



Source Apportionment of Urban Background Particulate Matter in Birmingham, United Kingdom Using a Mass Closure Model

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ABSTRACT

Particulate matter (PM) collected during the summer period of 2011 at the urban background of Elms Road Observatory Site (EROS) in Birmingham, United Kingdom was studied and apportioned using the mass closure model. Particulate matter samples were analysed for Cu, Zn, Fe, Ni, Mn, Cl⁻, NO₃⁻, SO₄²⁻, PO₄³⁻, C₂O₄²⁻, Na⁺, NH₄⁺, K⁺, Ca²⁺, OC and EC using the standard procedures. Results showed mean mass concentrations of $5.42 \pm 1.7 \mu\text{g m}^{-3}$ for PM_{2.5} and $5.41 \pm 0.27 \mu\text{g m}^{-3}$ for PM_{10-2.5}. Organic carbon (OC, 26%) formed the major component of PM_{2.5} followed by sulphate (25%) and ammonium (12%). In the coarse PM fraction, ammonium, chloride and OC constituted 17, 15 and 14%, respectively of mass concentration. Metal concentrations in both PM fractions were less than 2% of the observed mass. The mass closure model applied to apportion PM_{2.5} and PM_{10-2.5} chemical species was able to identify four components namely: carbonaceous (45 and 19%, respectively), sea salt (7 and 25%), secondary aerosol (48 and 13%) and minerals (13 and 12%). The mass closure model was unable to explain all the chemical components in the coarse PM category leaving the unidentified mass as 31%. On the other hand, the model overestimated the mass of PM_{2.5} by 14%. The study showed secondary aerosol and carbonaceous species as the dominating sources of PM pollution in the study area.

Keywords: Particulate matter; Urban background; Mass closure model; Emission sources.

INTRODUCTION

The increase in the particulate matter emissions into the air via the anthropogenic and natural sources continues to degrade the air quality (Taiwo *et al.*, 2014a, b; Lin *et al.*, 2015; Sarigiannis *et al.*, 2015; Wang *et al.*, 2015). The influence of particulate matter on the visibility, atmospheric chemistry, human health, ecological systems, and global climate has been reported (IPCC, 2001; Chen *et al.*, 2010; Taiwo *et al.*, 2014a). Particulate matter varies in sizes, components, and composition depending on the primary emission sources, age, atmospheric processing and gaseous emissions (Vallius, 2005). The vehicular emissions, secondary aerosol, marine, resuspension of soil, industry, biomass burning, waste incineration and road dust constitute the major emission sources in the urban environment (Harrison *et al.*, 2003a; Charron *et al.*, 2005; Connell *et al.*, 2006). The

different chemical substances such as metals, water-soluble ions, elemental carbon, aromatic hydrocarbons, organic acids, alcohols, levoglucosans, sterols, polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds are considered as the particulate matter (PM) components (Harrison *et al.*, 2003a, b; Harrison *et al.*, 2004; Dall'Osto *et al.*, 2008; Harrison and Yin, 2010; Yin *et al.*, 2010; Taiwo *et al.*, 2014b). The toxicities of most of these substances had been documented. For instance, PAHs are carcinogenic cytogenic and mutagenic (Massolo *et al.*, 2002; Rehwagen *et al.*, 2005); metals including lead, cadmium, mercury are toxic to the human health as well as the environment (WHO, 2011). The proofs of the impacts of particulate matter on the intrauterine or postnatal death or congenital defects, prematurity, and foetal development had been established (Maisonet *et al.*, 2001; Perera *et al.*, 2003). In Toronto, USA, 1,700 annual premature deaths and 7,000 hospital visits have been associated with air pollution (Buset *et al.*, 2006). A wide range of PM effects on the human health has led to the establishment of health-based air quality standards and objectives at the local and international levels to minimize its emissions. In 2008, the European Union (EU) air quality standard for PM_{2.5} was also introduced as an annual limit value of $25 \mu\text{g m}^{-3}$ to be achieved between 2010 and 2015 (EU, 2008). A daily average value of $50 \mu\text{g m}^{-3}$ (not more than 7 days year⁻¹ exceedances), and an annual mean limit

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of $40 \mu\text{g m}^{-3}$ (not more than 35 exceedances per year) were set for PM_{10} (WHO, 2006).

The pragmatic mass closure model was developed by Harrison *et al.* (2003a) for reconstruction of the measured PM chemical species into major source components that could be used as aerosol tracers. This model had been applied to identify and apportion particulate matter collected from urban background, roadside and industrial sites (Harrison *et al.*, 2003a, Terzi *et al.*, 2010; Yin *et al.*, 2010; Zhang *et al.*, 2010). For instance, Zhang *et al.* (2010) employed the mass closure model to PM data collected from the industrial sites in Ordos region, Inner Mongolia, China. The model revealed contributions to PM as organic matter (23–37% for PM_{10} , 28–39% for $\text{PM}_{2.5}$), crustal material (15–19% for PM_{10} , 14–21% for $\text{PM}_{2.5}$), trace ions (13–14% for PM_{10} , 14–16% for $\text{PM}_{2.5}$) and trace elements (4% for PM_{10} , 5% for $\text{PM}_{2.5}$). The present study aims at identifying and apportioning the emission sources of $\text{PM}_{2.5}$ and $\text{PM}_{10-2.5}$ sampled from an urban background site in Birmingham, UK using the mass closure model.

METHODOLOGY

Brief Description of the Study Area

The background station is the Elms Road Observatory Site (EROS, 1.93°W ; 52.45°N) located in an open field within the University of Birmingham campus (Fig. 1). The site is about 3.5 km southwest of the centre of Birmingham, which has a population of over one million and part of a conurbation of 2.5 million population (Yin *et al.*, 2010). The possible anthropogenic sources of emission at the site include a nearby railway, some moderately trafficked B roads and other surrounding activities from the University and local residents (Yin *et al.*, 2010).

PM Sampling and Analysis

PM sampling was carried out using a Partisol sequential air sampler (Rupprecht and Patashnick Dichotomous Partisol-Plus Model 2025) during the summer period of 2011 (June 2–18). Two Partisol samplers were set-up and run simultaneously for 24 hours (12:00 noon–12:00 noon) for a 16-day sampling period. The average wind speed and temperature during the sampling were $4.5 \pm 1.7 \text{ m s}^{-1}$ and $12.5 \pm 4.3^\circ\text{C}$, respectively (data calculated from the Birmingham Tyburn Roadside's Automatic Urban Rural Network (AURN) Site at uk-air.defra.gov.uk/networks/aurm-site-info). Partisol 1 was fitted with quartz fibre filters, for the analysis of OC/EC and water-soluble ions while Partisol 2 was fitted with Teflon filters for determination of PM mass concentration and metal components.

Determination of PM Mass Concentrations

PM mass concentration ($\text{PM}_{2.5}$ and $\text{PM}_{10-2.5}$) was determined gravimetrically by weighing the Teflon filters before and after sampling with a Sartorius microbalance (model MC5). Before weighing, all filters were equilibrated for 24 hours in the weighing at a relative humidity of 38–45% and temperature of $20\text{--}22^\circ\text{C}$. An ionizing blower was used to eliminate the effects of static electricity during the weighing process (Harrison *et al.*, 2003b).

Determination of Water-Soluble Ions

After the removal of 1 cm^2 punch from the exposed quartz filter samples (for OC/EC determination); the remaining portion was extracted for water-soluble ions with 15 mL distilled de-ionized water (DDW, $18 \Omega\text{m}$) and sonicated in an Ultra-sonication bath for 30 minutes. The extracts were filtered and analyzed for major ions (phosphate, chloride, sulphate, oxalate and nitrate, calcium, ammonium, sodium

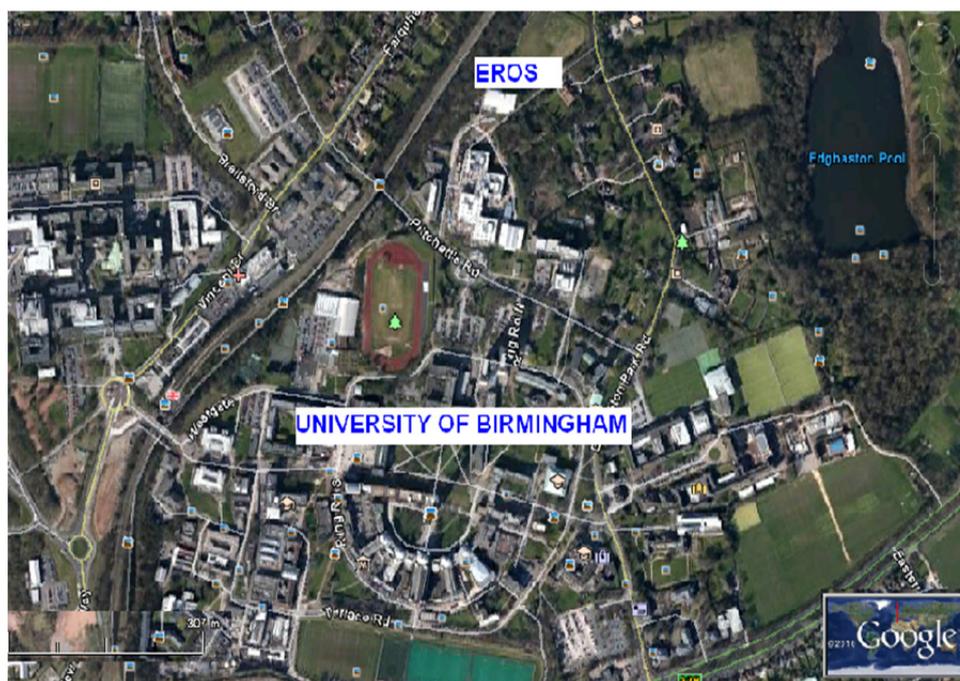


Fig. 1. The Google map showing the study area.

and potassium) using the Ion Chromatography System (ICS). The anions (PO_4^{3-} , SO_4^{2-} , NO_3^- , $\text{C}_2\text{O}_4^{2-}$ and Cl^-) were analysed using Dionex ICS-2000 equipped with an analytical column, AS 11 HC (2×250 mm) and a guard column, AG 11 HC (2×50 mm). About 3 mL of the digested sample was introduced into the autosampler of the Dionex ICS-2000 instrument. The eluant used for the determination of anions was potassium hydroxide. The cations (Ca^{2+} , NH_4^+ , Na^+ , K^+) were measured with Dionex DX500 equipped with an analytical column CS 12A (4×250 mm) and a guard column CG12A (4×50 mm). The eluant solution used was methane sulphonic acid. Calibration curve for determination of water-soluble ions was obtained with series of measured standards prepared in the concentration range of 0–20 ppm.

Metal Analysis

The exposed Teflon filters were digested using the reverse *aqua regia* procedures described in Harrison *et al.* (2003b). A 5 mL mixed acid extractant (65 mL concentrated nitric acid and 185 mL concentrated hydrochloric acid dissolved in 1 L DDW) was introduced into the exposed filter samples and heated at 100°C for 30 minutes in a water bath and then placed in the ultrasonic bath set at 50°C for further 30 minutes. This cycle was repeated and the resulting digested solution transferred to a graduated flask and diluted to 10 mL with distilled deionized water. The extracts of filter samples were analysed for metals (Mn, Cu, Zn, Fe and Ni) using Graphite Furnace Atomic Absorption Spectrophotometer (GFAAS, Perkin Elmer™ Instrument, USA). The instrument was calibrated with appropriate standards ($0\text{--}100 \mu\text{g L}^{-1}$) to obtain the calibration curves.

Organic and Elemental Carbon Analysis

Organic and Elemental Carbon (OC/EC) analyses were determined using the Sunset Laboratory Thermal-Optical Carbon Aerosol Analyzer. A 1 cm^2 portion of exposed quartz fibre filter punch was placed into the manganese dioxide (MnO_2) oven of the analyser for OC/EC measurement.

Thermal-Optical Carbon Aerosol Analyzer uses a thermal desorption that was combined with an optical transmission of laser light through the sample to speciate carbon collected on a filter paper (Sunset Laboratory Inc., 2000). The instrument measures OC using the Flame Ionization Detector (FID) during an initial non-oxidizing temperature ramp from ambient to 870°C under helium atmosphere. EC is measured during the second temperature ramp from 550 to 850°C under helium/oxygen mixture. The full procedures for determination of OC/EC had been described elsewhere in Yin *et al.* (2010). The OC/EC instrument was calibrated with sucrose standards ($1\text{--}5 \mu\text{g L}^{-1}$).

Data Analysis

Data collected were analysed for simple descriptive statistics of mean and standard deviation using the Windows Microsoft Excel package. Data are also presented in tables and pie charts.

Mass Closure Model

The mass closure model uses eight components of the measured PM chemical species with their corresponding conversion factors to infer contribution to aerosol sources through mass reconstruction. The eight components are presented in Table 1. They include:

- Ammonium sulphate $\{(\text{NH}_4)_2\text{SO}_4\}$ derived from reaction of sulphuric acid (formed as a result of oxidation of sulphur dioxide) and ammonia.
- Ammonium nitrate (fine mode, NH_4NO_3) derived from neutralization of nitric acid vapour (product of oxidation of nitrogen dioxide) by ammonia.
- Ammonium sulphate and ammonium nitrate are known as secondary aerosol.
- Sodium nitrate (coarse mode, NaNO_3) is formed from the reaction of marine aerosol or sea salt with nitric acid vapour.
- Sodium chloride (NaCl) is derived mainly from sea salt.
- Calcium is represented by gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$).

Table 1. Components for constructing mass closure model and their conversion ratios.

Analyte	Conversion to	Numeric factor
Sulphate	$(\text{NH}_4)_2\text{SO}_4$	1.38
	Hydrate	1.29
Nitrate (fine)	NH_4NO_3	1.29
	Hydrate	1.29
Nitrate (coarse)	NaNO_3	1.37
	Hydrate	1.29
Chloride	NaCl	1.65
	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	4.30
Iron	Soil/road dust	5.50 (roadside)
		9.00 (background)
		3.50 (roadside increment)
Elemental Carbon	Elemental Carbon	1.00
Organic carbon	Organic compounds	1.30 (roadside)
		1.40 (background)
		1.20 (roadside increment)
Water content		$(\text{Nitrate} + \text{Sulfate}) \times 0.29$

Source: Harrison *et al.* (2003).

- Iron, which is a tracer for road dust is generated from traffic. Mineral source is a sum of calcium and iron components.
- Elemental carbon (EC) is derived from incomplete combustion of fossil fuels.
- Organic carbon (OC) is produced from both primary and secondary sources.
- Carbonaceous species is the sum of EC and OC.
- Water content also formed a part in pragmatic mass closure model, although it is not measured in the chemical analysis. Water bound PM could form 20–35% of the PM mass concentration (Tsyro, 2005).

Further detailed procedures of mass closure model can be seen elsewhere in Harrison *et al.* (2003).

Quality Assurance

All the measuring and analytical instruments were properly calibrated during the period of sampling and laboratory analyses. Field blank filter samples (6) were analyzed for water-soluble ions, metals and OC/EC to correct the background concentration of elements present in the filters, and also to determine the detection limits (Taiwo *et al.*, 2014a). Before sampling, the quartz filters (Whatman) were pre-treated by heating in an oven set at 500°C for 4 hours to remove any background OC present in the filters. All chemicals used for metal extraction were of ultra-pure grade. The procedure for metal analysis was evaluated by the analysis of NIST SRM 1684a in the earlier work (Allen *et al.*, 2010), and more recent trials have shown high efficiency (> 85%) for all elements. The sample concentrations were calibrated with a series of mixed standards.

RESULTS AND DISCUSSION

Composition of Particulate Matter

The physical and chemical composition of fine and coarse particulate matter is presented in Table 2. The mean

mass concentrations were $5.42 \pm 1.7 \mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$ and $5.41 \pm 0.27 \mu\text{g m}^{-3}$ for $\text{PM}_{10-2.5}$. These mass concentrations were lower than the values previously reported at urban background sites in the UK (Harrison *et al.*, 2004, Harrison and Yin, 2010, Gietl *et al.*, 2010; Yin *et al.*, 2010) and other European countries (Querol *et al.*, 2004). In many European countries, the concentration of $\text{PM}_{2.5}$ measured in the urban background sites varied from 1.0 to $30 \mu\text{g m}^{-3}$ (Querol *et al.*, 2004). For $\text{PM}_{10-2.5}$, the mass concentration obtained in this study was also lower than the value previously reported by Harrison *et al.* (2004) at the urban background locations in London and Birmingham, UK. The low mass concentrations of fine and coarse PM obtained in this study could be attributable to effectiveness of the air quality policies in the UK (AQEG, 2012). PM_{10} concentrations in most cities in the UK including Birmingham had over the years, reduced tremendously (AQEG, 2005). For instance, the annual PM_{10} mean value for Birmingham (data from the AURN Birmingham City Center and Tyburn Roadside sites) revealed a 45% decrease from $36.5 \pm 20.7 \mu\text{g m}^{-3}$ in 1995 to $20.1 \pm 9.4 \mu\text{g m}^{-3}$ in 2010 (Fig. S1 in the supplementary information). Previous studies have shown rare cases of $\text{PM}_{2.5}$ and PM_{10} exceedances at the EROS site, and during the period of the present study (Harrison *et al.*, 2003a, b, 2004, Harrison and Yin, 2008; Yin *et al.*, 2010; Taiwo *et al.*, 2014b).

In this study, the major contributor to fine PM was secondary aerosol, which constituted 48% of the measured $\text{PM}_{2.5}$ mass. Organic carbon made up 26% of the measured $\text{PM}_{2.5}$ mass (Fig. 2(a)). This is similar to the report of Harrison *et al.* (2004) at four different urban background sites in the UK where the carbonaceous species dominated the $\text{PM}_{2.5}$ mass. In the coarse PM portion, organic carbon formed 14% of the total measured mass (see Fig. 2(b)) while the values of EC was less than 1% of the mass concentration. The combined carbonaceous species constituted 35 and 14% of $\text{PM}_{2.5}$ and $\text{PM}_{10-2.5}$ respectively. The OC/EC ratio obtained

Table 2. Physical and Chemical of Composition of $\text{PM}_{2.5}$ and $\text{PM}_{10-2.5}$ at EROS.

(ng m ⁻³)	$\text{PM}_{2.5}$				$\text{PM}_{10-2.5}$			
	Mean	SD	Min	Max	Mean	SD	Min	Max
*PM mass	5.42	1.7	2.31	8.84	5.41	0.27	2.20	12.03
OC	1411	434	692	2256	733	318	157	1295
EC	489	312	52.6	1049	16.7	109	< 5.0	241
Cl ⁻	232	160	64.1	598	810	670	75.3	1908
NO ₃ ⁻	587	435	127	1449	304	319	< 26	1099
SO ₄ ²⁻	1334	955	561	3805	207	275	< 150	856
PO ₄ ³⁻	190	95.8	16.4	315	172	86.1	48.4	319
C ₂ O ₄ ²⁻	104	29.6	68.9	165	59.8	8.80	46.3	76
Na ⁺	238	406	< 127	1345	310	270	11.7	1240
Ca ²⁺	24.6	67.1	< 20	201.9	102.8	124.4	< 26	295.1
NH ₄ ⁺	637	657	< 33	1929	921	1227	< 26	3128
Cu	8.33	23.3	< 0.2	80.3	18.1	22.9	< 0.05	63.3
Mn	38	23.9	4.13	71.3	40.7	27.4	< 0.02	78.9
Ni	7.56	8.6	< 0.1	23.8	17	19.6	< 0.02	69.3
Fe	6.77	25.5	< 2.0	66.6	4.62	18.7	4.62	56.8
Zn	13	8.7	2.92	29.2	1.5	9.6	< 0.3	9.8

* PM mass in $\mu\text{g m}^{-3}$, SD-standard deviation.

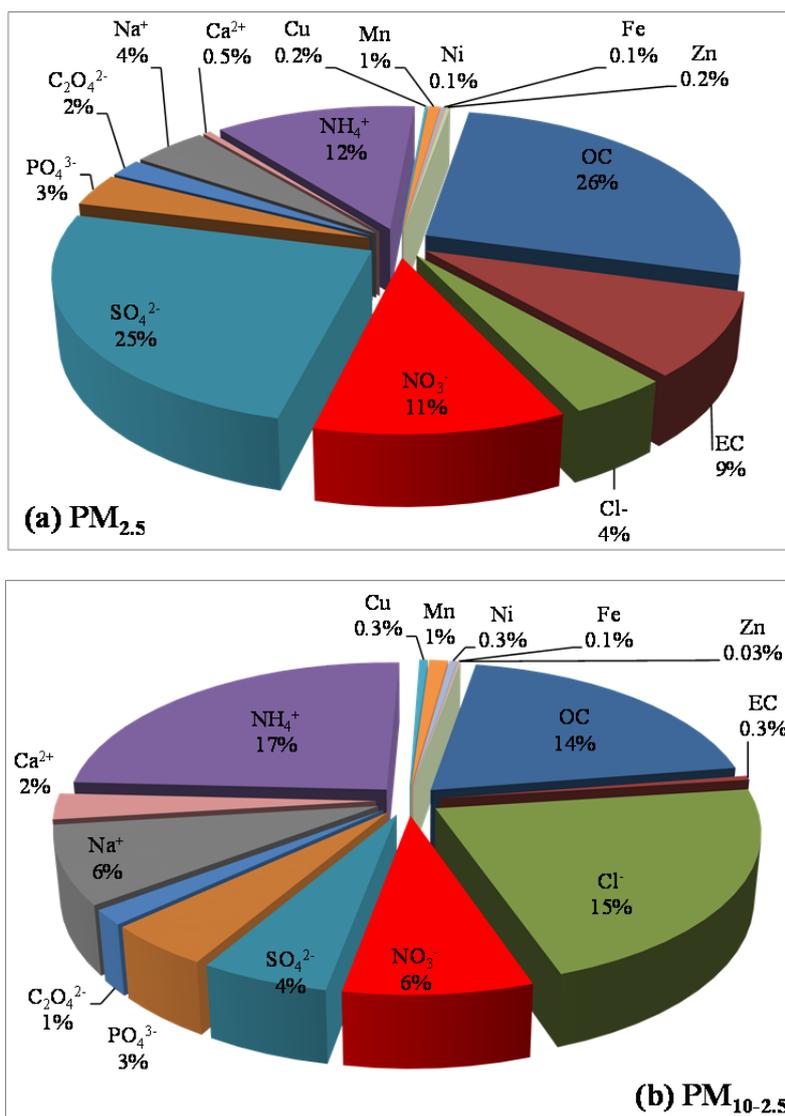


Fig. 2. Percent components of Particulate Matter (a-fine PM, b-coarse PM).

in this study was 2.9 for PM_{2.5}; this was slightly higher than the typical OC/EC ratio measured in the European cities (Querol *et al.*, 2004). The OC/EC ratio value for PM_{10-2.5} was 44. The OC/EC ratio of about 3.0 obtained for PM_{2.5} occurred within the range 3–15 reported during the photochemical active period in New York, USA (Rattigan *et al.*, 2010). According to Rattigan *et al.* (2010), the OC/EC ratio of 1.5 is a confirmation of traffic domination while OC/EC ratio value between 4 and 6 signifies impacts from regional forest fire plumes or long range urban plumes. The secondary OC formation might be responsible for the high PM_{2.5} OC/EC ratio observed in the study area. EC is primary emitted from incomplete combustion of fossil fuel. A weak correlation was found between OC and EC in PM_{2.5} ($R^2 = 0.02$) suggesting dissimilar emission sources. The high ratio of OC/EC observed for coarse PM in this study might suggest other emission sources of OC apart from anthropogenic origins. The coarse OC may arise from sources such as fossil fuel combustion, mechanical wear of tyres and from biological origins including plant debris, pollen

and fungal spores (Pavuluri *et al.*, 2011; Laongsri, 2012).

Sulphate formed the highest percentage of anionic species (25%) measured in the fine PM fraction and chloride (15%) in PM_{10-2.5} components. Cationic species was dominated by NH₄⁺ in PM_{10-2.5} (17%) and also in PM_{2.5} (12%). The marine aerosol (NaCl) constituted one-fifth of PM_{10-2.5} (Harrison and Yin, 2000). The OM/SO₄²⁻ ratio was calculated to infer sources to PM pollution in this study. The high OM/SO₄²⁻ (6.4) suggests biogenic influence and less photochemical aging (Ziemba *et al.*, 2007). Smaller OM/SO₄²⁻ (0.4–0.6) indicates anthropogenic activities and photochemical aging. The OM/SO₄²⁻ ratio in this study was calculated as 1.48 and 4.96 for PM_{2.5} and PM_{10-2.5}, respectively indicating anthropogenic and biogenic influences. Oxalate mean concentration was higher in the fine PM ($104 \pm 29.6 \text{ ng m}^{-3}$) than in the coarse PM mode ($59.8 \pm 8.8 \text{ ng m}^{-3}$) contrary to the findings of Yao *et al.* (2003) where oxalate dominated the coarse PM sampled in Beijing, China. High oxalate concentration in the fine mode is usually related to heterogeneous formation (Yao *et al.*, 2003). The PM metal

values were generally low constituting less than 2% of the total mass (Figs. 2(a) and 2(b)). This is consistent with the study of Harrison and Yin (2010) at the EROS sampling sites. Manganese was the highest observed metal ($37.99 \pm 23.85 \text{ ng m}^{-3}$ for $\text{PM}_{2.5}$ and $40.69 \pm 27.40 \text{ ng m}^{-3}$ for $\text{PM}_{10-2.5}$) followed by Zn in the fine mode and Cu in the coarse PM. The mean values of Mn and Ni in this study were higher than the values reported in $\text{PM}_{2.5}$ by Harrison and Yin (2010) at the EROS background. However, Cu, Fe and Zn concentrations were less than the values reported by Harrison and Yin (2008). The high Mn and Fe in the coarse PM may be linked to re-suspended dust from the nearby railway.

Mass Closure Model of Particulate Matter (PM)

The result of mass closure model of EROS background particulate matter (PM) was presented in Fig. 3. The reconstructed mass for fine PM accounted for 114% of the measured PM mass, while only 69% was accounted for in the coarse particle mode. The model was better fit for $\text{PM}_{2.5}$ in this study ($R^2 = 0.67$) than $\text{PM}_{10-2.5}$ ($R^2 = 0.34$). The mass closure model underestimated the reconstructed mass for $\text{PM}_{10-2.5}$ and overestimated the calculated mass for $\text{PM}_{2.5}$. Reason for this underestimation of mass might be attributed to non-inclusion of strongly water-bound component and also the adopted conversion factors for estimating organic matter and crustal material (Harrison *et al.*, 2003; Terzi *et al.*, 2010). Water bound component in particulate matter has been estimated to account for 20–35% of total PM mass (Tsyro, 2005). Inclusion of strongly water-bound has been reported by Yin *et al.* (2010) as a major reason for overestimation of mass closure model, which was contrary to the finding of this study. The problem of the model overestimation may be directly link to positive sampling artefacts. According to Turpin *et al.* (2000), overestimation of particulate OC may result from adsorption of organic vapour onto quartz-fibre filter material.

The pragmatic mass closure model revealed four major sources, which were secondary aerosol (ammonium sulphate + ammonium nitrate), minerals (calcium sulphate + iron rich dust), sea salt (sodium chloride) and carbonaceous aerosol (OC and EC). The fine PM was dominated by secondary aerosol and carbonaceous species representing 48 and 45%, respectively while $\text{PM}_{10-2.5}$ was predominantly sea salt (25%), carbonaceous aerosol (19%) and secondary aerosol (13%). In the previous study at EROS (Yin *et al.*, 2010) where only $\text{PM}_{2.5}$ was determined; the source contribution by mass closure model attributed 53 and 34% to secondary aerosol in the summer and winter seasons, respectively. The high contribution by secondary aerosol at the EROS site is a reflection of the east to west gradient in secondary nitrate and secondary sulphate being observed all over the United Kingdom (AQEG, 2012; Taiwo *et al.*, 2014b). The high photochemical activities during the summer period could also contribute to the high values of secondary aerosol observed in agreement with the study of Yin *et al.* (2010). Emission of carbonaceous species in this site might originate from many diverse sources including the local traffic, secondary formation, combustion processes and biological plants. Yin *et al.* (2010) employed chemical mass balance (CMB) and pragmatic mass closure models to identify emission sources of fine particles in EROS site identified a smoking engine signature. This was traced to the use of mowers for cutting grasses at the site and also an old generating set occasionally used near the site. Moreover, this site is around 3.5 km to the Birmingham City Center where high vehicular emissions and combustion processes are expected to be high (Taiwo *et al.*, 2014b). The study of Wang *et al.* (2005) had assigned a high contribution to carbonaceous species (70%) in PM_{10} sampled during the wintertime in Christchurch, Australia. In other sampling locations around the world, contributions by carbonaceous species in PM were 40% in London, UK (winter and summer,

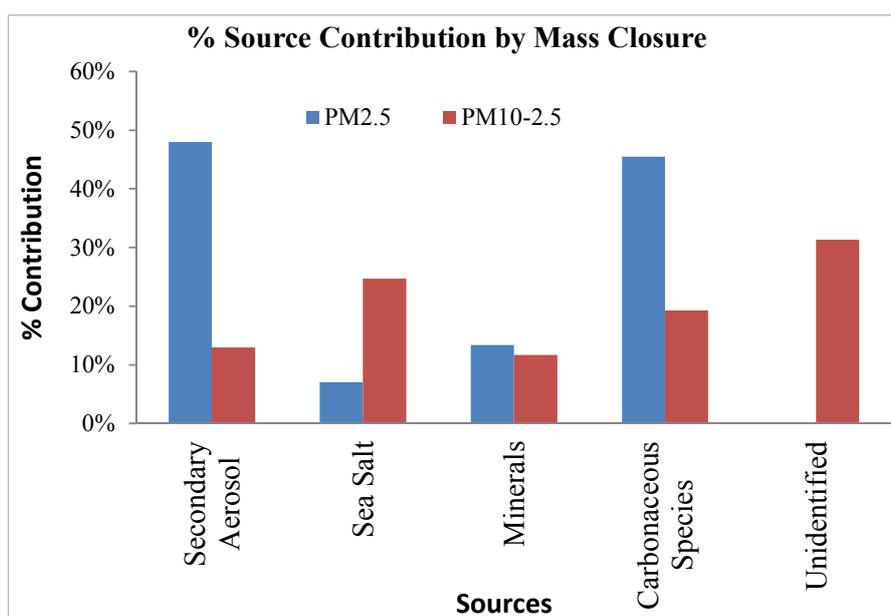


Fig. 3. Percent source contributions by Mass Closure Model.

Harrison *et al.*, 2004); 36% in New Zealand (winter and summer, Ho *et al.*, 2006); 31% in Mira Loma, California, USA (winter, Na *et al.*, 2004); 28% in Moitinhos, Portugal (summer, Pio *et al.*, 2008). According to Zhang *et al.* (2007), carbonaceous aerosol sometimes constitutes approximately 50% of urban fine PM.

Although, sea salt formed the major constituent of coarse particulate matter (25%); the mass closure model also assigned about 7% of PM_{2.5} to sea salt source. Sea salt in the PM coarse fraction may arise from the passage of clean continental marine air through the receptor site (Taiwo *et al.*, 2014c). Neutralization of hydrochloric acid vapour (from incinerator and power plants) by ammonia might also be responsible for chloride formation in the fine PM mode (Harrison and Yin, 2000).

Minerals formed 12% of the coarse particles, lower than the mineral component (48%) reported by Harrison *et al.* (2004). Sources of mineral dusts in this site might include: possible construction activities around the site, re-suspension of road dust, soil and fugitive emissions. EROS site is very close to the railway line that passes through the University of Birmingham campus to the Birmingham City center. This might also, contributed to the mineral contents of coarse PM. A study by Sillanpää *et al.* (2006) reported minerals (60%) as the largest portion of PM_{10-2.5} measured in Athens, Spain. The study of Jung *et al.* (2010) revealed the high fraction of iron-containing dust (29–87%) in PM sampled from the underground subway stations in Seoul, Korea.

CONCLUSION

This present study revealed low mass concentrations of fine and coarse PM and their measured chemical components compared to the past studies at the site. Organic carbon (OC), sulphate and nitrate dominated the PM_{2.5} fraction while PM_{10-2.5} was dominated by ammonium and chloride. The mass closure model revealed four major components including secondary aerosol, which formed the highest percentage of PM_{2.5} and marine aerosol, which constituted the major portion of PM_{10-2.5}. Other sources of PM in the study area were carbonaceous species and minerals. The mass closure could only account for 69% of the coarse PM mass, probably due to errors from the adopted conversion ratios and the water bound PM while the PM_{2.5} mass was over-estimated (114%), probably due to laboratory artefacts. The PM pollution measured in this site might therefore be influenced by the local emission sources including vehicular, combustion of fossil fuels, re-suspension of road and rail dust, construction activities, continental marine aerosol, incinerators and secondary formation. The coarse PM was predominantly controlled by natural origin while fine PM was majorly impacted by anthropogenic sources.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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