (Na^+, K^+), automated colorimetry for water soluble NH_4^+, and IMPROVE thermal/optical reflectance method (TOR) for organic carbon (OC) and elemental carbon (EC) (Chow et al., 1993b, 1996, 2001).

4. Results and discussion

4.1. Chemical abundances

Based on gravimetric analysis, $PM_{2.5}$ constituted 11–30% of the PM_{10} in soil and paved road dust. Tables 2 and 3 show the chemical compositions of source profiles for fugitive dust from all sources of $PM_{2.5}$ and PM_{10}, respectively. Fig. 2 shows the examples of PM_{10} chemical source profiles for paved road dust, and urban soil samples in Hong Kong. The height of each bar indicates the percent of the corresponding chemical species in emitted PM_{10}.

Al, Si and OC are abundant constituent in all paved road dust and soil samples. Generally speaking, the constituent with greatest concentration in the paved road dust profile was Si (19.24 ± 5.70%) and the second highest constituent was OC (13.93 ± 2.61%). Paved road dust samples are enriched in K (2.17 ± 0.40%), Ca (8.87 ± 1.39%) and Fe (5.09 ± 0.31%) also. Urban soil contained Si in the highest (27.11 ± 8.17%) abundance and Al in the second highest (15.14 ± 4.26%) abundance. They are enriched in OC (6.49 ± 2.82%), Fe (3.74 ± 0.26%) and K (2.35 ± 0.46%) also.

The elemental carbon (EC) abundance is higher (1.27 ± 0.75%) in paved road dust than in urban soil (0.36 ± 0.81%), with only 0.04% in the country park soil (collected by HKEPD). Substantial variations are found in the OC/TC ratios for different geological source profiles in other countries (Chow et al., 1994b). However

Table 2
Source profile chemical compositions (weight percent by mass) of fugitive dust for $PM_{2.5}$ in Hong Kong

Species	Country park soil	Urban soil	Paved road dust	Cement	Aggregate
NO_3^-	0.0463 ± 0.0375	0.0000 ± 0.2296	0.0542 ± 0.1037	0.0356 ± 0.0577	0.0593 ± 0.0290
SO_4^{2-}	0.2878 ± 0.1788	0.1463 ± 0.2321	1.4940 ± 0.4496	13.4523 ± 3.6178	0.2719 ± 0.0652
NH_4^+	0.1546 ± 0.0603	0.2780 ± 0.2335	0.0845 ± 0.1038	0.0304 ± 0.0230	0.0791 ± 0.0356
Sol. Na	1.3277 ± 0.5541	0.1027 ± 0.1808	1.1868 ± 0.3635	1.6756 ± 0.9330	1.0503 ± 0.2468
Sol. Mg	0.1439 ± 0.0614	0.1814 ± 0.2012	0.2438 ± 0.0992	0.4397 ± 0.1662	0.0651 ± 0.0111
Sol. K	0.1033 ± 0.0285	0.2101 ± 0.1834	0.3321 ± 0.0908	1.3036 ± 0.1049	0.2141 ± 0.0401
OC	5.0528 ± 0.5437	12.4943 ± 6.0769	14.7245 ± 2.6225	2.2723 ± 0.5556	1.3609 ± 0.4013
EC	0.0331 ± 0.0711	0.4808 ± 1.4671	1.2883 ± 0.7621	0.2718 ± 0.1373	0.0000 ± 0.0372
TC	5.0862 ± 0.5701	11.8792 ± 7.2860	15.6568 ± 3.1101	2.5444 ± 22.6067	1.3608 ± 0.4015
Al	11.7555 ± 0.4253	11.4706 ± 0.9203	4.0096 ± 0.4261	1.2291 ± 0.0805	6.8880 ± 0.4896
Si	14.6596 ± 0.5861	17.9548 ± 1.4008	10.2531 ± 0.7474	4.8333 ± 0.2921	19.8600 ± 1.4360
P	0.0190 ± 0.0155	0.0243 ± 0.0399	0.0913 ± 0.0439	0.0000 ± 0.0208	0.0018 ± 0.0266
S	0.1024 ± 0.0097	0.2190 ± 0.0368	0.6953 ± 0.1692	3.9984 ± 0.2780	0.0430 ± 0.0071
Cl	0.0000 ± 0.0216	0.0171 ± 0.0748	0.4509 ± 0.0870	0.0000 ± 0.2100	0.0732 ± 0.0258
K	1.0802 ± 0.0361	1.4059 ± 0.1179	1.6079 ± 0.0963	1.3519 ± 0.0851	3.8315 ± 0.1365
Ca	1.4805 ± 0.0509	2.7232 ± 0.2817	7.7560 ± 0.5788	36.2179 ± 1.0129	0.9921 ± 0.0322
Ti	0.1460 ± 0.0145	0.2549 ± 0.2335	0.2139 ± 0.0827	0.1087 ± 0.0091	0.1500 ± 0.0094
V	0.0062 ± 0.0160	0.0073 ± 0.1077	0.0009 ± 0.0446	0.0030 ± 0.0111	0.0066 ± 0.0109
Cr	0.0029 ± 0.0066	0.0243 ± 0.0225	0.0265 ± 0.0089	0.0096 ± 0.0018	0.0033 ± 0.0056
Mn	0.1155 ± 0.0043	0.1444 ± 0.0178	0.1096 ± 0.0112	0.0321 ± 0.0046	0.2525 ± 0.0073
Fe	3.9208 ± 0.0877	4.4386 ± 0.3370	6.1638 ± 0.7923	1.6633 ± 0.0429	3.7226 ± 0.0929
Co	0.0252 ± 0.0627	0.0028 ± 0.0692	0.0238 ± 0.0983	0.0116 ± 0.0267	0.0227 ± 0.0595
Ni	0.0000 ± 0.0000	0.0050 ± 0.0095	0.0042 ± 0.0052	0.0012 ± 0.0047	0.0000 ± 0.0023
Cu	0.0240 ± 0.0015	0.0189 ± 0.0106	0.0695 ± 0.0078	0.0259 ± 0.0012	0.0137 ± 0.0007
Zn	0.0451 ± 0.0023	0.2714 ± 0.0249	0.5923 ± 0.0496	0.0446 ± 0.0041	0.0326 ± 0.0016
Ga	0.0024 ± 0.0026	0.0064 ± 0.0181	0.0005 ± 0.0078	0.0002 ± 0.0018	0.0016 ± 0.0019
As	0.0009 ± 0.0061	0.0025 ± 0.0256	0.0015 ± 0.0232	0.0017 ± 0.0032	0.0000 ± 0.0040
Se	0.0006 ± 0.0016	0.0038 ± 0.0109	0.0007 ± 0.0045	0.0008 ± 0.0010	0.0005 ± 0.0011
Br	0.0023 ± 0.0014	0.0007 ± 0.0101	0.0042 ± 0.0043	0.0001 ± 0.0014	0.0001 ± 0.0013
Rb	0.0229 ± 0.0011	0.0226 ± 0.0074	0.0156 ± 0.0031	0.0096 ± 0.0007	0.0398 ± 0.0012
Sr	0.0125 ± 0.0014	0.0118 ± 0.0099	0.0212 ± 0.0035	0.0652 ± 0.0017	0.0055 ± 0.0004
Y	0.0175 ± 0.0010	0.0044 ± 0.0119	0.0082 ± 0.0046	0.0018 ± 0.0008	0.0221 ± 0.0013
Zr	0.0092 ± 0.0010	0.0082 ± 0.0142	0.0094 ± 0.0055	0.0089 ± 0.0017	0.0071 ± 0.0008
Mo	0.0030 ± 0.0037	0.0031 ± 0.0264	0.0017 ± 0.0108	0.0181 ± 0.0021	0.0019 ± 0.0027
Pd	0.0013 ± 0.0132	0.0167 ± 0.0833	0.0008 ± 0.0345	0.0007 ± 0.0117	0.0006 ± 0.00991
Ag	0.0009 ± 0.0149	0.0015 ± 0.1009	0.0051 ± 0.0408	0.0017 ± 0.0129	0.0012 ± 0.0111
Cd	0.0027 ± 0.0156	0.0089 ± 0.1070	0.0141 ± 0.0431	0.0020 ± 0.0133	0.0035 ± 0.0116
In	0.0034 ± 0.0176	0.0000 ± 0.1187	0.0078 ± 0.0485	0.0028 ± 0.0144	0.0027 ± 0.0129
Sn	0.0045 ± 0.0224	0.0095 ± 0.1483	0.0332 ± 0.0565	0.0083 ± 0.0168	0.0038 ± 0.0163
Sb	0.0040 ± 0.0254	0.0001 ± 0.1745	0.0122 ± 0.0700	0.0055 ± 0.0198	0.0037 ± 0.0184
Ba	0.0269 ± 0.0833	0.0402 ± 0.6268	0.1508 ± 0.2364	0.0251 ± 0.0593	0.0175 ± 0.0597
La	0.0145 ± 0.1157	0.0782 ± 0.8417	0.0190 ± 0.3328	0.0148 ± 0.0805	0.0172 ± 0.0812
Au	0.0003 ± 0.0046	0.0021 ± 0.0337	0.0000 ± 0.0247	0.0002 ± 0.0034	0.0006 ± 0.0032
Hg	0.0010 ± 0.0035	0.0041 ± 0.0241	0.0009 ± 0.0102	0.0014 ± 0.0024	0.0011 ± 0.0024
Tl	0.0005 ± 0.0037	0.0000 ± 0.0239	0.0009 ± 0.0111	0.0012 ± 0.0025	0.0008 ± 0.0026
Pb	0.0299 ± 0.0021	0.0694 ± 0.0239	0.1209 ± 0.0170	0.0141 ± 0.0018	0.0186 ± 0.0016
U	0.0003 ± 0.0047	0.0000 ± 0.0239	0.0007 ± 0.0100	0.0006 ± 0.0028	0.0014 ± 0.0056

in this study, the OC/TC ratios are over 0.9 for all paved road and soil samples in both $PM_{2.5}$ and PM_{10} samples. The ratios are higher when compared with other studies (OC/TC ratios are between 0.66 and 0.80) (Watson and Chow, 2001). High concentrations of OC and low concentrations of EC were observed in all samples. The effect of motor vehicle emissions, including brake and tire wear and oil drips, presumably results in greater abundances of OC and EC in paved road dust and urban soil near the heavy trafficked road. An inspection and enforcement program for smoky vehicle control in Hong Kong commenced in 1998, which has enhanced black smoke (EC is the major component in black smoke) testing procedures for annual roadworthiness

Table 3
Source profile chemical compositions (weight percent by mass) of fugitive dust for PM_{10} in Hong Kong

Species	Country park soil	Urban soil	Paved road dust	Cement	Aggregate
NO_3^{3-}	0.0337 ± 0.0295	0.0104 ± 0.1180	0.0388 ± 0.1071	0.0105 ± 0.0270	0.0179 ± 0.0274
SO_4^{2-}	0.1215 ± 0.0421	0.0881 ± 0.1190	0.8375 ± 0.1515	8.4269 ± 3.0489	0.1532 ± 0.0494
NH_4^+	0.0655 ± 0.0300	0.0869 ± 0.1194	0.0527 ± 0.1014	0.0278 ± 0.0228	0.0444 ± 0.0250
Sol. Na	0.9083 ± 0.2024	0.0396 ± 0.0908	0.7183 ± 0.1643	1.5107 ± 1.2424	0.8437 ± 0.1721
Sol. Mg	0.0581 ± 0.0114	0.0921 ± 0.0812	0.2083 ± 0.0720	0.5079 ± 0.1951	0.0475 ± 0.0100
Sol. K	0.0578 ± 0.0081	0.0635 ± 0.0915	0.2664 ± 0.0845	0.7932 ± 0.1086	0.1010 ± 0.0162
OC	4.1800 ± 0.4443	6.4928 ± 2.8169	13.9289 ± 2.6065	1.3232 ± 0.4035	1.0356 ± 0.4473
EC	0.0419 ± 0.0458	0.3643 ± 0.8114	1.2690 ± 0.7514	0.1154 ± 0.0955	0.0042 ± 0.0327
TC	4.2219 ± 0.4529	6.5966 ± 3.4990	14.9861 ± 3.1360	1.4376 ± 0.4683	1.0400 ± 0.4556
Al	17.2983 ± 5.0893	15.1449 ± 4.2593	7.4344 ± 2.0851	2.2557 ± 0.6638	10.4302 ± 3.0605
Si	21.2314 ± 6.6703	27.1144 ± 8.1662	19.2385 ± 5.6979	8.1734 ± 2.5614	32.2679 ± 10.1096
P	0.0121 ± 0.0244	0.0363 ± 0.0405	0.0865 ± 0.0476	0.0000 ± 0.0354	0.0021 ± 0.0364
S	0.0539 ± 0.0108	0.1584 ± 0.0551	0.5304 ± 0.1244	1.5990 ± 0.1365	0.0266 ± 0.0080
Cl	0.0000 ± 0.0302	0.0204 ± 0.0526	0.6194 ± 0.1931	0.0000 ± 0.2672	0.0218 ± 0.0480
K	1.8553 ± 0.3578	2.3506 ± 0.4555	2.1656 ± 0.4023	0.8698 ± 0.1944	4.3552 ± 0.8388
Ca	1.2502 ± 0.2034	1.4088 ± 0.3541	8.8671 ± 1.3857	38.9732 ± 6.2664	0.9551 ± 0.1550
Ti	0.1766 ± 0.0162	0.3174 ± 0.1135	0.2379 ± 0.0965	0.1112 ± 0.0080	0.1025 ± 0.0076
V	0.0056 ± 0.0114	0.0106 ± 0.0547	0.0020 ± 0.0532	0.0034 ± 0.0096	0.0030 ± 0.0111
Cr	0.0027 ± 0.0048	0.0081 ± 0.0133	0.0327 ± 0.0117	0.0067 ± 0.0013	0.0196 ± 0.0027
Mn	0.0966 ± 0.0044	0.0785 ± 0.0095	0.1016 ± 0.0089	0.0274 ± 0.0018	0.14270 ± 0.0056
Fe	3.2599 ± 0.1427	3.7439 ± 0.2582	5.0867 ± 0.3142	1.7741 ± 0.0786	2.1624 ± 0.0785
Co	0.0179 ± 0.0521	0.0021 ± 0.0581	0.0107 ± 0.0813	0.0132 ± 0.0284	0.0121 ± 0.0346
Ni	0.0000 ± 0.0019	0.0013 ± 0.0051	0.0078 ± 0.0042	0.0017 ± 0.0044	0.0083 ± 0.0012
Cu	0.0202 ± 0.0013	0.0161 ± 0.0051	0.0600 ± 0.0054	0.0241 ± 0.0013	0.0710 ± 0.0030
Zn	0.0370 ± 0.0028	0.1651 ± 0.0122	0.5149 ± 0.0347	0.0365 ± 0.0040	0.0378 ± 0.0018
Ga	0.0030 ± 0.0013	0.0018 ± 0.0094	0.0008 ± 0.0083	0.0000 ± 0.0017	0.0014 ± 0.0016
As	0.0007 ± 0.0047	0.0014 ± 0.0154	0.0004 ± 0.0215	0.0015 ± 0.0030	0.0001 ± 0.0029
Se	0.0003 ± 0.0011	0.0013 ± 0.0057	0.0009 ± 0.0049	0.0004 ± 0.0011	0.0004 ± 0.0011
Br	0.0017 ± 0.0010	0.0040 ± 0.0051	0.0041 ± 0.0044	0.0000 ± 0.0013	0.0001 ± 0.0014
Rb	0.0293 ± 0.0030	0.0211 ± 0.0047	0.0175 ± 0.0038	0.0052 ± 0.0004	0.0474 ± 0.0025
Sr	0.0101 ± 0.0008	0.0096 ± 0.0049	0.0234 ± 0.0042	0.0697 ± 0.0031	0.0050 ± 0.0005
Y	0.0174 ± 0.0017	0.00523 ± 0.0062	0.0084 ± 0.0049	0.0018 ± 0.0009	0.0231 ± 0.0011
Zr	0.0118 ± 0.0011	0.0114 ± 0.0074	0.0118 ± 0.0060	0.0093 ± 0.0011	0.0081 ± 0.0008
Mo	0.0021 ± 0.0024	0.0009 ± 0.0138	0.0037 ± 0.0114	0.0112 ± 0.0014	0.0019 ± 0.0029
Pd	0.0007 ± 0.0090	0.0050 ± 0.0418	0.0018 ± 0.0364	0.0008 ± 0.0102	0.0013 ± 0.0090
Ag	0.0012 ± 0.0101	0.0014 ± 0.0500	0.0015 ± 0.0434	0.0014 ± 0.0113	0.0009 ± 0.0101
Cd	0.0016 ± 0.0106	0.0022 ± 0.0529	0.0024 ± 0.0460	0.0011 ± 0.0117	0.0014 ± 0.0107
In	0.0015 ± 0.0119	0.0098 ± 0.0587	0.0095 ± 0.0512	0.0012 ± 0.0127	0.00134 ± 0.01189
Sn	0.0056 ± 0.0150	0.0146 ± 0.0650	0.0289 ± 0.0620	0.0073 ± 0.0150	0.0045 ± 0.0152
Sb	0.0027 ± 0.0173	0.0107 ± 0.0866	0.0060 ± 0.0749	0.0027 ± 0.0177	0.0023 ± 0.0174
Ba	0.0189 ± 0.0571	0.0369 ± 0.3129	0.1000 ± 0.2566	0.0180 ± 0.0553	0.0204 ± 0.0583
La	0.0115 ± 0.0789	0.0400 ± 0.4213	0.0458 ± 0.3603	0.0110 ± 0.0739	0.0133 ± 0.0791
Au	0.0002 ± 0.0032	0.0005 ± 0.0176	0.0007 ± 0.0238	0.0000 ± 0.0031	0.0001 ± 0.0033
Hg	0.0008 ± 0.0024	0.0015 ± 0.0125	0.0007 ± 0.0108	0.0013 ± 0.0021	0.0012 ± 0.0025
Tl	0.0007 ± 0.0026	0.0000 ± 0.0125	0.0005 ± 0.0116	0.0008 ± 0.0024	0.0007 ± 0.0025
Pb	0.0234 ± 0.0029	0.0619 ± 0.0147	0.1061 ± 0.0155	0.0111 ± 0.0020	0.0095 ± 0.0011
U	0.0002 ± 0.0046	0.0007 ± 0.0124	0.0007 ± 0.0106	0.0006 ± 0.0024	0.0012 ± 0.0065

inspections since late 1997. The stringent emission standards for diesel vehicles may have greatly reduced the EC emission from vehicles. Crop debris and agricultural chemicals (e.g. fertilizers, pesticides, herbicides) might also enhance the abundance of OC in soil (Chow et al., 1994b). Zinc was much more abundant (0.51 ± 0.03%) in paved road profiles than in urban soils (0.17 ± 0.01%) and that is as low as 0.04% in soil of country park collected by HKEPD. As Zn is used as a vulcanization agent in vehicle tyres (Alloway, 1990), Fergusson and Kim (1991) concluded that the Zn could be contributed from galvanized materials, tire wear and the use of zinc compounds in rubber production. The high wear rates at high temperature of subtropical areas
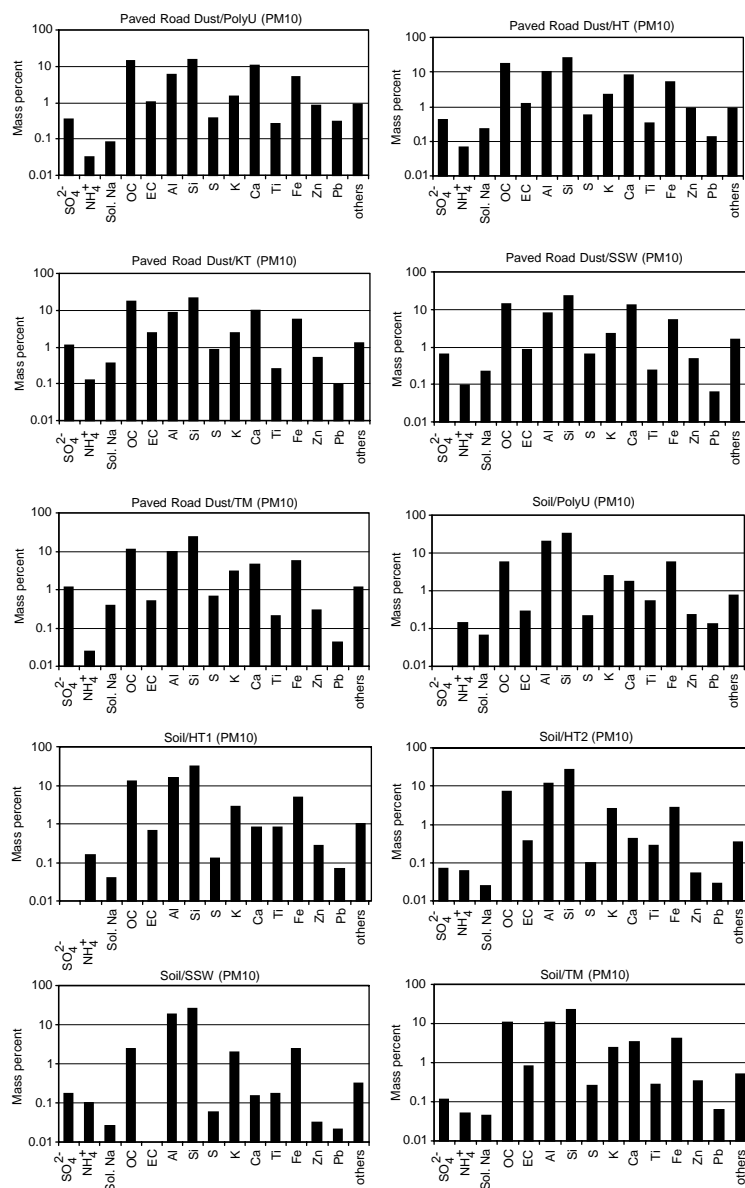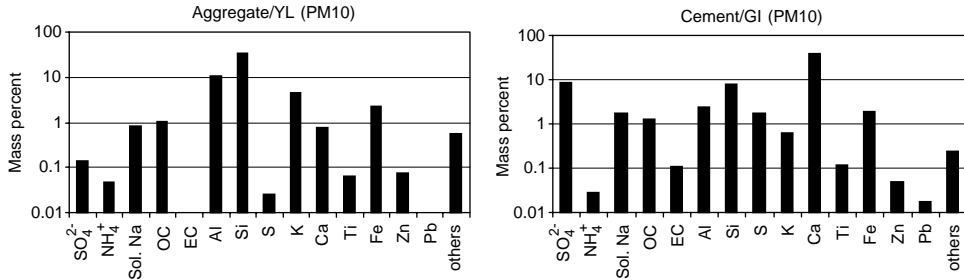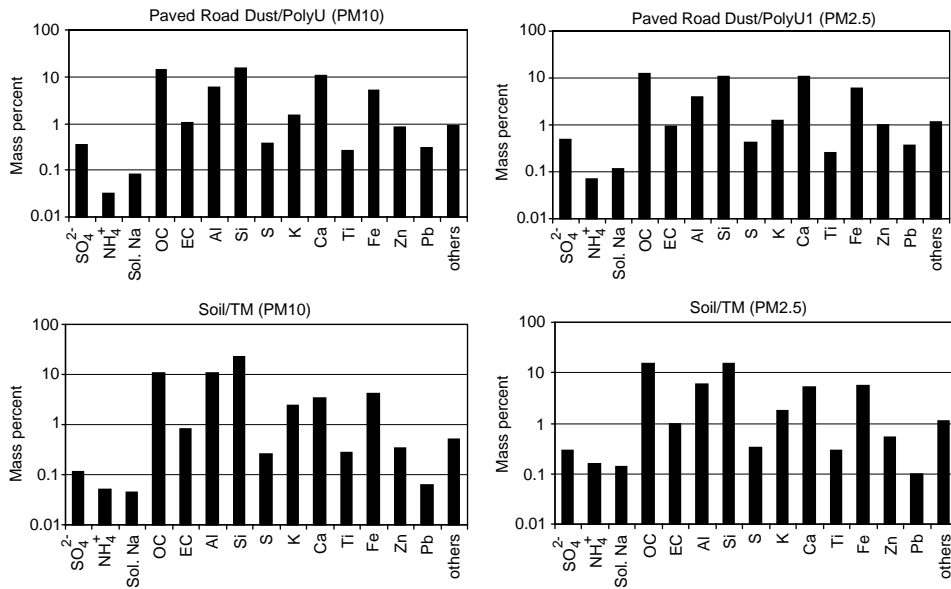
Fig. 2. PM_{10} source profiles for paved road dust and soil.

such as Hong Kong may contribute to the high Zn content in the paved road dusts (Li et al., 2001). Lead (Pb) is used in gasoline in some countries (Chow et al., 1994b; Sinha and Banerjee, 1997; Vega et al., 2001) but Hong Kong sells only unleaded gasoline for motor vehicles. The Pb abundance in paved road dust $(0.106 \pm 0.02\%)$ is higher than urban soil $(0.06 \pm 0.01\%)$. Sulfate is more abundant in paved road dust $(0.84 \pm 0.15\%)$, and is as low as 0.1% in the soil profiles. Sulfate in the atmosphere is generally assumed to be a secondary fine aerosol compound produced from gas to particle conversion of SO_2. The reasons for its associa-

tion with crustal elements can be the chemical binding of sulfate with crustal elements in the road (Kumar et al., 2001). NO_3^- and NH_4^+ are generally low, in the range of 0–0.1%. Na and Cl^- abundances are also low. The chemical abundances at different sampling locations were similar, with evident enrichment by vehicular emission (Zn, OC, and EC, etc.) components for urban paved road dusts compared with country park soil.

In Hong Kong, there are several big construction developments within the urban area. Therefore, the emissions from construction materials such as cement

Fig. 3. PM_{10} source profiles for aggregate and cement.

Fig. 4. Comparisons of PolyU paved road dust and Tuen Mun (TM) soil profiles for PM_{10} and $PM_{2.5}$.

and aggregate dusts have also increased. Fig. 3 shows the PM_{10} chemical profiles of aggregate and cement.

The aggregate profile contained Si in the highest abundance $(32.27 \pm 10.11\%)$ and Al in the second highest abundance $(10.43 \pm 3.06\%)$ in PM_{10}. Aggregate samples are enriched in K $(4.36 \pm 0.84\%)$ and Fe $(2.16 \pm 0.08\%)$ also. However, Ca is the most enriched, exceeding 35% of $PM_{2.5}$ and PM_{10} for the cement profile; sulfate were the second highest compounds, especially in $PM_{2.5}$ fraction $(\sim 13\%)$.

Chemical profiles of $PM_{2.5}$ and PM_{10} are similar for a given source type. Fig. 4 shows PolyU paved road dust and Tuen Mun (TM) soil profiles in the two size fractions. Higher abundances of major crustal species such as Si and Al were observed in PM_{10} fraction. However, abuandances of K, Ca, Ti, Fe and OC differ by no more than a few percent among the two fractions. Other sources profiles, not shown here, exhibit similar patterns.

4.2. Correlations of chemical species

High correlations $(r > 0.7, P < 0.01)$ were observed between mass concentration and traditional crustal elements (Si, Al, K, Ca, Ti, and Fe) in soil and dust samples. However, higher correlation was observed in the PM_{10} fraction than in the $PM_{2.5}$ of paved road dust and urban soil samples. Also good correlation $(r > 0.84, P < 0.01)$ of traffic pollutants, such as Zn and Pb, were found with mass concentration of dust samples of both fractions. For EC, just fair correlation was observed in PM_{10} of both samples. The emissions from vehicles were the dominant sources of EC in paved road dust, therefore the mass percentage of EC might depend on the traffic volume of vehicles on that paved road.

Previous source apportionment studies (Chow et al., 1992a, b) show that the chemical abundances and variabilities are sufficient to separate geological contributions from other source types, but they are
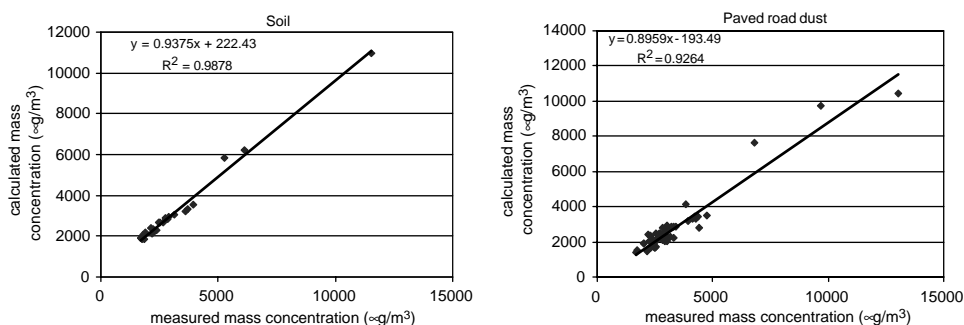
Fig. 5. Calculated soil and paved road dust mass concentrations versus measured soil and paved road dust mass concentrations for PM_{10} fraction.

insufficient to distinguish paved road and native soil compositions from each other (Watson et al, 2001). In this study, Si, Al, K, Ca, Ti, and Fe are good indicators for PM_{10} fraction of soil and paved road dust samples, and Zn and Pb can be used as other indicators for paved road dust.

4.3. Reconstructed versus measured mass

In chemical mass closure analysis for ambient particulate matter, crustal matter is reconstructed by using the concentrations of elements, such as Al, Si, Ca, Ti, and Fe (and K) to estimate the unmeasured oxides. In order to evaluate the effectiveness of this calculation in Hong Kong environment, the calculated crustal matter concentrations were compared with the measured mass concentrations (by using gravimetric measurement) in this study. Following are the equations used:

$$\text{crustal matter} = 1.16\,(1.90\text{Al} + 2.15\text{Si} \\ + 1.41\text{Ca} + 1.67\text{Ti} + 2.09\text{Fe}),$$

where the factor 1.16 is to compensate for the exclusion of MgO, Na_2O, K_2O and H_2O from crustal mass calculation (Chan et al., 1997).

Fig. 5 shows the scatter plots of calculated mass concentrations versus measured mass concentrations for PM_{10} fraction. Only soil samples (PM_{10}) have good agreement with the calculated values (relative mean deviation was below 10%). Two-tailed paired *t*-tests were used to evaluate the significance between the weighted values and calculated values. All *t*-values were compared to the critical values of *t* (for $P = 0.05$). Paired *t*-test show no significantly difference (e.g. paired *t*-test for PM_{10} data set = 0.69, cf. critical $|t| = 2.07$) resulted between the calculated crustal matter concentrations and the measured mass concentrations. Large variations of vehicular pollutants (OC, EC, Zn, and Pb) in paved road dust and fine fraction of soil samples in Hong Kong made the calculated values not matched with the measured mass concentrations for all samples.

5. Conclusion

Chemical compositions of the soil and paved road dust materials that generate fugitive dust emissions were determined in Hong Kong. The $PM_{2.5}$ constituted 11–30% of the PM10 in soil and paved road dust. Al, Si, and OC are abundant constituents in all paved road dust and soil samples. For aggregate profile, Si was the most abundant constituent. PM_{10} and $PM_{2.5}$ are enriched with Ca (exceeding 35%) for the cement profile. Sulfate were the second highest compounds, especially in $PM_{2.5}$ fraction ($\sim 13\%$).

High concentrations of OC and low concentrations of EC were observed in PM_{10} samples. The OC/TC ratios are higher (over 0.9) when compared with other studies (OC/TC ratios are between 0.66 and 0.80). Pb and Zinc was the markers for paved road profiles and contaminated urban soil in Hong Kong. The effect of motor vehicle contributions to paved road dust and urban soil (e.g. brake and tire wear, oil drips, deposited exhaust) is evident in larger abundances of Zn, OC and EC. However, the concentrations of Zn, OC, and EC in country park soil (collected by EPD) were lower than in urban soil. The chemical profiles at different sampling locations for paved road dust, urban soil or country park soils were similar. $PM_{2.5}$ and PM_{10} chemical abundances for a given source type were similar for most species. High correlations ($r > 0.7$) were observed between mass concentration and traditional crustal elements (Si, Al, K, Ca, Ti, and Fe) in soil and dust samples. Also higher correlation was observed in PM_{10} fraction than in $PM_{2.5}$ of both samples. However, when the calculated crustal matter concentrations were compared with the measured mass concentrations, only the measured mass concentrations of PM_{10} soil samples have good agreement with the calculated values. Two-tailed paired *t*-tests were used to evaluate the significance between the measured values and calculated values. Paired *t*-test shown that no significantly differences resulted between the two values. Large variations of vehicular pollutants (OC, EC, Zn, and Pb) in paved

road dust and fine fraction of soil samples in Hong Kong made the calculated values not matched with the measured mass concentrations for all samples.

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