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Review

Organic carbon and elemental carbon in Asia: A review from 1996 to 2006

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Abstract

The principal sources of organic carbon (OC) and elemental carbon (EC) are anthropogenic or biogenic, whereas secondary sources are atmospheric oxidation processes of specific precursor gases. These compounds are considered atmospheric contaminants and adversely affect human health. Numerous studies have monitored atmospheric particulates and gaseous phases of OC and EC in Asia over the last decade. This work compares and analyzes different sample collection, pretreatment and analytical approaches. The principal carbonaceous sources are traffic exhaust and industrial emissions. The OC and EC concentrations are highest in high traffic areas, followed by urban sites, and lowest in suburban sites. Many characteristics of these sites, such a dense population, are important to research. The major OC to EC ratios in Asia cities were 1.0–3.0. This work elucidates the characteristics, sources, distributions, and characteristics of atmospheric carbonaceous species in Asia.

Keywords: OC; EC; Asia; Precursor gases; Analytical methods

Contents

1. Introduction

Atmospheric pollution generated by airborne fine particulates is an environmental issue of particular concern, principally due to their adverse human health effects, as demonstrated by epidemiological studies [1–6]. Particulates <2.5 μm ($PM_{2.5}$) in aerodynamic diameter are generally considered "fine" particulates, and have been implicated in adverse human health effects [7,8]. Notably, $PM_{2.5}$ is composed of a mixture of many chemical species. Significant particulate components are organic compounds, such as organic carbon (OC) and elemental carbon (EC). Additionally, $PM_{2.5}$ consists of trace elements and ions. Oxides of aluminum, silicon, calcium, titanium, iron, and other metal oxides are typically in suspended dust, and oxide concentrations can result from local geology and industrial sources. Inventories of fine particulate emissions and source apportionment by chemical speciation of $PM_{2.5}$ are basic techniques used by control bodies. Particularly, assessing the role of traffic emissions is typically extremely useful when determining the priority and extent of regulatory actions.

Carbonaceous aerosols have significant effects on global and regional climates, and adverse effects on human health and local environments. In highly polluted atmospheres, carbonaceous species account for 20–50% of the fine particulate mass [9]. Identifying the physical and chemical characteristics of atmospheric aerosols is therefore crucial. The OC component in

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aerosols has two sources: primary sources are either anthropogenic or biogenic, and secondary sources are atmospheric oxidation processes of particular precursor gases. Additionally, OC is typically emitted from primary emission sources and generated by chemical reactions involving primary gaseous OC species in the atmosphere [10]. Notably, OC is predominant in the range of fine particulates $\leq PM_{2.5}$, and a minor component in coarse particulates 2.5–10 μm in diameter ($PM_{2.5–10}$). Particles of OC and EC exist primarily in aerodynamic particles with diameters of 0–1 μm [11]. Thus, OC and EC are more common as fine particulates than as coarse particulates [12], indicating that aerosols in human-made pollution are predominantly present in fine fractions, and usually exist in large quantities in coarse fractions [13]. However, the contribution of secondary particles to measured PM_{10} is largely more uniform across countries than that of primary particles as secondary particles form relatively slowly in atmosphere and have a long lifetime therein [14].

Organic carbon and EC particles are products of incomplete combustion of carbonaceous fuels. Furthermore, EC is predominantly a primary pollutant, emitted directly by combustion processes. Organic carbon has both primary and secondary origins. Primary OC is emitted in particulate form; whereas secondary OC is formed in the atmosphere via volatile organic compound (VOC) gas-to-particle conversion processes [15]. The chemical transformations of EC is emitted from combustion sources; therefore, OC is a good indictor of primary anthropogenic air pollution levels [16].

Recent studies have determined that the contribution of EC to global warming is likely substantial [17]. Furthermore, biomass combustion is a significant primary source of numerous trace substances that are reactants in atmospheric chemistry and of soot particulate matter that decreases visibility and absorbs incident radiation [18]. Chemically, biomass smoke particulates contain thermally unaltered and partially altered biomarker compounds emitted from straw burning.

This review study elucidated OC and EC emission characteristics, sources, and sampling and analytical methods in China, Korea, Japan and Taiwan. These countries have similar atmospheric conditions and levels of traffic. This work examines atmospheric OC and EC data from these Asian countries to elucidate the sources, distributions, measurements, research and characteristics of aerosol OC and EC concentrations.

2. China

The OC and EC concentrations were compared with those in recent studies of other Asian cities (Table 1). Concentrations and distributions of OC and EC in atmospheric particulates were measured at 11 sites in Hong Kong, Shanghai, the Pearl River Delta and Beijing, China. Different atmospheric EC sources, such as traffic, industry, urban and suburban, were also investigated in China.

Ho et al. [19] analyzed PM_{10} and $PM_{2.5}$ samples collected using high-volume (hi-vol.) air samplers. The OC and EC concentrations were analyzed using the selective thermal manganese dioxide oxidation (TMO) technique. Experimental data suggest that OC measured in urban areas in Hong Kong may be emitted directly as a primary aerosol. Furthermore, industrial emissions were a major source of organic compounds, indicating that the source of secondary OC may be transportation vehicles and transformation of anthropogenic organic species [20].

Yu et al. [21] utilized high-volume samplers (Andersen Instruments, GA, USA) to collect OC and EC concentrations in PM_{10}. The EC and OC concentrations were analyzed using a thermal/optical carbon analyzer (Sunset Laboratory, USA). Their experimental results indicated that winter OC concentrations are at minimum two times higher than those in summer in Hong Kong.

At sites in the Pearl River Delta region, $PM_{2.5}$ and PM_{10} samples were collected on pre-fired quartz filters with mini-volume samplers and analyzed using thermal optical reflectance (TOR). Average OC and EC concentrations in $PM_{2.5}$ were 14.7 and 6.1 $\mu g\,m^{-3}$, respectively, whereas those in PM_{10} were 19.7 and 7.8 $\mu g\,m^{-3}$, respectively. Carbonaceous aerosol accounted for 40.2% of $PM_{2.5}$ and 35.9% of PM_{10} concentrations. Secondary OC accounted for 42.6 and 38.4% of total OC in $PM_{2.5}$ and PM_{10}, respectively [23].

Ye et al. [24] demonstrated that carbonaceous material accounted for 41.4% of the $PM_{2.5}$ mass, 73% of which was organic, as determined by TOR in Shanghai, China.

Dan et al. [25] identified that organic aerosols constituted up to 42% of $PM_{2.5}$ in winter based on a 1.6 ratio for OC to organic particulates. Secondary OC was estimated at >50% and as high as 95% of total OC in summer based on a minimum OC/EC ratio of 0.9. Additionally, OC and TC were measured using a C/H/N elemental analyzer (Germany Vario EL, Germany). Overall, OC was the most abundant species, constituting no less than 30% of total $PM_{2.5}$ mass at sites at Tsinghua University and downtown Beijing (Chegongzhuang). The OC and EC concentrations were measured using TOR [26].

Concentrations of OC and EC in air were measured during 1994–2002 in China. The concentration ranges of OC and EC in PM_{10} were 7.02–29.1 and 1.85–10.1 $\mu g\,m^{-3}$, respectively. The concentration ranges of OC and EC in $PM_{2.5}$ were 1.36–21.15 and 3.32–20.16 $\mu g\,m^{-3}$, respectively. The OC and EC concentrations in $PM_{2.5}$ were ranked from highest to lowest in the following order: Beijing > Shanghai > Pearl River Delta Region > Hong Kong. However, the OC and EC PM_{10} concentrations were ranked from highest to lowest in the following order: Beijing > Pearl River Delta Region > Shanghai > Hong Kong. Moreover, the OC and EC concentrations have the same concentration levels at sampling sites, such as traffic sites in Hong Kong and Shanghai; higher concentrations of OC and EC were measured at Beijing sampling sites. Physical dispersion/transport may account for the relatively higher concentrations in Beijing. However, average concentrations of OC and EC in $PM_{2.5}$ were higher than those in PM_{10}. The distribution of EC is correlated with particles sized <1 μm in diameter in polluted urban areas [27,13].

The average OC and EC concentrations in China due to traffic were higher than industrial and suburban concentrations; the OC and EC concentrations were 14.16 and 8.08 $\mu g\,m^{-3}$ (traffic), 14.17 and 6.96 $\mu g\,m^{-3}$ (industrial) 7.02 and 1.85 $\mu g\,m^{-3}$

Table 1
Summary of organic carbon (OC), elemental carbon (EC) concentrations experiments in Asia

Country	Reference	Sampling site	Major source	Sampling device	Analysis	Particle size	Number	OC ($\mu g\,m^{-3}$)	EC ($\mu g\,m^{-3}$)	Sampling period
China	Ho et al. [19]	Hong Kong	Traffic	High-volume sampler	Thermal manganese dioxide oxidation (TMO) method	PM_{10}	–	14.16	8.08	November 2000–February 2001.
			Industrial			14.15	6.96			
			Suburban			7.02	1.85			
	Ho et al. [20]	Hong Kong	Mixed residential, commercial, traffic and industrial area	Filtered laboratory	Thermal/optical reflectance (TOR) method	PM_{10}		1.03	N.D.	During 2001 year
	Yu et al. [21]	Hong Kong	Mixed residential, commercial and industrial area	High-volume sampler	Thermal/optical carbon analyzer	PM_{10}	1880	8.9	4.9	January 1998–December 2001
	Cao et al. [22]	Pearl river delta region	Mixed urban, suburban, traffic and industrial area	Mini-volume sampler	Thermal optical reflectance (TOR) method	PM_{10}	62	19.7	7.8	January and February, 2002
	Ye et al. [24]	Shanghai (Tongji University)	Downtown	Low-flow rate samplers (LFS)	Thermal/optical reflectance (TOR) method	$PM_{2.5}$	–	14.34	6.21	March 1999–March 2000
		Shanghai (Hainan Road)	Traffic	Low-flow rate samplers (LFS)	Thermal/optical reflectance (TOR) method	$PM_{2.5}$	–	15.43	6.77	May 1999–March 2000.
	Dan et al. [25]	Beijing	Urban	Aerosol middle-flow impact sampler	Elemental analyzer	$PM_{2.5}$	149	20.44	20.10	July–August 2001, December 2001, June–July 2002, December 2002, March 2003
	He et al. [26]	Beijing (Tsinghua University)	Residential	Low-flow rate samplers (LFS)	Thermal manganese dioxide oxidation (TMO) method	PM_{10}	54	29.1	10.1	July 1999–September 2000.
		Beijing (Chegongzhuang)	Downtown	Low-flow rate samplers (LFS)	Thermal manganese dioxide oxidation (TMO) method	$PM_{2.5}$	54	21.5	8.7	July 1999–September 2000.
Japan	Funasak et al. [28]	Osaka	Traffic	Andersen cascade impactor and multistage type low-volume air sampler	Thermal/optical reflectance (TOR) method	<PM2	–	5.2	3.4	October 1996
	Funasak et al. [12]	Osaka	Suburban	AND samplers and Andersen Cascade Impactor	Thermal manganese dioxide oxidation (TMO) method	PM_{10}	39	5	12.3	November 1994, October 1995, December 1997
	Ohta et al. [31]	Sapporo	Urban	Low-flow rate samplers (LFS)	Combustion method	$PM_{2.5}$	–	4.06	4.51	November 1991–October 1992
Korea	Kang et al. [31]	Seoul	Urban	Annular denuder system (ADS)	Thermal/optical reflectance (TOR) method	$PM_{2.5}$	14	18.0	8.13	October–November 2001
	Lee and Kang [23]	Chongju	Urban	Annular denuder system (ADS)	Thermal/optical reflectance (TOR) method	$PM_{2.5}$	58	4.99	4.44	October 1995–August 1996
	Kim et al. [10]	Seoul	Urban	Modiped Southern California Air Quality Study (SCAQS) sampler	Thermal manganese dioxide oxidation (TMO) method	PM_{10}	7	11.1	8.39	June 1994
	Kim et al. [16]	Kosan	Island	Low-volume aerosol sampler	Thermal manganese dioxide oxidation (TMO) method	$PM_{2.5}$	74	3.27	0.29	July 1994–December 1997
	Park et al. [9]	Sihwa	Industrial	Teflon-coated aluminum cyclone impactor	Thermal manganese dioxide oxidation (TMO) method	$PM_{2.5}$	58	9.8	1.8	February 1998 and 1999
	Park et al. [9]	Seoul	Urban	Teflon-coated aluminum cyclone impactor	Thermal manganese dioxide oxidation (TMO) method	$PM_{2.5}$	10	10.3	8.4	May and June 1999
	Park et al. [30]	Seoul	Urban	WINS impactor	Thermal manganese dioxide oxidation (TMO) method	PM_{10}	13	15.2	7.3	November and December 1999
Taiwan	Tsai and Chen [13]	Kaohsiung	Mixed urban, highway and industrial area	Miniature personal environmental monitor (MSP)	Elemental analyzer	PM_{10}	20	32.52	23.06	December 2002–January 2003
	Lin and Tai [33]	Kaohsiung	Urban	Dichotomous sampler	Elemental analyzer	PM_{10}	51	14.5	6.1	November 1998–April 1999
	Chen et al. [32]	Kaohsiung	Urban and industrial	High-volume air sampler	Elemental analyzer	PM_{10}	43	12.63	19.38	November–December, 1999.

(suburban) 1.03 and N.D. $\mu g\,m^{-3}$ (mixed sampling sites), respectively [19–26].

3. Japan

Concentrations and distributions of OC and EC in atmospheric particles were measured at three sites in Osaka and Sapporo sites, Japan, during 1991–1996. Particulate samples concentrations were collected using AND samplers (Shi-bata Co., Ltd., USA), an Andersen Cascade impactor (Model 3351) (Kanomax Co., Ltd., USA) and a low-volume air sampler Shi-bata. Carbonaceous species of atmospheric particulate matter was extracted and analyzed by TOR and thermal manganese dioxide oxidation method and combustion analysis.

Funasak et al. [28] demonstrated that EC was the predominant constituent of particulates in a tunnel, accounting for 71% by mass of PM <2 μm in aerodynamic diameter. The correlation coefficient of EC concentrations in diesel traffic volume was significant. The OC and EC concentrations were examined using TOR. Moreover, a simple estimation for the EC content ratio in diesel exhaust particles indicated that roughly 30% of indoor PM_{10} particulates were from diesel exhaust [12]. Organic carbon and EC in the tunnel sample were assessed using thermal oxidation via a CHN-CORDER (Yanaco Co., Ltd., Myanmar). Ohta et al. [29] determined that concentrations were 2.25–6.93 $\mu g\,m^{-3}$ for EC and 2.29–6.73 $\mu g\,m^{-3}$ for OC, respectively, analyzed using the Karl Fischer approach as well as EC and organics. The amount of organics was determined by multiplying the amount of OC by 1.20.

The concentrations for OC and EC in PM_{10} were 5 and 12.3 $\mu g\,m^{-3}$ in Japan [12], respectively. Furthermore, the concentrations of OC and EC in $PM_{2.5}$ were 1.1–5.2 and 2.3–4.51 $\mu g\,m^{-3}$, respectively. The OC and EC concentrations in $PM_{2.5}$ were ranked from highest to lowest in the order of Sapporo > Osaka. The OC and EC concentrations had the same concentrations at traffic and urban sampling sites. Furthermore, average OC and EC concentrations at traffic sites in Japan were higher than those at urban and suburban sites, and were in the order from highest to lowest of traffic > urban > suburban sites [28,29].

4. Korea

The OC and EC concentrations at eight sampling sites in five cities – Seoul, Chongju, Kosan, Sihwa and Kwangju, Korea – were compared with those obtained by recent studies for other Asian cities (Table 1). The different sources of airborne EC, such as traffic, industry, urban, island, and suburban were measured. The OC and EC concentrations were analyzed using TOR and TMO.

In Sihwa, Korea, suburban site, average OC and EC concentrations were 9.8 and 1.8 $\mu g\,m^{-3}$, respectively, based on an analysis of carbonaceous species by TMO [9]. However, Park et al. [30] compared the results obtained for the same sampling site during summer.

Kim et al. [10] measured $PM_{2.5}$ concentrations collected using a low-volume sampler at sites on Cheju Island, Korea, during July and August 1994. Selective thermal oxidation with MnO_2 as a catalyst was utilized for analysis. At Seoul, mean EC concentrations in $PM_{2.5}$ and PM_{10} were 7.57 and 8.39 $\mu g\,m^{-3}$, respectively, and mean OC concentrations in $PM_{2.5}$ and PM_{10} were 9.97 and 11.1 $\mu g\,m^{-3}$, respectively. However, EC concentrations were lower than those in the other Asian capitals. Additionally, biogenic emissions of OC were also important in addition to emissions transported to from outside Cheju Island [16].

Lee and Kang [23] showed that OC and EC concentrations were strongly correlated; the annual mean ratio of OC to EC concentrations was 1.12, suggesting that OC measured in the Chongju area may be emitted directly in particulate form as a primary aerosol. These OC and EC samples were analyzed using TOR at the Desert Research Institute (DRI) in Reno, USA.

Kang et al. [31] simultaneously measured $PM_{2.5}$ concentrations using two sets of annular denuder systems (ADSs) in Seoul. The carbonaceous species, OC and EC, were analyzed by TOR at the DRI. Formation of secondary OC was one reason that accounted for the high OC concentrations. Atmospheric formation of secondary OC is typical during ozone episodes as secondary OC is formed by condensation of low-vapor-pressure products during photo-oxidation of hydrocarbons.

The OC and EC concentrations in air were measured during 1994–2001, Seoul. The OC and EC concentrations in PM_{10} were 11.1 and 15.2 $\mu g\,m^{-3}$, respectively, and 8.39 and 7.3 $\mu g\,m^{-3}$, respectively [10,30]. The concentration ranges for OC and EC in $PM_{2.5}$ were 3.27–18 and 0.19–8.39 $\mu g\,m^{-3}$, respectively. The OC and EC concentrations in $PM_{2.5}$ were the same as those at sampling sites in urban Seoul [9,10]; this experimental finding is because these two studies utilized the same analytical approach TMO and sampling period. However, relatively lower OC and EC concentrations were identified at Kosan sampling sites [16]. The low levels of air pollution on Cheju Island may account for these low concentrations at Kosan. Furthermore, average urban OC and EC concentrations were higher than industrial and island concentrations; the order from highest to lowest was urban > industrial > island sampling sites [9,10,16,23,30,31].

5. Taiwan

Tsai and Chen [13] identified the chemical characteristics of winter aerosol at four sites in southern Taiwan – using the Gaussian Trajectory transfer coefficient model (GTx) – to identify the major air pollutant sources impacting Kaohsiung sampling sites. Aerosol samples were collected using one $PM_{2.5}$ and one PM_{10} miniature personal environmental monitor (MSP) at each sampling site. Carbon was heated in an oven to 340–345 °C for 20 min to remove any OC. One quarter of the filter will then be used Heraeus CHN-O-Rapid elemental analyzer (EA) to analyze carbon. The detector will be analyze on the base of the amount of carbon dioxide content. Analyses were performed using a 1.1 min heating time, 950 °C oxidation tube temperature. Analytical results suggested that OC constitutes 55–71% of TC. At Kaohsiung, the daytime OC/EC ratio in the fine fraction was

higher than that at night, indicating that daytime direct emissions of primary organic aerosols are greater than emissions of carbonaceous material EC aerosols.

Chen et al. [32] analyzed concentrations of carbon elements in PM_{10} during pollution episodes at four sampling sites – Chao-Chou (CC), Da-Liao (DL), Lin-Yuan (LY), and Hsiao-Kang (HK) – in southern Taiwan. A quartz-fiber filter was employed to collect PM_{10} particles during carbonaceous species analysis. At four sampling sites, two high-volume air samplers for PM_{10} (GBM-2000H) (Graseby-Andersen, USA), and an elemental analyzer were utilized (EA 1110) (Carlo Erba, Italy). Measurement results suggested that the concentration of OC emitted from combustion exhaust was reduced by photolysis, evaporation and reactions with other components during dispersion and transportation processes.

Concentrations and distributions of EC and OC in particulates were measured at Kaohsiung City, Taiwan [33]. Both PM_{10} and $PM_{2.5}$ samples were collected between November 1998 and April 1999 using a dichotomous sampler and were analyzed for carbonaceous species using an elemental analyzer. On average, carbonaceous species accounted for 21.2% of $PM_{2.5}$ and 18.1% of PM_{10}. Organic carbon was the predominant carbonaceous species and accounted for 72.2 and 70.4% of TC for $PM_{2.5}$ and PM_{10}, respectively.

Concentrations of OC and EC in $PM_{2.5}$ were 17.04 and 10.4 $\mu g\,m^{-3}$ [13] and 11.59 and 4 $\mu g\,m^{-3}$ [33], respectively. Furthermore, the range of OC and EC concentrations in PM_{10} were 12.63–32.25 and 6.1–23.06 $\mu g\,m^{-3}$ in Taiwan, respectively. These studies utilized the same analytical method (Elemental analyzer) as that at Kaohsiung [13,32,33].

6. Summary

Atmospheric EC is primarily derived from anthropogenic sources and not by reactions involving gaseous hydrocarbon precursors in the atmosphere. Organic carbon can be emitted directly from sources as primary particles; however, secondary organic aerosols can also form in the atmosphere from low-vapor-pressure products via atmospheric chemical reactions.

In this study, the highest OC concentration of PM_{10}, 32.51 $\mu g\,m^{-3}$ [13] was in Kaohsiung, Taiwan, at mixed suburban, highway and industrial area sampling sites. Additionally, the lowest average OC concentration, 1.03 $\mu g\,m^{-3}$, was in Hong Kong, China [20] at a mixed residential, commercial, traffic and industrial area sampling sites. Moreover, the highest EC concentration of PM_{10}, 23.06 $\mu g\,m^{-3}$ [13], for was similar to the highest OC concentration, in Hong Kong. The lowest average EC concentration was measured in Hong Kong, China [20] at a mixed residential, commercial, traffic and industrial area sampling site. The highest OC concentration of $PM_{2.5}$, 21.5 $\mu g\,m^{-3}$, He et al. [26] was in Beijing at Tsinghua University, China, at downtown sampling sites. A suburban sampling site in Osaka, Japan, had the lowest average OC concentration, 1.1 $\mu g\,m^{-3}$ [28], whereas suburban sites in Beijing, China, had the highest EC concentration of $PM_{2.5}$ (20.1 $\mu g\,m^{-3}$) [25]. The lowest average EC concentration was in Shanghai on Hainan Road, China, a mixed residential, commercial and industrial sampling site [21].

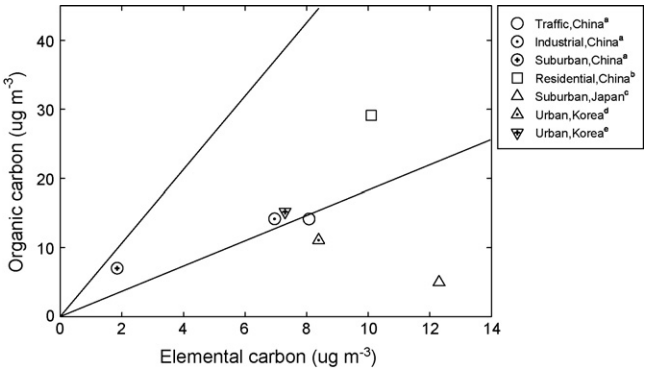

Fig. 1. Average PM_{10} OC vs. average PM_{10} EC by using TMO for different areas in Asia: this study (a) Ho et al. [19]; (b) He et al. [26]; (c) Funasak et al. [12]; (d) Kim et al. [10]; (e) Park et al. [30].

The analytical methods for measuring OC and EC concentrations in Asian cities were TOR, TMO, EA and combustion methods. Studies in Hong Kong [19,20], Beijing [26], Osaka [28], Seoul [9,10,30] and Kosan [16] utilized the TMO for analysis. However, only the combustion approach was employed in Sapporo, Japan [29]. All studies in Taiwan [13,32,33] utilized EA for analysis. Moreover, all experimental results demonstrated low correlation between analysis methods for Asia cities.

The TOR scheme utilized for carbonaceous species analysis generates slightly lower EC and higher OC values compared to those generated by TMO [34]. However, these two approaches generate similar values for TC (OC + EC). Separating and quantifying primary and secondary OC particulates is difficult. No simple direct analytical technique is available; thus, these studies utilized simple indirect methods. The ratios of OC to EC concentrations were utilized to determine emission and transformation characteristics of carbonaceous aerosols. However, a higher ratio of OC to EC can be expected and is indicative of secondary formation of air pollution. Several studies obtained OC to EC ratios > 2.0 to identify the presence of secondary organic aerosols [35,36]. These low values result from high EC values rather than low OC values. As the relationship between OC and EC concentrations for both coarse and fine particulates is good (Figs. 1–3), most OC measured at Seoul was likely emitted from primary anthropogenic sources along with EC.

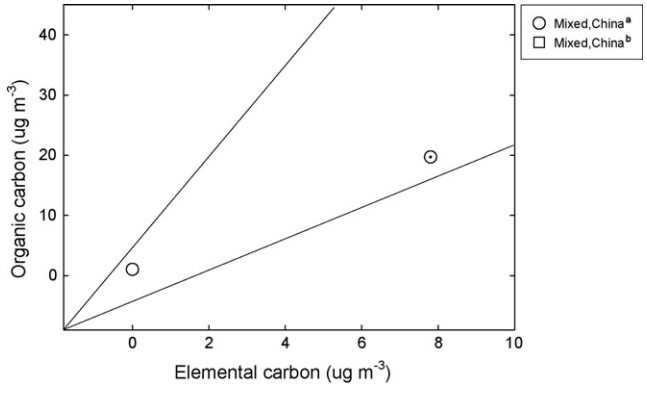

Fig. 2. Average PM_{10} OC vs. average PM_{10} EC by using TOR for different areas in Asia: this study (a) Ho et al. [20]; (b) Cao et al. [22].

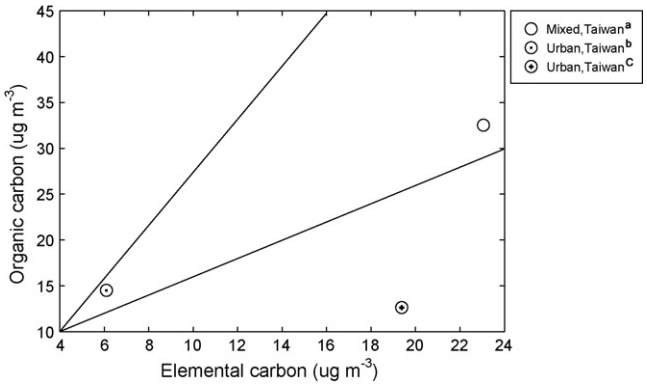

Fig. 3. Average PM_{10} OC vs. average PM_{10} EC by using EA for different areas in Asia: this study (a) Tsai and Chen [13]; (b) Lin and Tai [33]; (c) Chen et al. [32].

The concentration distributions of OC and EC in this study were compared with those in other Asian cities. Average OC to EC ratios at Asia sites ranged from N.D. to 3.8, with an overall average of 2.3 in PM_{10}. These values are similar to average OC to EC ratios of 1.8 $\mu g\,m^{-3}$ for mixed residential, commercial and industrial areas [21], and 2.0 $\mu g\,m^{-3}$ for an industrial area [19] in Hong Kong, China. Additionally, the average OC to EC ratios in Asian cities was 0.5–5.4, with an overall average of 2.5 in $PM_{2.5}$. These values are similar to the average OC to EC ratios of 2.4 for a mixed urban, suburban, traffic and industrial area (PRDR) [23] and downtown Beijing [26], China.

The OC to EC ratios were <1 at suburban sites in Osaka, Japan [28], for PM_{10}, demonstrating the contribution of motor vehicle exhaust to atmospheric pollution. The OC and EC concentrations in Sapporo, Japan, were measured using the two-step combustion method (at 300 and 850 °C). The OC/EC ratios were >3.0 at suburban sites in Hong Kong, China, for PM_{10} [19], suggesting the presence of secondary organic aerosols. However, the sampling conditions at Asian utilized the same analytical method TMO, and sampling period. Atmospheric transport likely accounts for the higher OC to EC ratios at suburban sites in Hong Kong. The OC to EC ratios in Osaka [12] and at Sapporo sites [29] were <1 for $PM_{2.5}$, demonstrating the influence of fresh motor vehicle exhaust. Additionally, the OC to EC ratios were >3.0 in Hong Kong [19], Kosan [16] and Sihwa sites [9] for $PM_{2.5}$, demonstrating the presence of secondary organic aerosol. Furthermore, the ratio of OC to EC ratios in Asia cities was 1.0–3.0 [23–25,13,28,30,31,33].

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