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Characterization of Spatial Impact of Particles Emitted from a Cement Material Production Facility on Outdoor Particle Deposition in the Surrounding Community

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Abstract

The objective of this study was to estimate the contribution of a facility that processes steel production slag into raw material for cement production to local outdoor particle deposition in Camden, NJ. A dry deposition sampler that can house four 37-mm quartz fiber filters was developed and used for the collection of atmospheric particle deposits. Two rounds of particle collection (3–4 weeks each) were conducted in 8–11 locations 200–800 m downwind of the facility. Background samples were concurrently collected in a remote area located ~2 km upwind from the facility. In addition, duplicate surface wipe samples were collected side-by-side from each of the 13 locations within the same sampling area during the first deposition sampling period. One composite source material sample was also collected from a pile stored in the facility. Both the bulk of the source material and the <38 μm fraction subsample were analyzed to obtain the elemental source profile. The particle deposition flux in the study area was higher (24–83 mg/m^2 day) than at the background sites (13–17 mg/m^2 -day). The concentration of Ca, a major element in the cement source production material, was found to exponentially decrease with increasing downwind distance from the facility ($P < 0.05$). The ratio of Ca/Al, an indicator of Ca enrichment due to anthropogenic sources in a given sample, showed a similar trend. These observations

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suggest a significant contribution of the facility to the local particle deposition. The contribution of the facility to outdoor deposited particle mass was further estimated by three independent models using the measurements obtained from this study. The estimated contributions to particle deposition in the study area were 1.8–7.4% from the regression analysis of the Ca concentration in particle deposition samples against the distance from the facility, 0–11% from the U.S. Environmental Protection Agency (EPA) Chemical Mass Balance (CMB) source-receptor model, and 7.6–13% from the EPA Industrial Source Complex Short Term (ISCST3) dispersion model using the particle-size-adjusted permit-based emissions estimates.

INTRODUCTION

Facilities that crush or grind raw materials have the potential to emit particles into the ambient air.^{1–3} The large particles may deposit on outdoor surfaces surrounding such facilities, and the fine particles may stay suspended in air for a longer period. Those smaller particles can be a concern for community health because fine particles (PM_{2.5}, particulate matter smaller than 2.5 µm in diameter) can be inhaled and penetrate into the lung deep.^{4,5} Indeed, numerous studies have shown strong associations of fine particles with cardiopulmonary health effects.^{6–9} In addition, the particles deposited on outdoor surfaces can be a source of exposure through hand-to-mouth activities and dermal adherence. Furthermore, dust deposition can negatively affect the quality of life for residents near such facilities, because it requires frequent cleaning and laundering, creates unsightly conditions, and lowers the value of residential property.

However, the spatial impact of particle emission from such facilities on particle deposition in local communities has not been well characterized. Only a few studies investigated deposition rates¹⁰ and particle concentrations¹ related to particle emission from cement facilities. Those studies reported that the deposition rate of Ca exponentially decreased with the increase in distance from the cement factories¹⁰ and demonstrated elevated total suspended particulate (TSP) concentrations in residences close to the cement plant.¹

This study was undertaken to investigate the contribution of particulate emissions from a cement material production facility to particulate deposition in a nearby residential neighborhood—the Waterfront South (WFS) area of Camden, New Jersey (NJ).¹¹ The residents in WFS have had a longstanding concern with the dustiness of their environment, and anecdotally identified the target facility as a significant source of dust in their community. This facility receives steel production slag and grinds it for use in cement production. The cement material is subsequently transported from the facility by trucks to other areas. Thus, suspension of particles may occur due to wind blowing over raw cement material piles, grinding operation, transportation process, and fugitive emissions in the facility. In addition, WFS is subject to many other PM emission sources, including industrial and mobile sources in the area.¹¹ Thus, identification of the contribution from a single source to local particle deposition is challenging.

The objectives of this study are to (1) determine the spatial distribution of particle deposition in WFS and (2) estimate the contribution of particulate emissions from the facility to outdoor deposited particle mass in the neighborhood. To achieve these goals, we conducted

two spatial sampling campaigns with sampling durations of 3 and 4 weeks by deploying PM deposition samplers around the facility. We also conducted one-time surface wipe sampling of the dust around the facility to assess the impact of irregular particulate emissions as a discrete plume. On the basis of the measurements, we employed three independent methods to estimate the contribution from the facility to local deposited particle mass. The methods were (1) a regression analysis of Ca, a marker element for cement related activities; (2) the EPA-approved Chemical Mass Balance (CMB) source-receptor model; and (3) the EPA-approved Industrial Source Complex Short Term (ISCST3) dispersion model. Results obtained from the three independent modeling approaches can provide confidence in the estimates that were obtained from the measurements.

METHODS

Study Area

The WFS neighborhood is located in south Camden, NJ (Figure 1). It has a population of approximately 1700 residents. Most of the residents in WFS are minority and low-income.¹² The focus of this study (henceforth referred to as “the facility”) is located approximately 200 m upwind of the WFS. The facility contains several stacks that perform the grinding operation and are potential sources of particulate emissions. In addition, the raw cement material (RCM) is stored uncovered in a pile approximately 9 m high in the yard of the facility. Although this material forms crusts that prevent large-scale emissions from the pile, fugitive emission of particles from the pile may, nonetheless, occur during windy weather and transport of the material. In addition to this facility, WFS is subject to various other particle emission sources, including a local sewage treatment plant, several metal processing and recycling plants, car scrapping and painting facilities, iron workshops, heavy diesel truck traffic, etc.¹¹ Most of the WFS residents live within 200 m of stationary or mobile sources.¹¹

Deposition Sampling

Previous studies demonstrated that spatial sampling is a powerful approach to examine the impact of a local industrial facility on community air pollution.^{11,13} The PM mass and elemental concentration obtained from spatial sampling can be used to estimate the spatial impact of particulate emissions from the facility on the WFS air quality. To perform spatial sampling, a passive sampling system is often needed to allow samples to be collected from multiple locations simultaneously in the study area. This is because the passive samplers are less expensive than active samplers, easy to operate, and do not require a power supply.¹⁴ Prior to field sampling, we developed a dry deposition sampler for the study. Dry deposition is more relevant to our study purpose than wet deposition because wet deposition depends on the intensity and duration of precipitation.¹⁰

The dry deposition sampler was developed on the basis of consideration of particle deposition mechanisms of convective diffusion, inertial impaction, and gravitational settling on the collection substrate.^{4,15} To successfully collect samples for a duration of 1 month, weather conditions such as heavy rain and strong wind and the security of the sampler were considered in the design. The schematic diagram of the deposition sampler is presented in

Figure 2a. The sampler is plastic, with a conical hood to protect the filters from rain and wind during field sampling. The sampler is painted green to be inconspicuous. The sampler can house four 37-mm quartz fiber filters (Pall Life Sciences, Ann Arbor, MI). In addition, all samplers were simultaneously deployed in open area so that solar radiation and thus temperature gradient did not vary dramatically by site.

Prior to field sampling, we conducted field tests to (1) evaluate the precision of PM mass collection by the four filters placed in one hooded deposition sampler; (2) examine whether the hood may affect the particle collection via deposition by comparing the PM mass measured by the hooded deposition sampler and the co-located un-hooded deposition sampler; and (3) examine the TSP collection of the deposition sampler by comparing the PM mass collected by a dry deposition sampler and the co-located active sampler. The field evaluation tests were conducted at various locations (e.g., residential porch/terrace/backyard, bus stop, park shelter, etc) for a period of 1–3 weeks. Good precision (4–18% of relative standard deviation, RSD) was obtained for the PM mass measured for the four filters placed in each of the three deposition samplers. In addition, there was no significant difference in the mass collected by the hooded and un-hooded samplers (paired t test; $P = 0.55$; $N = 6$ tests). These results indicate that the over the deposition sampler did not affect PM collection by deposition. Therefore, the hooded deposition sampler was used for sampling in the study. To further evaluate the performance of the deposition sampler, the relative percent difference (RPD) of the average PM mass measured by the two co-located deposition samplers was determined during field study, and the results are reported in the QA/QC section. The PM mass collected by the deposition sampler was, however, approximately 40% ($N = 3$ tests) of that collected by the active sampler. The morphological analysis results (see Table 1) suggest that the lower PM mass collected by the deposition sampler might result from the low collection efficiency for large particles (particles $> 35 \mu\text{m}$). The potential impact of the low collection efficiency on the study results are discussed in Particle Size Distribution section.

We would like to note that the deposition sampler developed in this study was a prototype. The modified version of the deposition sampler is being evaluated under various environmental conditions, such as wind speed, particle diameters, etc., and the results will be published in the future.

Field Sampling

Particle Deposition Sampling—The sites for particle deposition sampling in WFS were selected by assuming that the RCM piles stored at the facility were the main sources of PM emissions from the facility. Additionally, fugitive particulate emissions during transport of the material and resuspension of the aged particles by wind or other mechanical forces may contribute to the particle deposition levels in the study area. Using the approach of Hinds,⁴ we first estimated the travel distances of different sized RCM particles that may be suspended by wind blowing over the pile prior to deposit on the deposition sampler hung 2.5 m above the ground. The particles were assumed to originate from the middle (4.5 m above ground level) or top (9 m above ground level) of the RCM piles. The median wind velocity of 3.5 m/s ¹⁶ was used for the estimation. On the basis of the estimation, particles in the

range of 10–38 μm in diameter are likely to settle in the areas within a distance of 200–800 m downwind of the facility (i.e., the WFS residential area). Thus, 8–11 sites that were spatially distributed in WFS residential area and located 200–800 m downwind of the facility were selected for PM deposition sampling. Ideally, samplers would have been located precisely and with a greater spatial resolution on the major downwind (southwest) axis. However, given the practical considerations of finding suitable and secure locations in this densely populated area, this was not feasible. Nonetheless, all of the WFS sampling locations were close to this theoretical downwind axis (Figure 1). In addition to the appropriate distance from the facility, the selected sampling sites addressed unconfined space that would not interfere with particle deposition and accessibility by field personnel. Most of the sampling sites were located at locations in residential homes (such as balconies, terraces, porches, etc.) in order to make it more likely that the samplers would be secure against vandalism and tampering. Interferences from overhanging roofs and awnings were avoided by hanging the samplers at the corners of these structures. An example of a deposition sampler deployed in the field is shown in Figure 2b. One background site was selected in Gloucester City Park, which was located 2.2 km upwind (southwest) of the facility (Figure 1).

We conducted two rounds of particle deposition samplings in WFS. The first round was conducted from July 5 to July 26, 2007. PM samples were simultaneously collected from the 11 locations in WFS and one location in the background site (Figure S1), and a duplicate sampler was placed at each of the 12 locations. However, the samplers from four sampling locations, including the samplers located at the background site, were lost during this first round. The second sampling was conducted from August 17 to September 17, 2007, and two samplers were placed at each of the eight WFS locations and the two locations in the background area (Figure S2). All of the samplers were recovered after the 31-day sampling period.

Surface Wipe Sampling—During the first round of particle deposition sampling, surface wipe samples were collected from the 13 locations within 500 m downwind of the facility (Figure S3). The selected surfaces included tops of outdoor ledges/sills, air conditioners, and electrical boxes that were protected from the direct scavenging effect of wind. In addition, those surfaces were flat and relatively smooth so as not to impede wipe sampling. However, in this study, the mass of collected particle from open surfaces may be lower than those from surfaces with canopies such as trees. Zhang et al.¹⁷ reported lower deposition velocity for open surfaces than surfaces with forest canopies.

The selected surfaces were visually inspected prior to wipe sampling. A moistened wipe, 13×17.5 cm² (Cliniguard Dry Washcloths; TENA, Waukegan, WI), was used for surface dust collection. The detailed descriptions of the sampling method can be found in our previous study.¹⁸ Two wipe samples were collected side-by-side from each location. Besides the 13 sites in WFS, four wipe samples were concurrently collected from two locations at the background site.

Collection of RCM from the Facility—The raw cement material used by the facility all came from a similar source and underwent only physical processing onsite. Thus, the

location and timing of obtaining the RCM source sample were not considered critical with respect to the potential variability of the physical and chemical composition of the material. Three 150-g RCM samples were collected from the top layer of the exposed material at three different spots on the pile. The three spots were at approximately 6 m above the ground. The samples were stored in wide-mouth bottles (0.5 L glass jar) and transported to the laboratory at EOHSI (Environmental and Occupational Health Sciences Institute). The three samples were composited into one sample, and the composite sample was stored in a temperature-controlled (4 ± 1 °C) cold room at EOHSI until analysis.

Sample Preparation and Analysis

RCM Preparation—The RCM sample was dried in a Fisher Isotemp oven at 70 °C to remove moisture, and sieved to 250-, 75-, and 38- μ m-diameter fractions using the U.S. Standard Test Sieves (Fisher Scientific, Pittsburgh, PA).

Elemental Analysis—All of the samples (i.e., the un-sieved bulk RCM, the <38 μ m fraction of the RCM, the particle deposition samples, and the surface dust samples) were analyzed for elemental composition. Briefly, samples were extracted with 1 mL of concentrated high purity nitric acid by the microwave-oven-assisted digestion method (EPA method TO-3051). The digest was analyzed for elements by an inductively coupled plasma mass spectrometer (ICPMS; VG Elemental, Winsford, UK) according to the EPA method 200.8. Si was not measured in the study, because the digestion method does not quantitatively dissolve Si from the sample. Accuracy was measured against elemental standards (High Purity Standards, Inc., Charleston, SC) certified to 0.5%. Acceptable quality assurance checks were taken to be $100\% \pm 20\%$ of the certified values.

Microscopic Analysis—Three deposition samples collected from the locations close to the pile (distance <300 m) and one sieved RCM sample (<38 μ m) were analyzed for morphology, size distribution, and elemental composition by MVA Scientific Consultants (Duluth, GA). Particle size and elemental composition were measured using a JEOL Model JSM-6500F field emission scanning electron microscope (SEM), operating in automated mode under the control of a Thermo Noran System SIX X-ray analysis system. The morphological examination was conducted by polarized light microscopy (PLM) analysis using an Olympus SZ-40 stereomicroscope at magnifications from 7 $\times$ to 40 $\times$.

QA/QC

To check the precision of the deposition sampling during the field study, the RSD of the particle mass collected by the four filters placed in one deposition sampler was calculated. In addition, the RPD of the average particle mass between the two co-located deposition samplers was also determined. The RSD was $13\% \pm 10\%$ ($N = 31$ deposition samplers) and the RPD was $13\% \pm 11\%$ ($N = 13$ pairs). Six (three laboratory blanks and three field trip blanks) for deposition sampling and six wipe blank samples were analyzed for elemental concentrations, and the results are reported in Tables 2 and 3, respectively.

Data Analyses

Data from the two deposition sampling campaigns were combined into one data set for data analyses. For locations with duplicate samples, the arithmetic mean of the two samples was used for analysis. Specific analyses conducted in the study are described below.

Particle Mass and Elemental Concentrations versus Distance from the Facility

—Associations between particle mass/elemental concentrations and the distance from the facility were assessed using the Spearman correlation coefficient (r_s). A negative correlation coefficient ($P < 0.05$) suggested a decrease in particle mass/elemental concentrations with increasing distance from the facility.

Enrichment Factors for Elements and Ca/Al Ratios—The enrichment factor (EF) is a better indication of anthropogenic source contribution than gross elemental data.¹⁰ EF is defined as the ratio of an elemental concentration in a sample to the concentration in the crustal geologic material. In our study, we calculated enrichment factors for all the elements that we quantified. The enrichment factors were calculated by eq 1 using Ti as a reference element.¹⁹ Ti was chosen on the basis of the following criteria: (1) generally high concentrations in reference crustal material; (2) very low levels in pollution sources; (3) ease of determination by a number of analytical techniques; and (4) freedom from contamination during sampling.

$$EF_s = \frac{E_s/Ti_s}{E_r/Ti_r}, \quad (1)$$

where EF_s is the enrichment factor for element s ; E_s is an elemental concentration or loading for element s in the examined sample; Ti_s is a Ti concentration or loading in the examined sample; E_r is an elemental concentration in reference crustal material; and Ti_r is a Ti concentration in reference crustal material.

The value for Ti_r was obtained from average crustal material.²⁰ If EF is greater than 5, it indicates the presence of an element that is significantly enriched in the sample relative to the reference material.¹⁰

Taking Ca and Al as the marker elements for cement and natural sources, respectively,^{10,19} Ca/Al ratios were calculated for the sample collected from all the WFS sites. The ratio, another indicator of the contribution from the facility to particle deposition in the community, indicates relative Ca enrichment in the samples. Al was selected because (1) Al is one of the major crustal elements and (2) Al is not significantly affected by traffic emissions in urban and rural aerosols.¹⁹

Ca Regression Analysis—If particulate emission from the facility is the main source of particle deposition in the surrounding area, an exponential decrease of Ca, the most abundant element in cement material, is expected with distance from the facility. Thus, the Ca concentrations measured in the deposition samples were regressed against the distance from the facility. The resulting regression model was then used to predict the Ca concentrations at designated distances from the facility, and the predicted Ca concentrations

were divided by the Ca concentration in RCM (sieved $<38\ \mu\text{m}$). The resulting value is an estimate of the percent contribution of the facility emission to deposited particle mass at the corresponding distance in WFS.

Chemical Mass Balance (CMB) Model—The EPA CMB model (version 8.2)²¹ was used to estimate the contribution of the facility to the particle deposition in the local area. The CMB model uses the detailed source profiles from specific sources to estimate the contribution of each source to total PM mass at receptor locations. In this study, site-specific source profiles (other than those from the study facility) were not available. Therefore, source profiles from a well-characterized urban surrogate data set, the Portland Aerosol Characterization Study (PACS),²² were employed for modeling. The PACS source profiles are comprehensive, including typical PM sources, such as natural (e.g., marine aerosol and continental dust) and anthropogenic sources (e.g., automobile exhaust, oil combustion, and industrial emissions), in both fine ($<2.5\ \mu\text{m}$) and coarse-size ($<30\ \mu\text{m}$) fractions. Elemental concentrations in reference rock²⁰ and soil²³ were included in building the CMB source profile. Thus, the CMB source profiles for modeling were constructed with (1) the elemental composition $<38\ \mu\text{m}$ RCM fraction, (2) two elemental compositions in reference rock and soil, and (3) 16 PACS source profiles.

The elemental concentrations for the 18 deposition samples collected from the two rounds of deposition samplings were used in the CMB estimation. We assumed a 10% uncertainty in the CMB input values for the mean of each element if the uncertainty could not otherwise be estimated.²⁴ As discussed above, Si concentrations were not quantified for the RCM or particle deposition samples due to limitation of the extraction method employed in the study. Thus, Si was treated as a missing value in the CMB input.

Industrial Source Complex Short-Term (ISCST3) Model—The airborne TSP concentrations emitted from the facility, including emissions from the stacks, RCM piles, and transport of RCM by trucks, were previously estimated by the New Jersey Department of Environmental Protection (NJDEP) using the EPA's regulatory model—ISCST3 atmospheric dispersion model. The model is based on a steady-state gaussian plume algorithm, and is applicable for estimating ambient impacts (e.g., pollution concentration or deposition flux on receptors) from point, area, and volume sources out to a distance of about 50 km.^{25–27} The assumptions of the NJDEP modeling work were geared toward predicting emission under worst-case conditions rather than under average conditions. Specifically, the modeling assumed that the facility was operated 24 hours per day and 7 days per week. The modeling was conducted by the use of emission rates (g/sec) estimated for all PM sources related to the facility operation (e.g., RCM piles, stacks, conveyors, dust filters, etc.). In addition, the 5-yr average meteorological data in Camden, NJ, were used for modeling. We assumed that the particle emission from the facility during our study period was similar to that during the 5-yr reference period.

RESULTS AND DISCUSSION

Particle Deposition, Surface Dust, and Spatial Distribution

The particle mass (mg) measured for the deposition samples are summarized in Table 2. The particle mass ranged from 0.77 to 1.88 mg in the first deposition sampling and 0.80 to 1.60 mg in the second round. Those values correspond to a deposition flux of 34–83 and 24–48 mg/m²·day for the first and second sampling campaigns, respectively. A lower particle mass (0.5 ± 0.1 mg) and deposition flux (15 ± 2.8 mg/m²·day) was obtained at the two background sites during the second round of sampling (note: the deposition samples were lost at the background sites during the first sampling). In addition, an exponential decay of the deposition flux with increasing distance from the facility ($R^2 = 0.4599$; $P < 0.01$) was observed (Figure 3). These observations suggested significant contribution of the facility to particle deposition in WFS.

The particle mass (mg) and the corresponding loading ($\mu\text{g}/\text{cm}^2$) of the surface wipe samples are presented in Table 3. Surface wipe samples showed a larger variability in loading and mass compared to the deposition samples. The mass and loading of the surface wipe samples ranged from 1.71 to 227 mg and from 8.5 to 379.4 $\mu\text{g}/\text{cm}^2$, respectively. In contrast to the deposition data, no relationship was observed between the distance from the facility and the surface wipe mass or loading. It is suspected that the scavenging effects of rain and wind prevented accumulation of particles on surfaces and thus obscured spatial patterns of deposition.

Particle Size Distribution

The particle counts for the RCM and three deposition samples are tabulated in Table 1, and the frequency (count fraction) distribution by particle size is plotted in Figure 4. For the RCM (<38 μm fraction), most particles (86.4%) were concentrated in the fine PM size (<2.5 μm). The coarse particles (2.5–10 μm) accounted for 10.5% of the particle count. A similar particle size distribution was found in the three deposition samples, that is, 84–88% for fine particles and 11–16% for coarse fraction (2.5–10 μm). As discussed in the Deposition Sampling section, the collection efficiency for large particles (>10 μm in diameter) was low, which may underestimate the total particle deposition in WFS. Also, the low collection efficiency may obscure the spatial variation of particles and reduce the significance in calculation of exponential decay of deposition mass with the distance from the facility. This is because the particle size distribution may differ by site, that is, more large particles are expected to be in the sampling sites closer to the facility than those farther from the facility.

Elemental Concentrations/Loadings and Spatial Distribution

The elemental concentrations (ng/mg) for the RCM as well as the particle deposition samples are presented in Table 2, and the elemental loadings (ng/cm²) for the surface dust samples are provided in Table 3. The elemental distribution in the RCM was determined for two fractions: the bulk (un-sieved) RCM and sieved (<38 μm in fraction) RCM. In the bulk RCM, Ca was the most abundant element among those measured, accounting for 21% of the RCM mass (64% of the mass of measured elements), followed by Al (7%), Mg (4%), and Fe (0.3%). In the sieved RCM (<38 μm fraction), Ca accounted for 30% of the RCM mass

(87% of the measured elements), followed by Al (2%), Mg (1%), and Fe (1%). However, in the deposition samples, Ca accounted for only 5% of the mass of the deposition samples (45% of the mass of the measured elements), followed by Fe (3%), Al (1%), and Mg (1%). The low Ca percent for the deposition samples suggests that other contributing sources, besides the facility emission, are present in the deposition samples collected in the WFS area.

The elemental concentrations/loadings for the particle deposition and surface dust samples against the distances from the facility were examined. The Ca concentration decreased with increasing distance from the facility ($r_s = -0.5641$; $P = 0.01$), suggesting a contribution of the PM emitted from the facility to the WFS area. There was, however, no clear trend between the elements in the surface dust wipe samples and distances from the facility ($P > 0.05$ for all elements).

Enrichment Factors (EF), Ca/Al Ratios, and Spatial Distribution

Ca was enriched in the WFS deposition samples and the EF for Ca ranged from 5.6 to 12.2 in WFS. The higher enrichment values (>5) indicate a contribution from the facility to outdoor deposited particle mass in WFS area. However, EF higher than 5 was not found for other elements in the deposition samples. In addition, a negative association was found between the EF of Ca and the distance from the facility but this was not significant ($r_s = -0.0806$; $P = 0.75$). The Ca/Al ratios in deposition samples were also negatively associated with the distances from the facility ($r_s = -0.3915$; $P = 0.11$). The lack of significance may be due to small number of samples ($N = 18$) or may reflect the associations were obscured by the low collection efficiency for large particles.

Contribution of the Facility to Outdoor Particle Deposition Estimated by the Ca Regression Model

On the basis of the significantly negative relationship between Ca concentration in the deposition samples and the distance from the facility, we estimated the contribution of the facility to the deposited particle mass in the surrounding area. In the model, the average Ca concentration obtained from the two background sites was subtracted from the Ca concentration at each of the 16 deposition sampling sites in WFS. For the five sites where Ca concentrations were lower than the average background Ca concentration, the average background concentration was used for the regression analysis. The background-corrected Ca concentrations were correlated with the distance from the facility ($r_s = -0.5575$; $P = 0.03$) and followed a logarithmic function (Figure 5).

$$\text{Ca Concentration} = [13,811 \times \ln(D)] - 445.26 \quad (R^2 = 0.3459; P = 0.02), \quad (2)$$

where D is the distance from the facility (km).

The contribution of the facility to the WFS outdoor particle deposition was then estimated by the ratio of the predicted Ca concentration and the Ca concentration in the RCM (301,980 ng/mg; $<38 \mu\text{m}$ fraction) using eq 3:

$$\% \text{ contribution} = \frac{13,811 \times \ln(D) - 445.26}{301,980} \times 100. \quad (3)$$

Assuming that the Ca concentration in the individual deposition sample originated from the facility and varies as a constant function of distance from the facility, the contribution of the facility to the WFS outdoor particle deposition is estimated to be from 1.8% to 7.4% for the distances of 0.2 to 0.7 km from the facility.

CMB-Model-Estimated RCM Contribution to Outdoor Particle Deposition

The RCM contribution to the WFS deposited particle mass was obtained for each receptor location from a total of 18 sites using the CMB model. The model explained the observed elemental profile in the sample with $R^2=0.96 \pm 0.02$ and $\chi^2=1.61 \pm 0.78$, and reconstructed $106\% \pm 25\%$ of the observed mass in the 18 deposition samples. The percent contribution of RCM to outdoor deposited particle mass was obtained from the ratio of the estimated RCM contribution to the sum of the estimates from all source contribution, and ranged from 5.6% to 19.9% in WFS and 8.9% in background sites. However, the background sites are located upwind of the facility and there should be no significant impact of the facility on the deposited particle mass at the background sites. Thus, the 8.9% of PM estimated for the background site indicated the background RCM-like sources. The actual contribution of the RCM to the deposited particle mass in WFS was corrected by subtracting the background contribution from the initial CMB-estimated contribution in WFS. The corrected % contribution ranged from 0% to 11%, which is comparable with the Ca regression estimates.

ISCST3-Model-Estimated Facility Contribution to Outdoor Particle Deposition

We attempted to estimate the contribution of the facility to the WFS deposited particle mass by comparing the deposition flux calculated from the ISCST3 predicted TSP concentrations against the deposition flux measured in this study. The estimated 24-hr averaged ground-level TSP concentrations over a 5-yr period were 56.2, 27.0, and $16.7 \mu\text{g}/\text{m}^3$ for the distance of 0.2, 0.5, and 0.8 km along the center plume line from the facility, respectively. The % contribution from the facility was calculated by eq 4:

$$\% \text{ contribution} = \frac{D_c}{D_m} \times 100, \quad (4)$$

where D_c is the deposition flux calculated from the ISCST3-model-predicted TSP concentration and size-dependent deposition velocity for the distance of 0.2, 0.5, and 0.8 km, and D_m is the deposition flux based on the field measurements at the distance of 0.2, 0.5, and 0.8 km, respectively.

The PM dry deposition flux is proportional to the airborne concentration and a size-dependent deposition velocity.²⁸ We initially estimated the size-dependent deposition velocity (see Table 4) from a uniform particle diameter at each particle size shown in Table 1. (Note: The detailed procedures for calculating the size-dependent deposition velocity can be found in Lim et al.²⁸) The estimated size-dependent deposition velocity was multiplied by the ISCST3-model-predicted TSP concentrations and corrected by the corresponding %

mass at each particle size provided in Table 1. The final calculated deposition flux (D_c) was 15, 7.2, and 4.5 $\text{mg}/\text{m}^2\cdot\text{day}$ for the distance of 0.2, 0.5, and 0.8 km, respectively (Table 4). On the basis of the deposition flux measured at each location reported in Table 2, the measured deposition flux (D_m) was estimated as 58.9, 37.8, and 30.1 $\text{mg}/\text{m}^2\cdot\text{day}$ for the distance of 0.2, 0.5, and 0.8 km, respectively. Equation 4 provided estimated contributions of the emissions from the entire facility to the outdoor TSP concentrations. They were 25.5%, 19.1%, and 14.8% for the distance of 0.2, 0.5, and 0.8 km, respectively.

The contribution, however, was likely to be overestimated by the above approach. This is because 62.2% of the particle mass fraction in deposition samples came from the particles with a size smaller than 10 μm (see Table 1), whereas the ISCST3 model predicted the concentration for TSP. Thus, the mass concentration of PM_{10} instead of TSP should be used for estimate. An average $\text{PM}_{10}/\text{TSP}$ ratio of 63% was obtained from the NJDEP data at the monitoring site in Pennsauken, NJ (2 miles NE from the facility), during the period of 1997~1998,²⁹ and a value of 0.5~0.6 was recommended by the EPA³⁰ to convert TSP to PM_{10} . We assumed approximately 60% of TSP was PM_{10} in WFS area. On the basis of this factor, the deposition flux measured in WFS was corrected to represent PM_{10} only. The corrected deposition fluxes were 4.76, 2.28, and 1.41 $\text{mg}/\text{m}^2\cdot\text{day}$ for D_c and 36.7, 23.5, and 18.7 $\text{mg}/\text{m}^2\cdot\text{day}$ for D_m , respectively, for the distances of 0.2, 0.5, and 0.8 km, respectively. The corrected contributions from the facility to deposited particle mass were 13%, 9.7%, and 7.6% at the distance of 0.2, 0.5, and 0.8 km, respectively, based on the D_c and D_m calculated from PM_{10} . These values are in reasonable agreement with the CMB and Ca regression estimates.

CONCLUSIONS

This study investigated the contribution of particulate emissions from a single facility to outdoor particle deposition in a residential area in Camden, NJ, where there are mixed particulate emission sources. On the basis of the particle spatial deposition sampling results, emissions from the cement material production facility were found to contribute partially to the outdoor deposited particle mass within 800 m downwind of the facility. The contribution of the facility to local PM deposition was estimated by three independent approaches, namely, (1) a Ca regression analysis, (2) the EPA's CMB model, and (3) the EPA's dispersion model (ISCST3). The three estimates agreed closely, that is, approximately 2–13% of the total deposited PM mass in WFS came from the facility. The narrow range of estimates across the three modeling approaches gives confidence in the overall estimate. In addition, the study demonstrated that spatial sampling, coupled with multiple independent modeling approaches, is a useful and powerful tool to estimate the contribution of a single source to local particle deposition in an urban community with mixed sources of PM. Moreover, this study provided data on size-dependent deposition velocity and flux in an urban area. These data are useful for improving current dry deposition models by comparing them with the model-predicted data.

However, the lack of emissions data for specific sources in the study area may result in uncertainty in the CMB model predictions. A comprehensive study to characterize different chemical species and source profiles would be needed to accurately determine the

contribution of the specific facility to the particle deposition in an area with mixed sources of particle deposition using the CMB approach alone. Likewise, the imprecise conditions in the ISCST3 model and the limited number of observations in the Ca regression analysis may result in uncertainties in the estimates derived from those approaches. However, the combination of these independent approaches provided confidence in the estimate from any single approach. Finally, improvement of the collection efficiency of large particles by the deposition sampler is needed to accurately assess the impact of total PM emitted from the facility on local air quality.

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IMPLICATIONS

This study developed a practical approach, i.e., spatial sampling with a deposition sampler coupled with three modeling estimation methods, to examine the impact of a local industrial facility on particle deposition in an urban community with multiple emission sources of particles. The close agreement among the three independent model estimations suggests that the approach is feasible and reliable to estimate the contribution of a single source to outdoor particle deposition using the method employed in the study.

Figure 1.

The aerial photo of the study area. Note: A circle shows the neighborhood of Waterfront South (WFS), Camden, NJ. A wind rose plot (upper left corner) provides the wind direction and intensity in the study area during the period of 07/01/2007 to 09/30/02007 obtained from the meteorological data at the Philadelphia International Airport Weather Station (source: NOAA, National Climatic Data Center). A dashed arrow indicates the hypothetical downwind route for particulate emissions from the facility to the WFS perimeter in the prevailing wind direction (i.e., southwest).

Figure 2.

The schematic representation of the deposition sampler (a) and the deposition sampler deployed in the field (b).

Figure 3.

Measured particle deposition flux versus distance from the RCM pile at the facility.

Figure 4.

Frequency distribution by particle size for RCM (sieved <38 μm) sample collected at the yard of the cement facility and the deposition samples collected in the vicinity around the facility in Camden, NJ.

Figure 5.

Background-subtracted Ca concentration measured in deposition samples versus distance to the RCM pile.

Table 1

The particle size distribution (percent) for the RCM (sieved <38 μm in diameter), the particle deposition samples in Camden, NJ, and the averaged number count/mass percent for the three deposition samples for each particle size.

			Deposition Samples				
Particle Size (μm)	Particle Diameter ^a (μm)	RCM ^b Number Count	Particle Number Count			Avg. Number Count	Avg. Mass ^c
			Location 1	Location 2	Location 3		
0.5–1.0	0.75	56.0%	36.5%	4.4%	26.8%	22.6%	0.4%
1.0–2.5	1.75	30.4%	51.6%	79.6%	58.4%	63.2%	13.3%
2.5–5.0	3.75	6.5%	8.3%	15.9%	10.7%	11.6%	24.0%
5.0–7.5	6.25	2.4%	1.5%	0.0%	2.1%	1.2%	11.5%
7.5–10	8.75	1.6%	0.7%	0.1%	0.7%	0.5%	13.1%
>10	10.0	3.1%	1.5%	0.0%	1.4%	1.0%	37.8%
Particle size range		0.5–30.2	0.8–27.5	0.6–10.9	0.8–34.1	0.6–34.1	NA
Particle number counted		950	1206	889	2000	1365	NA

Notes:

^aThe particle diameter was calculated as a middle point of two values in each range, except 10 μm for particles >10 μm .

^bThe RCM sample was sieved to particles <38 μm in diameter.

^cThe averaged particle mass percent was estimated from the assumption of a uniform particle diameter in each range.

Table 2

Particle mass and elemental concentrations (ng/mg) by two deposition samplings in the study.

Round	Location	Avg. PM Mass (mg)	Deposition Flux (mg/m ² -day)	Distance ^a (km)	Al	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Pb	Ti	V	Zn
Bulk	RCM	NA	NA	0.00	69,042	213,961	DL ^b	17	3	3450	43,090	2168	DL ^b	1669	15	29
RCM	<38µm	NA	NA	0.00	18,991	301,988	DL ^b	34	58	7801	14,595	877	10	1006	10	148
I	A ^c	1.542	68	0.23	12,155	56,249	4	66	214	23,636	11,492	626	319	721	48	2144
	B ^c	1.880	83	0.37	7751	40,169	4	62	328	22,903	9665	426	521	439	41	12,335
	D ^d	1.422	63	0.36	8854	35,961	3	74	260	26,232	9049	422	420	545	33	1820
	E ^d	0.912	40	0.50	4472	24,436	3	43	157	13,763	4611	239	239	276	23	1740
	F ^c	1.098	49	0.66	7376	37,653	10	131	304	34,015	8167	484	512	437	40	3152
	G ^c	1.427	63	0.65	9265	34,463	5	80	275	24,125	8351	428	477	578	43	4454
	I ^c	0.768	34	0.55	18,176	49,015	7	313	356	46,407	14,202	759	772	1065	85	8676
	L ^d	0.966	43	0.45	14,684	61,438	11	177	335	43,196	14,876	787	730	780	66	4421
II	I ^c	1.604	48	0.19	13,942	71,856	2	79	169	24,652	13,114	738	319	1065	54	2328
	2 ^c	1.230	37	0.29	10,340	48,680	3	135	173	24,406	10,641	586	504	819	53	2397
	3	1.216	37	0.27	11,351	61,266	DL ^b	80	220	24,996	11,796	624	336	824	55	2517
	4 ^d	0.796	24	0.35	11,910	67,100	4	104	349	38,475	14,795	660	615	826	65	2990
	5	1.600	48	0.38	11,814	45,126	7	112	327	29,939	11,098	681	620	663	63	3576
	6	1.062	32	0.61	12,598	45,770	11	710	251	51,364	14,189	813	550	497	65	5797
	7	1.072	32	0.55	11,844	57,500	6	216	296	33,578	14,213	684	565	572	73	4328
	8 ^d	0.904	27	0.45	11,954	50,493	5	106	307	29,661	16,773	621	359	690	138	5105
	BG ^e	0.447	13	2.38	7284	33,202	6	124	186	20,249	8404	392	330	427	40	2118
	BG ^e	0.555	17	2.20	11,121	47,845	5	140	238	28,185	17,027	522	265	808	123	4848
TB ^f		NA	NA	NA	18	64	0.1	1	1	62	10	1	0	2	0	5

Notes:

^aDistance was obtained from the sampling site to the RCM pile located inside the facility.

^bDL = below the method detection limit.

^cMore than two samples were analyzed and the average values were reported here.

^dTwo types of samplers (hooded and un-hooded) were deployed, and the result of hooded sampler was reported here.

^eLocations are at the background site, Gloucester City Park (9 and 10 in Figure S2, respectively).

^fAverage concentration (ng/mg) in three trip blank samples.

Table 3

Surface dust mass/loading and elemental loadings (ng/cm²) by wipe sampling in the study.

Location	Avg. Mass (mg)	Avg. Loading (µg/cm ²)	Distance ^a (km)	Al	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Pb	Ti	V	Zn
A	50.06	40.4	0.24	3908	1022	0.2	34	20	2274	184	23	40	34	4	5882
B	36.08	19.4	0.24	361	361	0.3	1	3	561	94	7	5	1	1	26
C ^b	48.69	79.4	0.27	937	1954	0.1	24	10	3604	1643	31	27	1	4	121
D ^b	17.09	33.6	0.29	1137	667	0.4	8	6	1656	1179	14	19	2	3	31
E	112.10	182.8	0.27	1083	3565	0.1	16	14	3575	399	26	9	1	3	60
F	79.43	237.5	0.31	2499	23,251	0.5	22	32	12,275	2602	113	80	DL ^c	9	716
G	71.96	213.3	0.32	7708	10,067	656.8	78	224	96,808	2611	271	1142	16	84	10,299
H	31.06	69.7	0.34	1398	4255	0.3	23	26	10,452	872	71	53	1	7	95
I ^b	32.43	46.9	0.32	1005	1210	2.9	7	14	3651	376	23	233	53	5	98
J	18.30	33.4	0.50	1302	2021	0.5	8	16	4109	616	37	44	2	5	100
K	32.40	129.4	0.43	5451	14,474	1.1	58	131	24,297	4234	176	296	7	24	700
L	15.52	34.1	0.43	1386	2547	0.3	23	24	5731	806	45	44	2	6	258
M	26.18	60.5	0.37	1832	5596	0.1	15	20	7086	1451	38	104	DL ^c	9	489
BG ^d	12.87	13.6	2.01	236	344	0.0	4	3	605	121	6	6	DL ^c	2	37
BG ^d	168.77	187.5	2.01	2828	2230	0.1	29	42	7063	837	51	45	9	15	80
TB ^e	NA	NA	NA	900	187	0.0	1.1	0.2	22	64	0.2	0.0	0.8	0.4	5.3

Notes:

^a Distance was obtained from the sampling site to the RCM pile located inside the facility.

^b More than two samples were analyzed and the average values were reported here.

^c DL = concentration below the method detection limit.

^d Locations are at the background site, Gloucester City Park (N and O, respectively).

^e Average concentration (µg/mg) in three trip blank samples.

Table 4

The size-dependent deposition velocity/flux calculated from particle number count and the corrected deposition flux by particle mass percent for each size range.

Particle Diameter (μm)	Deposition Velocity (m/day)	Deposition Flux ($\text{mg}/\text{m}^2\cdot\text{day}$)			Corrected Deposition Flux ^a ($\text{mg}/\text{m}^2\cdot\text{day}$)		
		200 m	500 m	800 m	200 m	500 m	800 m
0.75	3.22	0.18	0.09	0.05	0.00	0.00	0.00
1.75	15.6	0.88	0.42	0.26	0.12	0.06	0.03
3.75	68.9	3.87	1.86	1.15	0.93	0.45	0.28
6.75	187	10.5	5.05	3.13	1.21	0.58	0.36
8.75	364	20.5	9.81	6.08	2.68	1.29	0.80
10.0	475	26.7	12.8	7.92	10.1	4.84	3.00
Total					15.01	7.20	4.46

Note:

^aThe deposition flux was corrected by averaged mass percent for each particle range reported in Table 1.