Chemical Characteristics of Submicron Particles in Winter in Xi'an

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Abstract

Daily submicron aerosol samples (PM_1, particles less than 1 μm in diameter) were collected continuously from Dec. 1 to Dec. 31, 2006 and the concentrations of 11 water-soluble ions (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, F^-, Cl^-, Br^-, NO_2^-, NO_3^- and SO_4^{2-}) and elemental carbon (EC) and organic carbon (OC) were determined in the filter samples to characterize the chemical composition of PM_1 over Xi'an during winter. The mean PM_1 mass concentration was 149.7 μg/m^3. Water-soluble ions were dominant chemical species and occupied to 46% of PM_1 mass. Na^+, NH_4^+, Ca^{2+}, Cl^-, SO_4^{2-} and NO_3^- were the major species of ionic compounds, which accounted for 95.3% of total ions concentration. The average OC and EC concentrations were 23.7 ± 10.27 μg/m^3 and 4.6 ± 1.8 μg/m^3, respectively. Carbonaceous aerosol is another major component of PM_1, and total carbonaceous aerosol occupied to 27.5% of PM_1 mass. High OC and OC/EC ratio were found in Xi'an in comparison with the past studies in Hong Kong and Taipei. Factor analysis on the eight carbon fractions shows that coal combustion and gasoline automobile exhaust, diesel automobile exhaust, and biomass burning were found to be statistically significant and explained 93% of the carbonaceous aerosols contributions.

Keywords: PM_1; Water-soluble ions; Carbonaceous aerosol.

INTRODUCTION

The chemical composition of ambient aerosol were demonstrated an important factor in component deposition, human health and visibility in urban regions (Horvath, 1996; Lundgren *et al.,* 1996; Yadav *et al.,* 2003; Schichtel *et al.,* 2001; Tsai and Cheng, 1999; Tsai *et al.,* 2003; Zhang *et al.,* 2003; Zhang *et al.,* 2008a, b). The major components of urban ambient TSP (Total suspended particulate), PM_{10} (particles less than 10 μm in diameter), and $PM_{2.5}$ (particles less than 2.5 μm in

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diameter) were extensively measured and reported as sulfate (SO_4^{2-}), nitrate (NO_3^-), organic carbon (OC) and elemental carbon (EC). However, much less is known, and even less has been done about PM_1 (particles with a diameter 1.0 µm, submicron particle). Although some literatures (Vallius *et al.,* 2000; Cabada *et al.,* 2004) reported that the major components of PM_1 and $PM_{2.5}$ originated from the same sources by using MOUDI sampler, and they concluded the investigation of PM_1 did not yield significant new information in comparison with that obtained from the $PM_{2.5}$, it is clear that PM_1 was a better indicator for anthropogenic sources than $PM_{2.5}$, because, compared with $PM_{2.5}$ and PM_{10}, it minimized interference from natural sources (Lundgren *et al.,* 1996; Lee *et al.,* 2006). Epidemiological studies (Dockery *et al.,* 1993; Schwartz *et al.,* 1996; Wilson and Suh, 1997; Pope, 2000) have suggested a statistical association between health effects and ambient fine particle concentrations, especially the submicron fraction that can penetrate into the alveolar region of the lungs.

Xi'an, the capital of Shaanxi province, (area of 1066 km^2, population 5.1 million), is one of the largest cities in Northwest China. Air quality in Xi'an has become a serious concern due to the persistently high mass levels of PM_{10} and $PM_{2.5}$ (Cao *et al.,* 2005a, b; Zhang *et al.,* 2002). Although clean fuels such as natural gas have progressively replaced coal for residential heating and cooking inside Xi'an's Second Ring Road since 1998, the number of motor vehicles in Xi'an has grown rapidly, increasing from ~180,000 in 1997 to ~500,000 in 2006. Therefore, PM pollution in Xi'an continues to be a serious problem. Prior studies mainly focused on the chemical characteristics of TSP, PM_{10} and $PM_{2.5}$ in Xi'an (Cao *et al.,* 2005a, b; Shen *et al.,* 2008; Zhang *et al.,* 2002). Up to now, much less data about PM_1 in Xi'an have been available. In this paper, PM_1 mass, 11 kinds of water-soluble ions, organic carbon (OC) and elemental carbon (EC) were measured in winter (heaviest pollution season) in Xi'an. The objectives of this study were to: (1) determine the mass levels of PM_1, ionic species, and carbonaceous aerosol and (2) to evaluate the PM_1 pollution levels in Xi'an.

METHODOLOGY

Aerosol Samples Collection

The PM_1 samples were collected on 47 mm Whatman quartz microfibre filters (Whatman Ltd, Maidstone, UK) from the roof surface of a 15-m high building. The sampling site is located in the southeastern part of downtown of Xi'an, only about 100 m from the South Second Ring Road. North and east of the sampling site are residential areas and the campus of Xi'an Jiaotong University, while to the south and west are the South Second Ring and Xingqin Roads, where the traffic is always heavy. Daily 24-h PM_1 (10:00 am to 10:00 am, local time) samples were obtained from 1st Dec 2006 to 31 Dec 2006 using a mini-volume sampler (BGI, USA) operating at a flow rate of 5 L/min. A total of 31 of aerosol samples were collected. During the sampling period, field blank filters were also collected by exposing filters in the sampler without drawing air through them; these were used to account for any artefacts introduced during the sampling procedure. The quartz filters were pre-heated to 800°C for 3 h before use to remove the carbonaceous contamination.

Aerosol mass loadings were determined gravimetrically using a Sartorius MC5 electronic microbalance (± 1 μg sensitivity, Sartorius, Göttingen, Germany). The filters were equilibrated for 24 hours at a constant temperature between 20°C and 23°C and relative humidity between 35% and 45% before weighing. Each filter was weighed at least three times before and after sampling following the 24 h equilibration period. The mean net mass for each filter was obtained by subtracting the pre-deployment weight from the average of the post-sampling readings.

Water-soluble Ions Analysis

One-fourth of each filter sample was used to determine the ion mass concentrations. Six anions (SO_4^{2-}, NO_3^-, Cl^-, F^-, Br^- and NO_2^-) and five cations (Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}) in aqueous extracts of the sample filters were determined by an ion chromatography (IC, Dionex 500, Dionex Corp, Sunnyvale, CA). To extract the water-soluble species from the quartz filters, each filter was put into a separate 20 mL vial containing 10 mL distilled-deionized water (a resistivity of 18 MΩ), and then shaken first by an ultrasonic instrument for 60 min and then by mechanical shaker for 1 hr for complete extraction the water-soluble compounds. The extracts were stored at 4°C in a clean tube before analysis. Cation concentrations were determined with the use of a CS12A column (Dionex Corp.) with 20 mM MSA eluent. Anions were separated by an AS11-HC column (Dionex Corp.), using 20 mM KOH as the eluent. The limits of detection were less than 0.05 mg/L for anions and cations. Standard Reference Materials produced by the National Research Center for Certified Reference Materials, China were analyzed for quality assurance purposes. Blank values were subtracted from sample concentrations. Replicate analyses were performed at the rate of one per group of 10 samples for quality control.

Carbonaceous Aerosol Measurement

The quartz PM_1 sample filters were analyzed for elemental carbon (EC) and organic carbon (OC) with the using of a DRI Model 2001 Thermal and Optical Carbon Analyzer (Atmoslytic Inc., Calabasas, CA, USA). A 0.5 cm^2 punch from the quartz filter was analyzed for eight carbon fractions following the Interagency Monitoring to Protect Visual Environments total organic carbon protocol (IMPROVE TOC, Chow *et al.,* 1993; 2001; Fung *et al.,* 2002). The method produced data for four OC fractions (OC1, OC2, OC3 and OC4 in a helium atmosphere at 140°C, 280°C, 480°C and 580°C, respectively), a pyrolyzed carbon fraction (OPC, determined when reflected laser light attained its original intensity after oxygen was added to the combustion atmosphere), and three EC fractions (EC1, EC2 and EC3 in a 2% oxygen/98% helium atmosphere at 580°C, 740°C and 840°C, respectively). The IMPROVE protocol defined OC as OC1 +

OC2 + OC3 + OC4 + OPC and EC as EC1 + EC2 + EC3-OPC. The analyzer was calibrated with known quantities of CH_4 daily. Replicate analyses were performed at the rate of one per group of ten samples. Blank sample was also analyzed and the sample results were corrected by the blank sample concentration. Additional quality assurance and quality control procedures have been described in detail in Cao *et al.* (2003) and Chow *et al.* (2007).

RESULTS AND DISCUSSION

Mass Concentration of PM_1

Fig. 1 showed the temporal variation of PM_1 mass in winter in Xi'an. The mass concentrations of PM_1 in winter were in the range of 51.1 μg/m^3-251.4 μg/m^3 with a mean

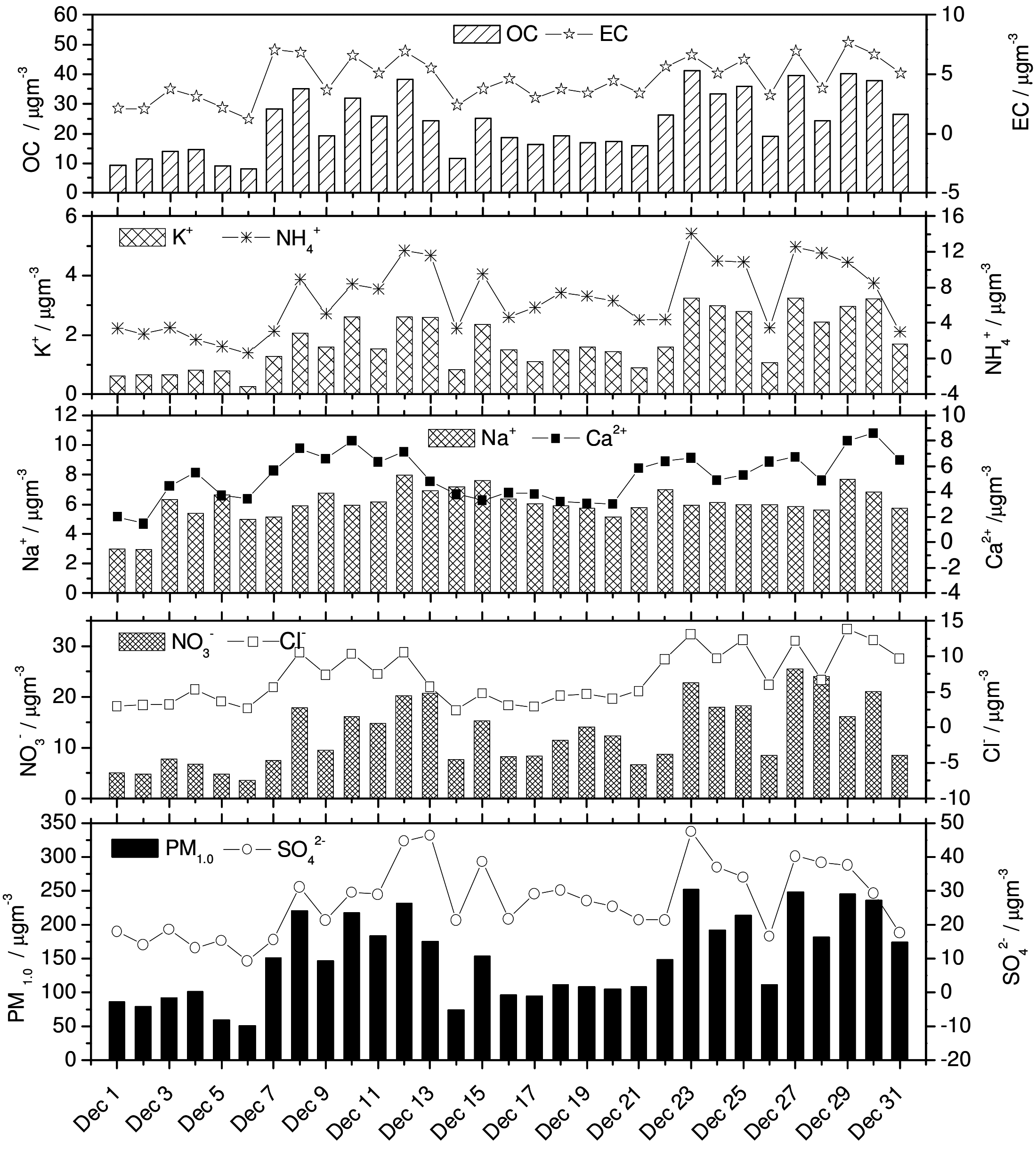

Fig. 1. Temporal variation of mass concentration for PM_1 and its chemical species in winter.

value of 149.7 μg/m^3. The PM_1 mass exceed the 24-hour America $PM_{2.5}$ standard of 35 μg/m^3 and annual mean value of 15 μg/m^3 concentrations for 31 days observation all (EPA, 2006). Our result can also compare with past studies in other cities. Lee et al. (2006) conducted the sampling with a Partisol-Plus Model 2025 Sequential Air Sampler operated at 16.7 L/min at a road site. The literature reported that the PM_1 level in Hong Kong during winter was 40.9 μg/m^3. Another study by Li and Lin (2002) demonstrated the PM_1 loading in an ambient general site (Chung-Shan) and a traffic monitoring station (Da-Tung) in Taipei were 14.0 μg/m^3 and 37.6 μg/m^3 respectively. As a result, remarkable high PM_1 levels were observed in winter in Xi'an and controlling measurement should be taken by the local government to alleviate the submicron particles pollution. High PM_1 levels should be linked to increasing emission from coal combustion and biomass burning for heating as we discussed in following sections.

Composition of Ionic Species in PM_1

The total ions concentration was 68.0 ± 25.4 μg/m^3 on average, which occupied about 46% of PM_1 mass. The result indicated water-soluble ions were the major components of submicron particles in Xi'an in winter. Prior literatures reported that water-soluble ions occupied one third or more in $PM_{2.5}$ mass in Chinese urban regions (He *et al.,* 2001; Hu *et al.,* 2002; Wang *et al.,* 2002; 2006). The mean concentrations for five cations of NH_4^+, Na^+, Ca^{2+}, K^+ and Mg^{2+} were 6.8 ± 3.8 μg/m^3, 6.0 ± 1.1 μg/m^3, 5.2 ± 1.8 μg/m^3, 1.8 ± 0.9 μg/m^3 and 0.5 ± 0.2 μg/m^3, respectively, which account for 9.8%, 9.2%, 8.1%, 2.4% and 0.8% in total ions concentration. For the ambient concentrations of NO_2^- and Br^- were below the IC detection limitation, other four anions were discussed here in detail. The mean mass concentrations of SO_4^{2-}, NO_3^-, Cl^- and F^- were 27.2 ± 10.5 μg/m^3, 12.7 ± 6.4 μg/m^3, 7.0 ± 3.6 μg/m^3 and 0.9 ± 0.2 μg/m^3, which occupied to 40.0%, 17.9%, 10.1% and 1.4% in total ions mass concentrations, respectively. Our observation demonstrated that Na^+, NH_4^+, Ca^{2+}, Cl^-, SO_4^{2-} and NO_3^- were major ions in PM_1, which account for 95.3% in total water-soluble ions mass concentration.

The relationships between 11 chemical species were calculated as shown in Table 1. Ca^{2+} and Mg^{2+} have a good relationship and with a high correlation coefficient value of 0.9, indicating that they originated from the same source. The molar ratio of Mg^{2+}/Ca^{2+} was a useful indicator to identify their source. As Xi'an is located at south margin of Chinese Loess Plateau, it was often suffered eolian dust from the arid and semi-arid regions in northwest China. Calculation of the Mg^{2+}/Ca^{2+} molar ratio in PM_1 in Xi'an was 0.18 in average (ranges from 0.14 to 0.25), which is a litter higher than the value observed in soil dust of 0.15 (Osada *et al.,* 2002). A little abundance of Mg^{2+} in PM_1 indicated not only soil dust, but other sources, such as combustion during heating season, also have an important contribution to Mg^{2+} and Ca^{2+} (Zhang *et al.,* 2002). It was demonstrated that water-soluble K has been commonly used as a marker for biomass burning (Andrea *et al.,* 1983; Watson *et al.,* 2001). Recently study by Cao et al. (2008) reported that K^+ was in a relative low level in fugitive dust of PM_1 fraction in Xi'an. In fact, wheat straw and maize stalks are burned for heat during winter in suburban region of Xi'an. As Xi'an is an inland city, marine influences on the urban aerosol particles can be disregarded. In addition, the Cl/Na ratio in the PM_1 samples was 4.35 in average, which were much higher than 1.8 of Cl to Na ratio of sea salt (Pytkowicz *et al.,* 1975). The relative abundance of Cl compared with Na can be explained by emissions from suburban biomass burning because strong relationship between Cl^- and K^+ was observed (Table 1).

As ammonium, sulfate and nitrate were the major components of PM_1, the source and formation of these species are our primary concern. The high NH_4^+ concentrations in aerosols from Xi'an may be related to the use of fertilizers on the Guanzhong Plain as well as contributions from local sanitary wastes (Zhang *et al.,* 2002). SO_4^{2-} commonly represents the stationary pollution sources such as coal combustion, while nitrate represents the mobile sources like vehicle exhaust (Arimoto *et al.,* 1996; Hu *et al.,* 2002; Yao *et al.,* 2002). High concentration of sulfate should be connected to the coal consumption for heat in winter. While high NO_3^- concentration should attribute to mobile emission source. It can be seen that NH_4^+ was strongly correlated with SO_4^{2-} and NO_3^- in PM_1, suggesting that these three major ions were in the form of ammonium sulfate/bisulfate and ammonium nitrate. To evaluate the chemical form among ammonium sulfate/bisulfate and ammonium nitrate and ammonium, comparisons between calculated and observed ammonium concentrations were conducted (Zhang *et al.,* 2002). If one assumes that the dominant compounds are NH_4HSO_4 and NH_4NO_3, one can calculate ammonium ion using Eq. (1); whereas if ammonium is in the form of $(NH_4)_2SO_4$ Eq. (2) applies:

$$\text{Ammonium } (\mu g/m^3) = 0.29\ (NO_3^-) + 0.19\ (SO_4^{2-}) \tag{1}$$

$$\text{Ammonium } (\mu g/m^3) = 0.29\ (NO_3^-) + 0.38\ (SO_4^{2-}) \tag{2}$$

where (NO_3^-) and (SO_4^{2-}) represent the mass concentrations of NO_3^- and SO_4^{2-}.

The correlation of calculated versus observed concentrations is higher when Eq. (1) is used; and this suggests that these three secondary ions exist mostly in the form of NH_4HSO_4 and NH_4NO_3.

Ion balance calculations are useful for evaluating the acid-base balance of aerosol particles. The microequivalents of cation and anion in PM_1 samples were calculated using following equations:

$$\text{C (cation microequivalents)} = Na^+/23 + H_4^+/18 + K^+/39 + Mg^{2+}/12 + Ca^{2+}/20 \tag{3}$$

$$\text{A (anion microequivalents)} = F^-/19 + Cl^-/35.5 + NO_3^-/62 + SO_4^{2-}/48 \tag{4}$$

Fig. 2 showed the relationship between cation and anion equivalents for all samples. A

Table 1. Correlation coefficients between chemical species.

R	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	F^-	Cl^-	NO_3^-	SO_4^{2-}	OC	EC
Na^+	1	0.40	0.44	0.62	0.49	0.39	0.37	0.31	0.46	0.42	0.41
NH_4^+		1	0.92	0.45	0.49	0.67	0.71	0.93	0.98	0.79	0.66
K^+			1	0.62	0.63	0.74	0.85	0.88	0.88	0.89	0.78
Mg^{2+}				1	0.90	0.75	0.77	0.50	0.43	0.73	0.74
Ca^{2+}					1	0.77	0.83	0.58	0.42	0.77	0.77
F^-						1	0.85	0.63	0.64	0.78	0.69
Cl^-							1	0.70	0.63	0.93	0.85
NO_3^-								1	0.87	0.72	0.62
SO_4^{2-}									1	0.67	0.62
OC										1	0.94
EC											1

strong correlation (R = 0.97) between cation and anion equivalents was observed, which indicates that these nine ionic species in Eq. 3 and 4 were the major ions existed in submicron particles in Xi'an. We note the slope of the orthogonal regression line is higher than the unity, which implies PM_1 samples tend to be acidic. In addition, other anions, such as CH_3COO^-, $HCOO^-$, $C_2O_4^{2-}$ and PO_4^{3-} were not investigated in this study. Prior study demonstrated their concentrations are typically low in aerosol samples from China (Wang *et al.,* 2005). The huge consumption of coal during heating season should carry the responsibility for the acidity of PM_1 samples.

Concentration and Sources of Carbonaceous Aerosol

The temporal variation of mass concentration for PM_1 OC and EC was given as shown in Fig. 1. The mean levels of PM_1 OC and EC were demonstrated to be 23.7 μg/m^3 and 4.6 μg/m^3, respectively. OC levels were in the range of 8.2 μg/m^3-41.3 μg/m^3, and EC was in the range of 1.2 μg/m^3-7.7 μg/m^3. In addition, OC and EC attributed to 15.8% and 3.1% of PM_1 mass. Lee *et al.* (2006) investigated the carbon concentration via the same analysis technique in Hong Kong during Jan and Feb.

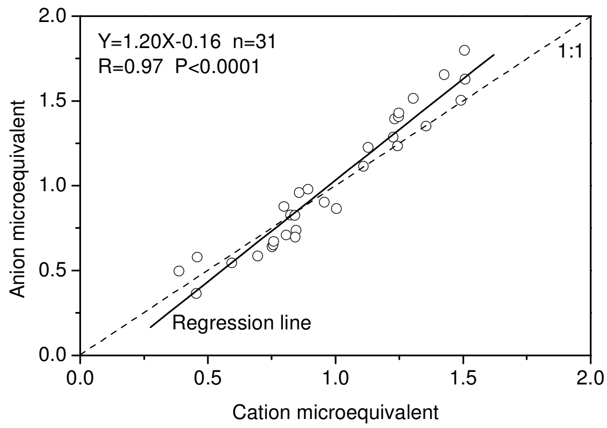

Fig. 2. Total anion microequivalents versus total cations microequivalents.

The mean OC and EC concentrations at a heavy traffic sampling site were 8.3 μg/m^3 and 9.0 μg/m^3 respectively. In generally, OC concentration in Hong Kong at roadside is lower than the value in Xi'an of this research, but EC levels in Hong Kong is a little higher than that measured in Xi'an. Another literature by Li and Lin (2002) reported the PM_1 carbon measurement at an ambient general site (Chung-Shan) and a traffic monitoring station (Da-Tung) in Taipei area by using a combustion technique. At Chung-Shan, PM_1 OC and EC concentrations on average were 3.4 $\mu g/m^3$ and 1.3 $\mu g/m^3$ in winter. While OC and EC levels in Da-Tung were 11.5 $\mu g/m^3$ and 11.3 $\mu g/m^3$ in August and 19.0 $\mu g/m^3$ and 13.4 $\mu g/m^3$ in June. In generally, carbon concentrations at Chung-Shan were much lower than those observed at Xi'an and Hong Kong. In addition, PM_1 OC level at the traffic monitoring station in Taipei was higher than that found in Hong Kong, but lower than the value in Xi'an. But the PM_1 EC concentration in Da-Tung was much higher than those found both in Hong Kong and Xi'an.

The correlation between OC and EC was used as an indicator of the source of carbonaceous aerosol. As shown in Fig. 3, a strong correlation between OC and EC was observed in PM_1 with a correlation coefficient of 0.93, indicating that OC and EC were from the same sources. The OC/EC ratios in PM_1 were in the range of 3.7-6.8 with a mean value of 5.2. The OC/EC ratios in current study are much higher than those observed at Hong Kong and Taipei (Lee *et al.,* 2006; Li and Lin, 2002), indicating PM_1 carbon in Xi'an is more abundant in organic carbon and shortage of elemental carbon. Some literatures studied the source profiles of OC/EC ratios applicable to speciated the emission inventories and receptor model of source apportionment (Cao *et al.,* 2003, 2005; Chow *et al.,* 2004; Dan *et al.,* 2004; Duan *et al.,* 2004). Watson *et al*. (2001) reported that the OC/EC ratios for coal combustion, vehicle emission, and biomass burning were 2.7, 1.1 and 9.0, respectively. Meanwhile, the author indicates that the source profiles are influenced heavily by many factors, such as the chemical composition of fuel, pollution control devises, sampling methods, sampling periods, and analytical techniques. Cao *et al*. (2005a) gave the OC/EC ratio source profile in $PM_{2.5}$ in Xi'an. That is the OC/EC ratios were 12.0 for coal combustion, 4.1 for vehicle exhaust, and 60.3 for biomass burning. From these two studies, we inferred that the source profile of carbonaceous aerosol were more complicated and influenced by many factors. Moreover, EC originates from the incomplete combustion of carbon containing materials directly, and does not form in atmosphere due to its nearly inert property. While ambient OC includes primary OC (originate from the combustion process directly) and secondary OC (produced by gas to particle conversion or chemical reaction in atmosphere). Only the ratio of primary OC to EC was proper to conducting the source identification. Therefore, one should care when using OC/EC ratio to trace the carbonaceous aerosol source. The strong correlation between K^+, SO_4^{2-} and NO_3^- with OC and EC showed in Table 1, implying biomass burning, coal combustion, and vehicle exhaust were the major contributor to PM_1 carbon in Xi'an.

The concentration of organic matter (OM) in atmosphere can be estimated by multiplying OC by 1.6 (Turpin and Lim, 2001). Total carbonaceous aerosol (TCA) was calculated by the sum of OM and EC. In winter, the mean TCA concentration is 42.5 μg/m^3, which attributed to 28.4% of PM_1 mass. It showed that carbonaceous aerosol is one of the major components of PM_1.

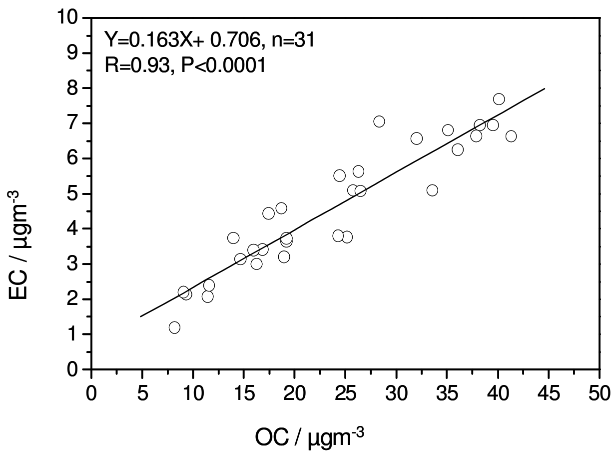

Fig. 3. Relationship between OC and EC.

By using the TOR method, the concentrations of OC1, OC2, OC3, OC4, EC1, EC2, EC3 and OP were measured separately in a run by the Thermal/Optical Carbon Analyzer. Carbon abundances in each of these fractions vary with different carbon sources (Watson *et al.,* 1994; Cao *et al.,* 2006). To determine the characteristic source and the contributing factors of carbonaceous aerosol observed in Xi'an, factor analysis (SPSS 8.0 software) was performed on the eight carbon fractions. The analysis was done with principal components extraction and varimax normalized rotation. The factor was not considered if its eigenvalue was < 1. Table 2 showed the results of factor analysis. Three factors were extracted to explain the sources and their contribution to carbonaceous aerosol. For all samples, these three factors were found to be statistically significant and explained 93% of the total variance. Factor 1 was highly loaded with OC1, OC2, OC3, OC4 and EC1. This factor was demonstrated to represent the coal combustion and gasoline vehicle exhaust (Chow *et al.,* 2004). Factor 2 was more abundant of high

Table 2. Factor analysis result of eight carbon fraction.

	Factor 1	Factor2	Factor3
OC1	0.761	0.233	0.344
OC2	0.813	0.197	0.438
OC3	0.901	0.186	0.367
OC4	0.911	0.158	0.302
EC1	0.63	0.147	0.76
EC2	0.317	0.906	0.106
EC3	6.61E-02	0.967	8.60E-02
OP	0.487	0.103	0.864
Variance	45.3%	24.2%	23.5%
	Coal Combustion and Gasoline Exhaust	Diesel Exhaust	Biomass Burning

temperature EC2 and EC3 and should represent diesel vehicle exhaust (Watson *et al.,* 1994). The highly loading of OP and EC1 in Factor 3 reflects contribution of biomass burning. Furthermore, the source attribution can be resolved for carbonaceous aerosol in PM_1. 45.3% of carbonaceous aerosol can explain by coal combustion and gasoline vehicle exhaust, 24.2% by diesel vehicle exhaust and 23.5% by biomass burning.

Material Balance of PM_1

The relative contributions of chemical species to PM_1 mass in winter is shown in Fig. 4. Carbonaceous aerosol, sulfate and nitrate were major chemical species and they attributed to 27.5%, 18.1% and 9.1% of PM_1 mass, respectively. As elemental composition were not identified in this study, soil dust and other uncertain fractions occupied to 34.2%. Therefore further work is recommended to identify those substances that make up the missing mass and to investigate the seasonal variation of PM_1.

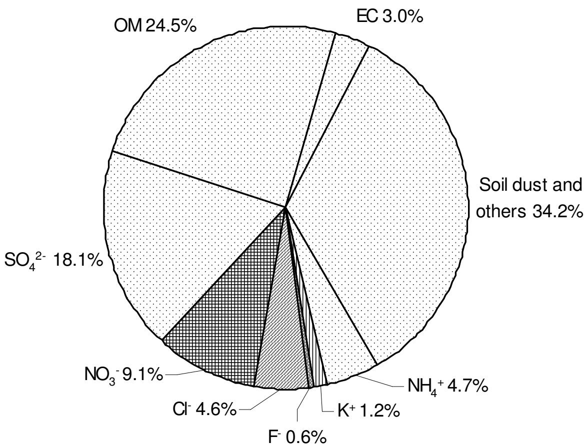

Fig. 4. Material balance of PM_1 in winter.

CONCLUSIONS

PM_1 level in winter in Xi'an was 149.7 μg/m^3, which was higher than those observed in Hong Kong and Taipei. Ionic species and carbonaceous aerosol were dominant of PM_1, which attributed 46.0% and 27.5% to the total particle mass. SO_4^{2-}, NO_3^-, Cl^- and NH_4^+ were major ions, which occupied to 18.1%, 9.1%, 4.6% and 4.7% of PM_1 mass. The three secondary ionic species were in the form of NH_4HSO_4 and NH_4NO_3. OC concentration in Xi'an in winter is higher than those at Hong Kong and Taipei. High OC/EC ratios were observed in Xi'an, which maybe due to more complicated sources of PM_1 carbon. Factor analysis for the eight carbon fractions demonstrated that coal combustion and gasoline exhaust, diesel exhaust, and biomass burning were three significant factors and explained 93% contributions of carbonaceous aerosol. The information obtained here is especially important for helping to enhance the current understanding of fine particles pollution problems confronting Xi'an.

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