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Establishing aerosol exposure predictive models based on vibration measurements

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ABSTRACT

This paper establishes particulate exposure predictive models based on vibration measurements under various concrete drilling conditions. The whole study was conducted in an exposure chamber using a full-scale mockup of concrete drilling simulator to simulate six drilling conditions. For each drilling condition, the vibration of the three orthogonal axes (i.e., a_x, a_y, and a_z) was measured from the hand tool. Particulate exposure concentrations to the total suspended particulate (C_{TSP}), PM_{10} (C_{PM10}), and $PM_{2.5}$ ($C_{PM2.5}$) were measured at the downwind side of the drilling simulator. Empirical models for predicting C_{TSP}, C_{PM10} and $C_{PM2.5}$ were done based on measured a_x, a_y, and a_z using the generalized additive model. Good agreement between measured aerosol exposures and vibrations was found with $R^2 > 0.969$. Our results also suggest that a_x was mainly contributed by the abrasive wear. On the other hand, a_y and a_z were mainly contributed by both the impact wear and brittle fracture wear. The approach developed from the present study has the potential to provide a cheaper and convenient method for assessing aerosol exposures from various emission sources, particularly when conducting conventional personal aerosol samplings are not possible in the filed.

1. Introduction

Aerosols in working and ambient environments can pose risks to human health as they are inhaled. To date, there is strong epidemiological evidence to support the association between occupational aerosol exposures and ill-health outcomes, such as silicosis, acute silicosis, lung cancer, and chronic obstructive pulmonary disease [1–4]. For ambient environments, particulate matter (PM) pollutions are known to be detrimental to human health. For example, Pope and Dockery found the respiratory symptoms could be related to PM_{10} pollution [5]. Schwartz and Morris found that PM_{10} pollution was associated with hospital admissions for cardiovascular diseases [6]. Several studies indicate that $PM_{2.5}$ might have a significant effect on the increase of the mortality in adults [7–9]. Although many types of aerosol samplers have been developed for assessing PM exposures, each individual sampler was usually designed simply for collecting one specific type of particulate matter. As a result, conducting PM exposure assessment has long been subject to individual's willingness to wear aerosol samplers and the cost arising from the considerable amount of samples to be analyzed if more than one particulate exposure type is of interest at the same time [10]. Yet, it is true that some high-time resolution particle size spectrometers (e.g., Aerodynamic Particle Sizer (APS, Model 3321, TSI Inc., St. Paul, MN, USA)) can be used to directly measure particle size distributions. The resultant data can be further converted to the concentrations of the particulate of different fractions, including PM_{10} and $PM_{2.5}$. Because of its simplicity in measuring particle size distributions, above method has been used to characterize aerosols in different environments from various emitting sources [11–14]. But its

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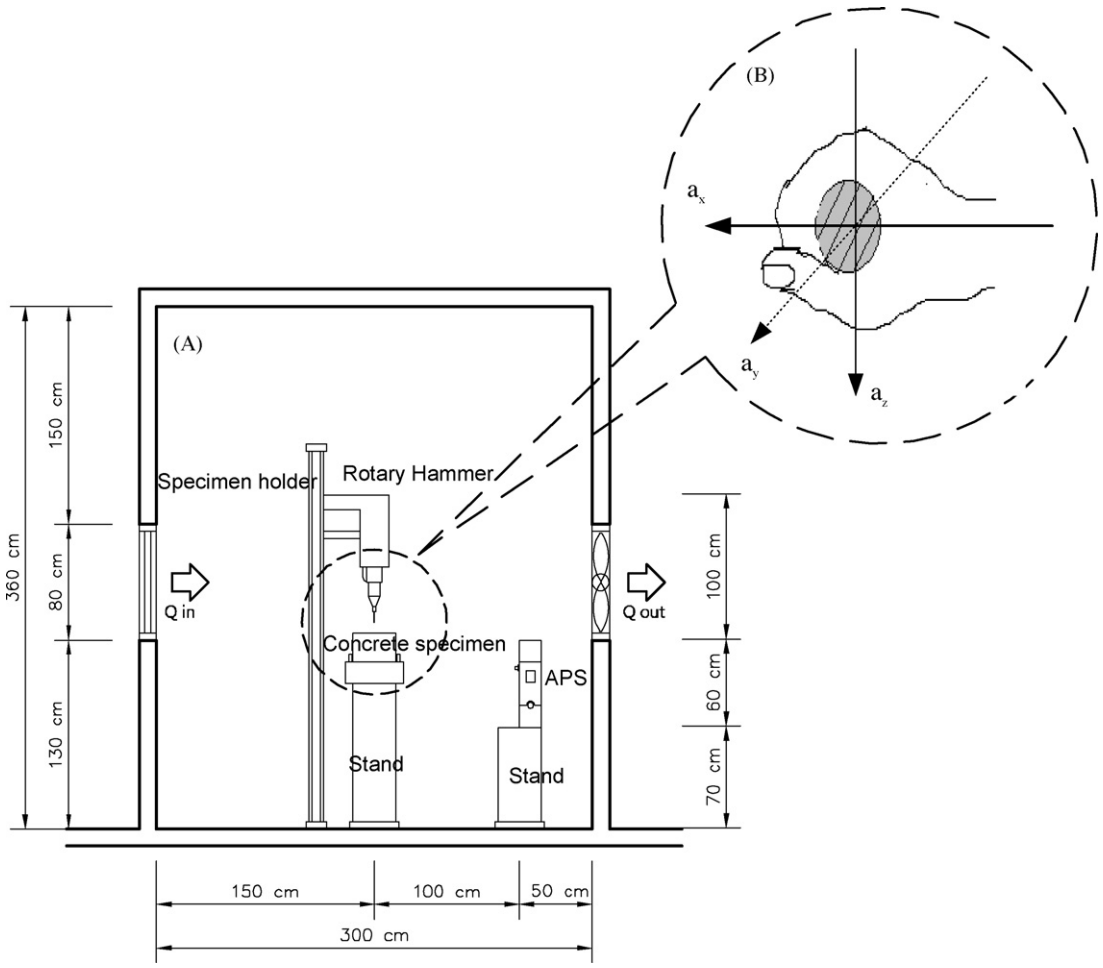

Fig. 1. Schematic of (A) test facilities used in the study, including a concrete drilling simulator and an APS for aerosol measurement, and (B) the *X*-axis, *Y*-axis, and *Z*-axis for conducting vibration measurements.

cumbersome volume and expensive cost have limited its use in the field.

In principle, the interaction between the drill bit and workpiece material is the main cause for noise, vibration and particle emissions during the drilling process [15]. Many efforts have been done to investigate vibration, noise, and aerosol exposures respectively for workers under various drilling conditions [16–22]. Moreover, the relationships between the drilling operation conditions and the characteristics of emitted particles have also been studied in several mining industries [23–26]. Vibration measurements have also been used to periodically examine the condition of the drilling tools for the maintenance purpose [16,27,28]. However, to the best of knowledge no study has been conducted to examine the relationship between the characteristics of the vibration and particles emissions.

It is known that conducting vibration monitoring is cheaper and easier than conducting conventional personal aerosol sampling in the field. Therefore, the present study was set out to examine whether the emitted vibration magnitudes could be used as a surrogate indicator to predict particulate exposures during the concrete drilling processes. The whole study was conducted in an exposure chamber using a full-scale concrete driller to simulate various drill conditions. Both vibrations and aerosol exposures were measured. Predictive models were established to relate aerosol exposures to the corresponding vibration measurement. The methodology developed from this study would be beneficial to industries for predicting particulate exposures, particularly when conducting conventional personal aerosol sampling are not possible in the filed.

2. Material and methods

2.1. Test facilities

All experimental work was performed using a full-scale mockup of concrete drilling simulator, including a rotary hammer (Handheld Rotary Hammer, Model GBH-4 DHC, Bosch Inc., Germany), holder of machine body, specimen holder, designed for simulating the real concrete drilling process (Fig. 1) and carried out in an exposure chamber ($L \times W \times H = 300\,\text{cm} \times 240\,\text{cm} \times 360\,\text{cm}$). The chamber had one air inlet ($80\,\text{cm} \times 80\,\text{cm}$) and one air outlet ($80\,\text{cm} \times 80\,\text{cm}$) on the opposite wall (Fig. 1). An axial fan was installed at the air outlet and inlet air was filtered. For each experiment, air velocities were measured at the cross section area designated for conducting aerosol samplings (9 points uniformly distributed in the area, see below) using a hot-wire anemometer (VelociCalc Plus, Model 8386A, TSI Inc., St. Paul, MN, USA). In the present study, the mean air velocities were consistently less than $0.24\,\text{m}\,\text{s}^{-1}$ and in a good agreement with the normal indoor environment ($<0.3\,\text{m}\,\text{s}^{-1}$) [29]. The concentration of particles inside the chamber was measured using the APS before each experiment was conducted to ensure free contamination from the previous experiment and the outside environment. The concentration of the background environment was consistently less than 26 particles m^{-3}.

2.2. Selected drilling operation parameters and testing conditions

Two operation parameters (and their selected testing levels), including the rotation speed (R_s: 265, 315, 460, 587 rpm) and drill bit size (Φ: 16, 28, 32 mm) were selected in this study. The selections of the above testing levels were according to the designed range of the drilling machine and real conditions found in construction sites. All drilling conditions selected in the present study can be seen in Table 1. The concrete specimen was a 10-cm-diameter circular block and its strength (4000 psi) was the one most used in constructive operations. Four repeated drilling experiments were conducted for each selected drilling condition. For each drilling experiment, it contained nine repeated drilling runs. Each drilling run included a 30-s drilling period and followed by a 150-s rest period. As a result, the total experimental time for each drilling experiment was 27 min. For each drilling condition, we used a brand new drill bit and a new concrete specimen. The whole study was conducted using a tachometer (Hand Tachometer, Model TM 5000, Line Seiki Co. Ltd., Japan) to measure R_s for each of the nine drilling runs to examine the operation stability for each drilling experiment. We found that the resultant relative standard deviations (RSDs) for all selected R_s were consistently less than 3.90%.

2.3. Conducting aerosol sampling

For each selected drilling condition, aerosol samplings were conducted at the downwind side of the concrete drilling simulator (distance 100 cm) at the height of 130 cm using the APS for particle size segregating sampling to determine the concentrations of different particle size exposed to operators (Fig. 1). The sampling flow rate of the APS was 5.0 l min^{-1}. All APS measurements were conducted using the summing mode [30]. The collected data was converted to a log-normal distribution using a curve fitting program (Data Merge Software module, Model 390069, TSI Inc., St. Paul, MN, USA) assuming all collected concrete particles had a shape factor of unity and a density (ρ) 2.30 g cm^{-3} [31]. In the present study, the exposure concentration (C_{TSP}) of the total suspended particulate (TSP) was determined by adding up the concentrations all selected particle sizes. The two exposure concentrations of the PM_{10} (C_{PM10}) and $PM_{2.5}$ ($C_{PM2.5}$) were calculated based on the conventions given in the U.S. Code of Federal Regulations 40CFR53.43 and 40CFR53.62, respectively. Both the mean and RSD were presented in this study to describe the exposure concentration for each drilling condition.

2.4. Conducting vibration measurements

For each drilling condition, we followed the ISO 5349 [32] to determine its vibration magnitudes (expressed as a root-mean-square acceleration magnitudes, m s^{-2}) using a human vibration meter (HVM 100, Larson Davis Inc., Depew, NY, USA). The measurements were conducted using a tri-axial PCB piezotronics with an ICP accelerometers mound on the front handle of the rotary hammer in each of the three selected orthogonal directions (i.e., *X*-axis, *Y*-axis, and *Z*-axis, as shown in Fig. 1). Above instruments (including the tri-axial ICP accelerometer) were calibrated before and after measurements using a portable vibration calibrator (calibration exciter, Type 4294, Brüel & Kjær Inc., Denmark). The energy-equivalent acceleration magnitudes for each of three orthogonal axes (i.e., a_x, a_y, and a_z) were determined for each selected drilling experiment by integrating the square of the frequency-weighted acceleration magnitudes over the whole test period. The mean acceleration magnitude and its corresponding RSD were presented in this study to describe a vibration exposure.

2.5. Proposing predictive models

We consider that the interaction between the drilling bit and workpiece material is the main cause for vibration and particulate emissions during the drilling process. We also assume that the emitted particle size distributions could be related to the corresponding vibration magnitudes of the three orthogonal axes of a_x, a_y, and a_z. Therefore, it can be expected that C_{TSP}, C_{PM10}, and $C_{PM2.5}$ for a given emission source are affected by its emitted vibration of the three orthogonal axes. In the present study, we adopt the generalized additive model (GAM) for the prediction purpose:

$$C_i = \alpha_i + \beta_i a_x + \gamma_i a_y + \delta_i a_z \quad (1)$$

where α_i is the background concentration, β_i, γ_i, and δ_i are the parametric coefficients for a_x, a_y, and a_z for the *i*th type of exposure concentration C_i (i.e., C_{TSP}, C_{PM10}, or $C_{PM2.5}$). The use of the GAM is mainly because it has the advantage to capture the shape of the relationship between the response variable (i.e., C_i) and the explanatory variables (i.e., a_x, a_y and a_z) by allowing non-parametric smoothers in addition to parametric forms [33]. The GAM has been widely used in many environmental health science fields for predicting ambient air pollutant concentrations and exploring the effect of air pollution on human health [34–37].

3. Results and discussion

3.1. Characteristics of aerosol exposures

Table 1 shows means and relative standard deviations (RSDs) of C_{TSP}, C_{PM10}, and $C_{PM2.5}$ for each of the six selected drilling conditions. For the drilling condition with Φ fixed at 16 mm, we found that the increase in R_s (from 265 to 587 rpm) would result in a significant increase in C_{TSP} (from 0.083 to 1.61 mg m^{-3}), C_{PM10} (from 0.045 to 0.498 mg m^{-3}), and $C_{PM2.5}$ (from 0.014 to 0.042 mg m^{-3}) (trend test, $p < 0.05$). For the drilling condition with the same Φ, the increase in R_s would result in the increase in the involved drilling energy. Apparently, our results suggest that the more drilling energy was involved, the higher exposure levels could be expected.

On the other hand, the increase in Φ would also result in more drilling energy involved in the drilling processes, if R_s remains unchanged. Therefore, it might be reasonably expected that the resultant particulate exposure levels could also be increased.

Table 1
C_{TSP}, C_{PM10}, and $C_{PM2.5}$ obtained from the six selected drilling conditions.

Drilling conditions		Measured exposure concentrations					
R_s (RPM)	Φ (mm)	C_{TSP} ($n=4$)		C_{PM10} ($n=4$)		$C_{PM2.5}$ ($n=4$)	
		Mean (mg m^{-3})	RSD (%)	Mean (mg m^{-3})	RSD (%)	Mean (mg m^{-3})	RSD (%)
265	16	0.083	13.8	0.045	9.74	0.014	2.44
315	16	0.262	14.5	0.099	4.48	0.027	5.46
460	16	0.789	15.3	0.257	10.3	0.042	9.87
587	16	1.61	12.5	0.450	11.7	0.040	10.6
587	28	1.55	6.39	0.490	9.42	0.041	14.9
587	32	1.45	11.4	0.530	12.5	0.048	13.5

Indeed, our results do reveal that, while R_s remained unchanged at 587 rpm, the increase in Φ (from 16 to 32 mm) would result in the increase in both C_{PM10} (from 0.450 to 0.530 mg m^{-3}) and $C_{PM2.5}$ (from 0.040 to 0.048 mg m^{-3}) (Table 1). But to the contrary, a decrease in C_{TSP} (from 1.61 to 1.45 mg m^{-3}) could also be found. Although the above trends were not statistically significant (trend test, $p > 0.05$), they clearly indicate that the resultant particulate exposure levels might not be simply explained by the involved drilling energy.

It is known that the generation of particles from drilling processes involves three main mechanisms, including the impact wear, brittle fracture wear, and abrasive wear [15]. Theoretically, the first two might be related to the generation of coarse particles, and the last one could be associated with the generation of fine particles [38]. Fig. 2 shows the generated particle size distribution for the selected drilling condition with R_s = 587 rpm and Φ = 16 mm for illustration. In Fig. 2A, all measured data were plotted in a log-probability scale. The resultant two distinct slopes indicate that the generated particles were in the form of bimodal. Fig. 2B shows the best fitted bimodal particle size distribution of all measured data. It contains a fine mode and a coarse mode each with a mass median aerodynamic diameter (MMAD) and geometric standard deviation (σ_g) of 5.89 μm and 1.92 and 16.01 μm and 1.57, respectively. The above results further confirm the generated particle size distribution from the drilling process was bimodal.

Based on the results shown in Table 1, it might be reasonable to assume that the increase in R_s, if Φ remains unchanged, would result in consistent increase in the impact wear, brittle fracture wear and abrasive wear (i.e., the increase in the generation of both coarse and fine particle fraction which leading to the increase in C_{TSP}, C_{PM10} and $C_{PM2.5}$). On the other hand, it might be also feasible to assume that the increase in Φ, while R_s remained unchanged, might result in an increase in the abrasive wear (i.e., an increase in the generation of the fine particle fraction which leading to the increase in both C_{PM10} and $C_{PM2.5}$, Table 1), but decrease in both impact wear, and brittle fracture wear (i.e., an decrease in the generation of the coarse particle fraction which leading to the decrease in C_{TSP}, Table 1). Yet, it is true that the effect associated with the change of the involved drilling energy on each individual particle generation mechanism still remains unknown. However, our results clearly suggest that the magnitude of various types of dust exposure level cannot be simply explained by the magnitude of the involved drilling energy.

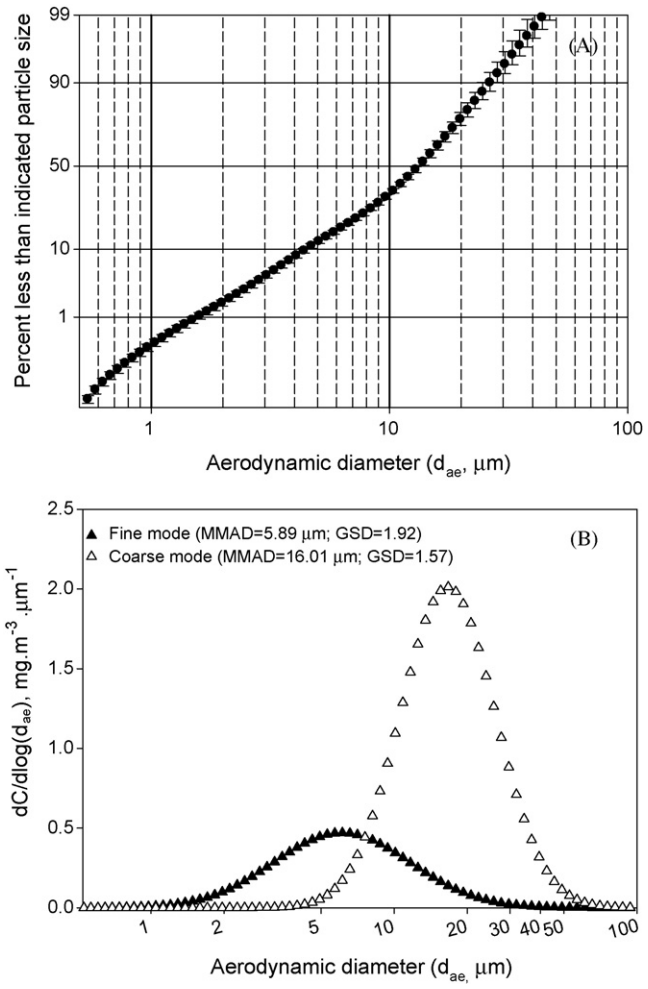

Fig. 2. The measured particle size distribution for the selected drilling condition of R_s = 587 rpm and Φ = 16 mm: (A) while plotted on a log-probability plot; (B) the best fitted bimodal.

3.2. Characteristics of hand-transmitted vibration exposures

Table 2 shows the means and their corresponding RSDs of a_x, a_y, and a_z for the six selected drilling conditions. For the drilling conditions with Φ fixed at 16 mm, the increase in R_s (from 265 to 587 rpm) would result in a significant increase in a_x (from 0.264 to 0.658 m s^{-2}), a_y (from 0.270 to 0.678 m s^{-2}), and a_z (from 0.760 to 1.90 m s^{-2}) (trend test, $p < 0.05$). Again, our results suggest that the more drilling energy (i.e., higher R_s) involved would result in the higher hand-transmitted vibration exposure levels. On the other hand, while R_s remained unchanged at 587 rpm, the increase in Φ (from 16 to 32 mm) would result in the increase in vibration magnitude, including a_x (from 0.658 to 1.13 m s^{-2}), a_y (from 0.678 to 1.61 m s^{-2}), and a_z (from 1.90 to 2.62 m s^{-2}) (trend test, $p < 0.05$) (see Table 2). In principle, if R_s remains unchanged for the selected drilling conditions, the increase in Φ would result in more drilling energy involved in the drilling processes. Therefore, it can be expected that the resultant vibration magnitudes could also be increased. Yet, it is true that the three main mechanisms associated with particle emissions also affect the magnitudes of the hand-transmitted vibration [15]. Although the extent of the above effect still remains unclear, our results do suggest that the more

Table 2
Magnitudes of a_x, a_y, and a_z obtained from the six selected drilling conditions.

Drilling conditions		Measured vibration					
R_s (RPM)	Φ (mm)	a_x (n = 4)		a_y (n = 4)		a_z (n = 4)	
		Mean (m s^{-2})	RSD (%)	Mean (m s^{-2})	RSD (%)	Mean (m s^{-2})	RSD (%)
265	16	0.264	1.80	0.270	1.96	0.760	4.50
315	16	0.350	4.42	0.418	3.45	1.20	3.88
460	16	0.605	4.40	0.582	1.35	1.59	7.77
587	16	0.658	5.55	0.678	4.66	1.90	2.29
587	28	0.843	1.82	1.02	4.88	1.98	3.33
587	32	1.13	4.65	1.61	2.40	2.62	5.09

Table 3
Regression results based on a_x, a_y, and a_z (unit: m s^{-2}) for predicting C_{TSP}, C_{PM10}, and $C_{PM2.5}$ (unit: mg m^{-3}).

Predicted exposures	Regression coefficient			Intercept	R^2	MSE[a]
	a_x	a_y	a_z			
C_{TSP}	0.025 ± 0.720	2.11 ± 0.522[b]	0.839 ± 0.236[b]	−1.27 ± 0.148[b]	0.969	0.016
C_{PM10}	−0.261 ± 0.084	0.095 ± 0.035	0.363 ± 0.028[b]	−0.193 ± 0.015[b]	0.999	2.79×10^{-5}
$C_{PM2.5}$	0.034 ± 0.006[b]	0.001 ± 0.002	−0.001 ± 0.002	0.013 ± 0.001[b]	0.997	3.10×10^{-7}

[a] The mean square error (MSE), MSE = $\sum d^2/N$.
[b] $p < 0.05$.

drilling energy involved, the higher vibration magnitudes could be expected.

3.3. Predicting aerosol exposure levels based on hand-transmitted vibration measurements

Table 3 shows the resultant regression coefficients (including their standard errors and p-values) and their corresponding coefficient of determinations (R^2) for the three proposed particulate exposure predictive models. The resultant predictive models are given as follows:

$$C_{TSP} = -1.27 + 0.025a_x + 2.11a_y + 0.839a_z \ (R^2 = 0.969, n = 24) \quad (2)$$

$$C_{PM10} = -0.193 - 0.261a_x + 0.095a_y + 0.363a_z \ (R^2 = 0.999, n = 24) \quad (3)$$

$$C_{PM2.5} = 0.013 + 0.034a_x + 0.001a_y - 0.001a_z \ (R^2 = 0.997, n = 24) \quad (4)$$

It can be seen that the measured a_x, a_y, and a_z can explain ~96.9, 99.9, 99.7% variations in C_{TSP}, C_{PM10}, and $C_{PM2.5}$, respectively. Fig. 3A–C respectively compares the model predicted exposure levels (denoted as $C_{TSP/P}$, $C_{PM10/P}$, and $C_{PM2.5/P}$, respectively) with the corresponding measured exposure levels (denoted as $C_{TSP/M}$, $C_{PM10/M}$, and $C_{PM2.5/M}$, respectively) for the six selected drilling conditions. These figures clearly indicate that the proposed models predict quite well in both the magnitude and trend of the experimental data.

In the present study, the magnitudes of regression coefficients obtained from the three predictive models could be further used to determine the respective contributions of a_x, a_y, and a_z to each individual type of particle exposure. We found that the magnitudes of the resultant regression coefficients presented in sequence (1) for a_x were: $C_{PM2.5}$ ($0.034 \pm 0.006^*$) > C_{TSP} (0.025 ± 0.720) > C_{PM10} (-0.261 ± 0.084); (2) for a_y were: C_{TSP} ($2.11 \pm 0.522^*$) > C_{PM10} (0.095 ± 0.035) > $C_{PM2.5}$ (0.001 ± 0.002); and (3) for a_z were: C_{TSP} ($0.839 \pm 0.236^*$) > C_{PM10} ($0.363 \pm 0.028^*$) > $C_{PM2.5}$ (-0.001 ± 0.002). Here, it should be noted that only four of the above regression coefficients were statistically significant (i.e., those values with *, including a_x in the predicting model of $C_{PM2.5}$; a_y, and a_z in C_{TSP}, and a_z in C_{PM10}). Based on the above results, it can be concluded that the increase in a_x would result in the increase in the particle exposure concentration with high fine particle fraction (i.e., $C_{PM2.5}$). On the other hand, the increase in both a_y and a_z would consistently result in the increase of those with high coarse particle fraction (i.e., C_{TSP} and C_{PM10}). It is known that the generation of coarse particles was mainly contributed by the two mechanisms of the impact wear and brittle fracture wear, and the generation of fine particles was mainly by the mechanism of the abrasive wear [38]. Based on the results obtained from this study and the above inference, it would be reasonable to expect that a_x might be mainly contributed by the abrasive wear. On the other hand, a_y and a_z could be mainly by both the impact wear and brittle fracture wear.

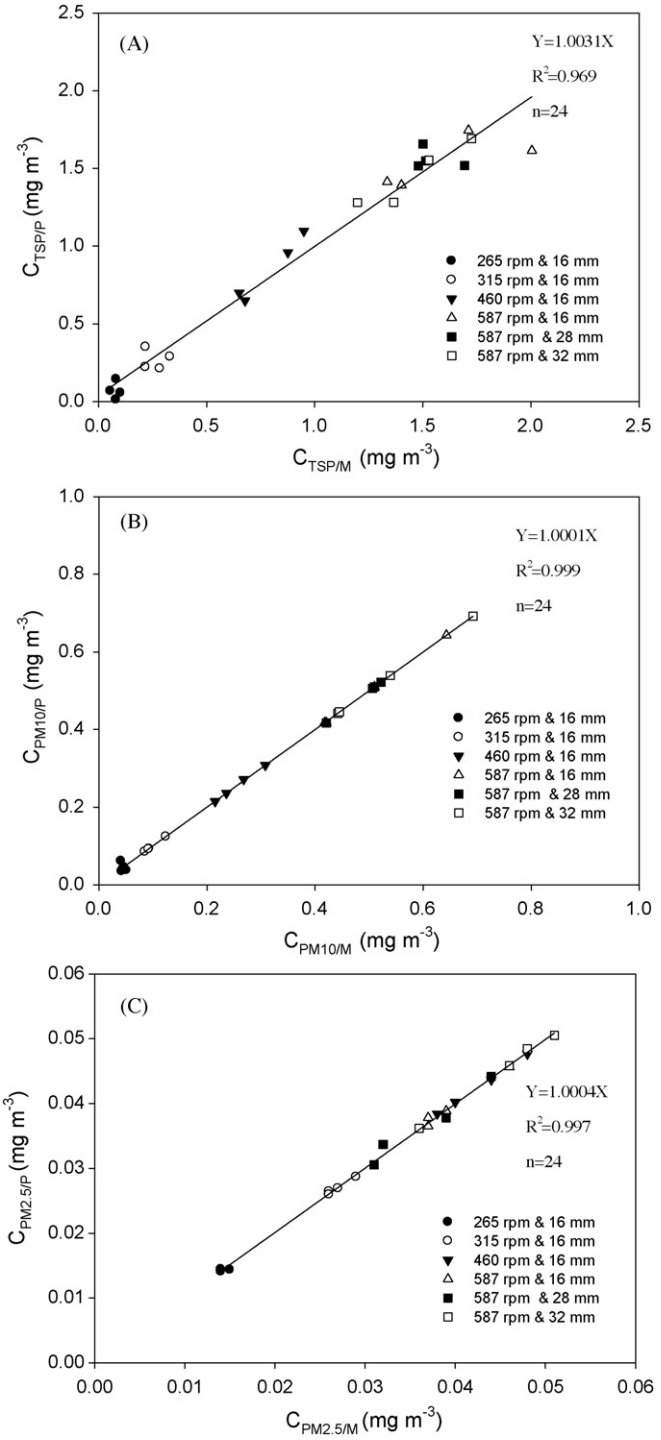

Fig. 3. Comparison the predicted concentrations with measured concentrations: (A) $C_{TSP/P}$ vs. $C_{TSP/M}$; (B) $C_{PM10/P}$ vs. $C_{PM10/M}$; (C) $C_{PM2.5/P}$ vs. $C_{PM2.5/M}$.

4. Conclusions

In this study, we found that the magnitude of various types of dust exposure level cannot be simply explained by the magnitude of the involved drilling energy. But for the hand-transmitted vibration, we found that the more drilling energy involved, the higher vibration magnitudes could be expected. Empirical models for predicting C_{TSP}, C_{PM10} and $C_{PM2.5}$ were done based on measured a_x, a_y, and a_z using the generalized additive model. Good agreement between measured aerosol exposures and vibrations was found with $R^2 > 0.969$. It can be concluded that the increase in a_x would result in the increase in $C_{PM2.5}$. On the other hand, the increase in both a_y and a_z would consistently result in the increase in both C_{TSP} and C_{PM10}. In addition, our results also suggest that a_x was mainly contributed by the abrasive wear. On the other hand, a_y and a_z were dominantly contributed by both the impact wear and brittle fracture wear. The approach developed from the present study have the potential to provide a cheaper and convenient method for assessing aerosol exposures from various emission sources, particularly for those conducting conventional personal aerosol samplings are not possible in the field.

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