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Characteristics and Emission Factors of Fugitive Dust at Gravel Processing Sites

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Abstract

Particles emitted from gravel processing sites have severely worsened ambient air quality. This study analyzed the fugitive dust emission characteristics at selected pollution sources using several kinds of particle samplers, including TSP, PM_{10}, $PM_{2.5}$, and dry deposition plate. It is the first attempt to modify emission factors of AP-42 with a systematical study, utilizing domestic information under dimensionless analysis at the gravel processing sites. Results showed that TSP concentrations at the boundary of gravel sites ranged from 280 to 1,290 $\mu g/m^3$. Moreover, PM_{10} concentrations ranged from 135 to 550 $\mu g/m^3$ which were 1.2 - 1.5 times $PM_{2.5}$ concentrations, which ranged from 105 to 470 $\mu g/m^3$. Emission of unpaved roads accounted for about 45 - 55% of the total emission at the gravel processing sites. The silt and moisture content of gravel/sand/dust affected the emission rate of each emission source and ranged from 0.1 to 8.3 % for silt and from 0.6 to 14 % for moisture. After statistical analysis using the least square method, the domestic emission factors of four main emission sources were developed. Furthermore, the size coefficient of emission factors for TSP, PM_{10}, and $PM_{2.5}$ emission rate estimation equation were also determined in this study.

Keywords: fugitive dust, emission factor, gravel processing sites, dimensionless analysis

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INTRODUCTION

Fugitive dust that originates from gravel processing sites contributes considerably to high-particulate concentrations in ambient air. Muleski (2001) and Gilliesa *et al*., (2005) found that emitted total suspended particulate (TSP) concentrations were roughly between 300 and 1,000 μg/m^3, a concentration of particulate pollutants capable of being associated with disease in respiratory organs. Four activities or situations contribute to making traditional gravel-processing sites major pollution sources: crackers, storage piles, unpaved surfaces, and bare ground (US EPA, 1994; Taiwan EPA, 2003). For example, the cracking process breaks the gravel into smaller sands and generates fugitive dust as a result of mechanical forces. Serious pollution could result if control strategies are not implemented or carried out properly (Taiwan EPA, 2003; Chang, 2004). Gravel or sand storage piles are other dust-emission sources at the gravel cracking sites. Howell *et al*. (1998), Etyemeziana *et al*. (2003), and Jorkevic *et al*. (2004) found that fugitive dusts easily resulted from storage piles through the process of wind erosion once wind speed reached higher than 2.5 m/sec on a sunny day. Unpaved roads are another important source since driving gravel trucks in the gravel processing site often releases large amounts of particles from the road, especially at speeds higher than 20 km/hr (Etyemeziana, *et al*., 2003). Fugitive dust originating from bare ground is often re-entrained or wind-blown. Dust and silt could easily be stirred up by wind speeds above 5.0 m/sec (Clausnitzer, 1996; Ho *et al*. 2003; and Chang, 2004). Since emission characteristics can differ greatly from each these four main sources, it is important to measure fugitive dust concentrations and particulate sizes of each separately. In this study, we investigated dust emission characteristics by using several kinds of samplers simultaneously to collect the dust emitted from different sources.

In addition, dust concentration and emission rates were evaluated to understand the influence of gravel finishing processes. Dust emission rates need to be predicted more reasonably in order to understand the pollution level of the gravel sites. However, it is difficult to precisely predict since few data exist about the relationship between influential parameters and emission rates. Influential parameters include weather condition, silt content, moisture content of gravel and sand, and types of emission sources (Clausnitzer, 1996; Kulshrestha, 1996; Liu, 2002; Veranth *et al*., 2003), all of which need to be measured simultaneously before their relationship can be determined. According to AP-42 (US EPA, 1994), it is convenient to predict emission rates by using emission factors; thus, the domestic dust emission factors of each emission source have to be developed for calculating the emission rate. This study modified the emission factors of AP-42 with systematic examination, using local information with dimensionless analysis.

MATERIALS AND METHODS

SAMPLING AND ANALYSIS

Four dust emission sources—cracker, storage piles, bare ground, and unpaved road—were selected to examine fugitive dust emission characteristics at each gravel extraction site, namely A, B, C and D. Samplers were located upwind and downwind of dust sources. The TSP, coarse suspended particulate (PM_{10}), and fine suspended particulate ($PM_{2.5}$) concentrations were measured to assess the ambient air quality at each gravel processing site. The samplers were operated simultaneously and for one hour per sample (Figure 1). The Graseby high volume sampler, GM-2000, was used to sample TSP, while the PM_{10} and $PM_{2.5}$ were measured with an Anderson 10μ- Inlet and an Anderson $PM_{2.5}$ impactor, respectively. Additionally, the silt content and moisture content of materials at piles, bare ground, and unpaved roads were measured to establish the basic emission characteristics. The silt content was determined by measuring the percentage of loose, dry dust that passed through a No. 200 sieve, a 75 mm mesh screen, according to the ASTM-C-136 method. The moisture content was obtained by calculating the percentage of loose dry dust. For each test condition, three runs were conducted to reduce the variation of concentrations.

To evaluate the emission rate, the dry deposition rate was also measured with a deposition plate in every season of the year. The plate size was 7 cm wide and 7 cm long. In addition, the upwind and downwind mass balance method was applied to establish the emission factors and to estimate the emission rates (Jutze, 1974; Cowherd, 1974; US EPA, 1994).

DEVELOPMENT OF EMISSION FACTORS

The local emission factors of each pollution source must be established to predict emission rates accurately. The emission factors of the AP-42 (US EPA, 1994) can not be applied in Taiwan since many original assumptions are not satisfied domestically. To develop fugitive dust emission factors at the gravel processing site, pollution sources were first classified as cracking process, unpaved road, bare ground and piles, according to emission characteristics. Next, upwind and downwind dust concentration measuring methods were used to measure TSP, PM_{10}, and $PM_{2.5}$ concentrations at each pollution source. This method included one monitoring site upwind and three downwind. Weather conditions were measured with a Davis, Inc. Weather Monitor II, and gathered from the Central Weather Bureau in Taiwan for comparison. Wind speed was averaged hourly for the calculation. For the third step, the influential factors of fugitive dust emission rate at each pollution source were identified. From previous studies (U.S. EPA, 1994; Kulshrestha, 1996; Chang, 2004), the main influential factors were moisture (M,

%), silt content (s, %), wind velocity (V, m/sec), vehicles speed (v, Km/hr) and vehicles number (n, VKT). Then, the downwind average concentration, C_d, at each pollution source was calculated from the average of three downwind dust concentrations. The emission rate (ER) of each source can be expressed by Equations (1) or (2). Generally, the gravel processing sites operating time is eight hours per day, 10 months per year.

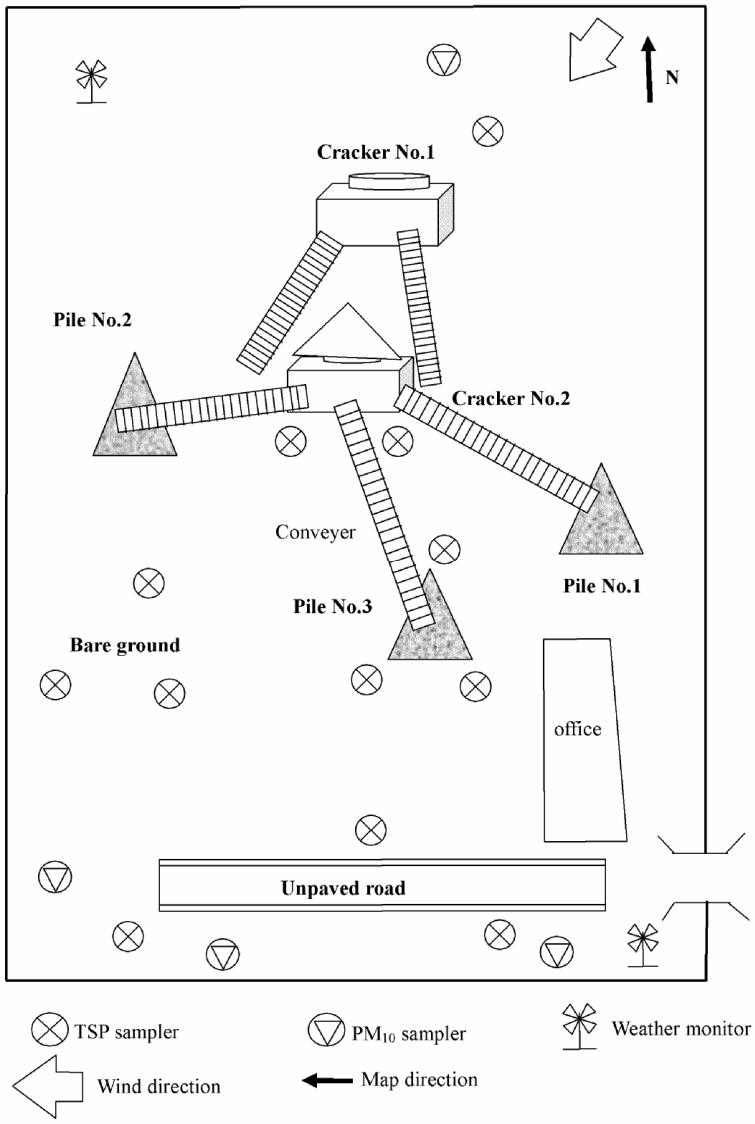

Figure 1. The location of the samplers at each pollution source

$$\text{ER } (\mu g/sec/m^2) = 1 / L \times \int_0^Y (C_d - C_u) \cdot u \cdot dy \quad (1)$$

$$\text{ER (kg/year)} = 0.00864 A_s / L \times \int_0^Y (C_d - C_u) \cdot u \cdot dy \quad (2)$$

where:

V: wind speed (m/sec)

A_s: projectional section area of pollution sources (m^2)

C_d: average concentration at downwind position

C_u: concentration at upwind position

According to Lan (1998), Tsai *et al*. (2001), Tsai and Miaw (2001), and Chang *et al*. (2005), the dust concentrations, including C_d and C_u, are not uniform throughout the vertical-projected area. Therefore, the dust concentrations must be modified before calculating the emission rate, as shown in Equation (3). The velocity profile was established according to Equation (4).

$$C = Co. \quad \exp(-0.154\ y) \quad (3)$$

where:

C: concentration profile (μ g/m^3)

Co: concentration at downwind or upwind position (μ g/m^3)

y: vertical height (m)

$$u = K. \quad u^*. \quad \ln(y/y^*) \quad (4)$$

where:

K: von Karman constant (K = 2.5)

u*: frictional velocity (u* = 0.45 m/ses)

y^*: rough thickness (y^* = 0.5 cm)

The fifth step was to establish the overall emission rate, OER, with Equation (5). It could be calculated from the summation of emission rate, calculated with Equation (2), and particulate deposition rate (DR), computed from Equations (6) or (7).

$$OER\ (kg/year) = ER + DR \quad (5)$$

$$DR\ (g/month) = D_f \times A_p \quad (6)$$

$$DR\ (kg/year) = D_f \times A_p \times 0.0001 \quad (7)$$

where:

D_f: dustfall deposition flux (ton/km^2/month or g/m^2/month)
A_p: overall surface area of gravel site (m^2)

Finally, the emission factor (EF) was developed from the overall emission rate divided by activity, such as the amount of gravel production rate, G_p, with following Equation (8). According to the records of the examined gravel production sites, the production rate is roughly 240,000 ton/year.

$$EF\ (kg/ton) = OER/G_p \quad (8)$$

CHARACTERISTICS OF GRAVEL PROCESSING SITE

It is important to investigate the operational characteristics of gravel processing sites before evaluating the emission rates. In the investigated gravel site, the operating time was eight hours per day and 10 months per year at each the gravel processing site. Furthermore, the gravel/sand production rate, the length of unpaved road, and the overall surface area of the selected gravel site was roughly the same as 240,000 ton/year, 100m, and 4,000 m^2, respectively. There were three storage piles at one gravel site which included coarse gravel pile, fine gravel pile, and sand pile. The size of each pile was approximately 10m high, 10m wide and 100m long.

RESULTS AND DISCUSSION

COMPARISON OF DUST EMISSION CHARACTERISTICS AT EACH POLLUTION SOURCES

In the four investigated gravel sites from A to D, the most important pollution source was unpaved roads. The highest TSP and PM_{10} levels up to 1,560 and 1,130 μg/m^3, respectively were located at the boundary of the unpaved roads. The particulate concentrations clearly exceed the Taiwan daily TSP and PM_{10} air quality standard of 250 and 125 μg/m^3, individually. After calculating emission rate emitted from unpaved road with mass-balance methods, as mentioned in Equation (2), this source accounted for

about 45 - 55% of the total emission rate at the gravel processing sites. In contrast, the smallest TSP and PM_{10} concentrations of 450 and 210 μg/m^3, respectively, were at piles nearby.

In Table 1, the downwind TSP average concentration of cracking processes was roughly 550 μg/m^3. In the same place, the PM_{10} concentration was roughly half that of the TSP concentration. Additionally, the ratio of fine particle concentration ($PM_{2.5}$) over TSP was approximately 27.2 ± 10%. The values are little smaller than the researched results, 37.2 ± 8%, of Ho *et al*. (2003) and Chang *et al*. (2004). The second most significant pollution source was the bare ground, which could result in 20 - 40% of the total emission rate, as shown in Table 1. Overall, the emission rates depended on the influential factors, such as moisture and silt content, and weather conditions at each pollution source. These influential factors and emission rates are discussed later.

Table 1. The downwind concentrations, emission rates and pollution contribution at each pollution source.

Items		Cracking	Piles	Bare ground	Unpaved road
Concentration (μg/m^3)	TSP	550 ± 320*	450 ± 330	1130 ± 340	1560 ± 510
	PM_{10}	360 ± 190	210 ± 160	880 ± 210	1130 ± 330
	$PM_{2.5}$	180 ± 140	150 ± 80	270 ± 70	570 ± 220
Emission rate (kg/year)	TSP	1330 ± 760**	1020 ± 640	3340 ± 530	5220 ± 1260
	PM_{10}	870 ± 430	430 ± 310	2730 ± 480	3250 ± 560
	$PM_{2.5}$	450 ± 290	220 ± 140	570 ± 130	1640 ± 530
Contribution (%)	TSP	12.2	9.3	30.6	47.8
	PM_{10}	12.0	5.9	37.5	44.6
	$PM_{2.5}$	15.1	10.7	19.1	55.0

*The concentration was measured at the downwind boundary of the cracking process; moreover, the concentration is the average of three downwind dust concentrations.

**The emission rate was calculated with TSP mass-balance method, as shown in Equation (2).

*The percent contribution was computed with TSP emission rate from cracking process over total TSP emission rate.

COMPARISON OF GRAVEL SITE DUST EMISSION CHARACTERISTICS

It is important to compare the emission rates between the four gravel sites before developing emission factors. In this study, the measured TSP concentrations ranged from 280 to 1,290 μg/m^3 and PM_{10} ranged from 135 to 560 μg/m^3. Both depended mainly on the weather conditions, including relative humidity (RH), temperature (Temp), and wind speed (V), but not on gravel site, as shown in Table 2. Meanwhile, weather conditions were gathered for the northern part of Taiwan. It was revealed that the differences between the emission rates of the gravel sites, namely A, B, C, and D, were not significant. The deviation of the emission rates between the four gravel sites was below 10%.

Table 2. The dust concentration and weather conditions at the gravel processing sites.

Site	A	B	C	D
TSP(μg/m^3)*	340 - 1140	520 - 1260	280 - 1020	390 - 1290
PM_{10}(μg/m^3)*	158 - 360	135 - 470	170 - 560	230 - 550
$PM_{2.5}$(μg/m^3)*	45 - 250	56 - 238	40 - 219	55 - 212
RH(%)	67 - 75	60 - 78	55 - 73	62 - 76
Temp(^{o}C)	23 - 26	25 - 28	24- 27	26 – 29
V(m/sec)	1.4 – 3.8	1.9 – 4.3	2.8- 5.4	2.1 – 6.7

*The concentration was measured at the boundary of gravel sites. Moreover, the concentration is the average of three downwind dust concentrations.
*RH, Temp, and V indicate the abbreviations of relative humidity, temperature, and wind speed, respectively.
*The weather conditions were gathered at northern part of Taiwan.

SEASONAL DIFFERENCES OF DUSTFALL DEPOSITION RATES

The dustfall deposition flux was measured to establish the overall emission rate of the gravel sites (see Equation (5). Particulate deposition rate was calculated with either Equation (6) or (7) by multiplying dustfall deposition flux and overall surface area of the gravel sites; roughly 4,000 m^2. The values of dustfall deposition flux ranged 12.9 to 21.8 ton/km^2/month during a dry period, from June to November, as shown in Table 3, in the northern part of Taiwan. In contrast, it ranged from 9.3 to 12.3 ton/km^2/month during the wet period from December to May. The difference was attributed to the seasonal wind with high humidity in the wet period. Furthermore, it was difficult to emit dust since the gravel and sand moisture content during wet period was higher than that during dry period. Notably, the difference between the dustfall deposition flux in spring and winter was not significant due to similar weather conditions, including wind speed, humidity, and precipitation. Similarly, there was little difference between summer and autumn dustfall flux.

Table 3. Comparison of dustfall deposition flux at different gravel sites. Unit: ton/km^2/month

Plant Month	A	B	C	D
Spring (3, 4, 5)	3.2 - 14.3	3.1 - 19.3	6.4 - 9.2	3.6 - 22.5
Summer (6, 7, 8)	11.9 - 15.2	21.5 - 23.3	10.5 - 15.1	22.3 - 24.2
Autumn (9, 10, 11)	11.9 - 13.6	19.7 - 22.8	12.4 - 17.5	13.2 - 24.5
Winter (12, 1, 2)	3.5 -11.9	8.8 -10.9	8.5 -12.3	6.4 -14.5
Dry period (6~11)*	13.3	21.7	12.9	21.8
Wet period (12~5)*	9.3	12.3	10.1	12.3

*The dustfall deposition flux during this period was calculated from the average of dustfall deposition flux in six months.
*The weather conditions were gathered at northern part of Taiwan.

THE INFLUENCE OF MOISTURE CONTENT AND SILT CONTENT

In this study, moisture and silt content of sand and gravel were measured at each pollution source to know the influences of both on emission characteristics. It was found that the concentration of fugitive dusts increased with a decrease in moisture. For example, the moisture content of gravel at the cracking area was between 5.1 and 14.0% higher than other pollution sources; *i.e.*, piles, roads, and bare ground. Meanwhile, the dust concentration at the boundary of the cracker was less than that at other pollution sources. The results explain why the dust emission rate from cracking processes was less than that from other pollution sources. In contrast, the concentration and emission rate of fugitive dust increased with the increase of silt content. The results concurred with Encinas (1999) who reported that the higher the silt content, the higher the dust emission rate. In this study, the dust emission rate from unpaved roads was found to be the largest among all pollution sources; silt content at 5.1 - 8.3% was highest, and the moisture content, 0.2 - 0.3%, was the lowest. In contrast, the TSP emission rate at the piles was only 20% of that at unpaved roads. Additionally, the silt content of gravel was only between 2.4 and 3.1%, whereas the moisture content could be up to 1.0 - 2.3%. This meant that the moisture and silt content really affected the emission rate of each pollution source. It is worthwhile noting that the emission rates of each pollution source are also affected by the activity, such as gravel production rate and number of vehicles passing.

RELATIONSHIP BETWEEN EMISSION FACTORS AND INFLUENTIAL PARAMETERS

Moisture and silt content are not the parameters which affect dust emission rates from the four pollution sources (Orlemann, 1983; US EPA, 1994; Smith *et al*., 1999). In this study, the influential sensitivity of each parameter was tested before developing emission factors. After determining the main influential parameters, it was necessary to establish the relationship between emission factors and influential parameters for computing the emission rates conveniently. By performing statistical regression between emission factors and influential parameters, the relationship could be constructed as follows:

Relationship at piles and cracking processes.

According to the relationship among emission factors, wind velocity, and moisture content of gravel in cracking sites and storage piles, the relationship could be obtained from AP-42 (US EPA, 1994) as in Equation (9).

$$EF = k(0.0016)\frac{\left(\frac{V}{2.2}\right)^{1..3}}{\left(\frac{M}{2}\right)^{1.4}} \tag{9}$$

where:

EF= emission factor, kg/ton

K = size coefficient, kg/ton

V = wind velocity, m/sec

M = moisture content, %

However, the dust emission rates from the investigated gravel sites were not only related to wind velocity and moisture content, but also to silt content. The silt content, wind velocity, and moisture content were divided dimensionless by each median value primarily for practical application. For this study, the evaluated median of silt content, wind velocity, and moisture content at the storage piles and nearby cracking processes was 1.3%, 2.5 m/sec, and 2.5%, respectively. After statistical analysis with the least square method, the regression equation could be developed as Equation (10) with the coefficient of determination (R^2) of 0.97, as shown in Figure 2.

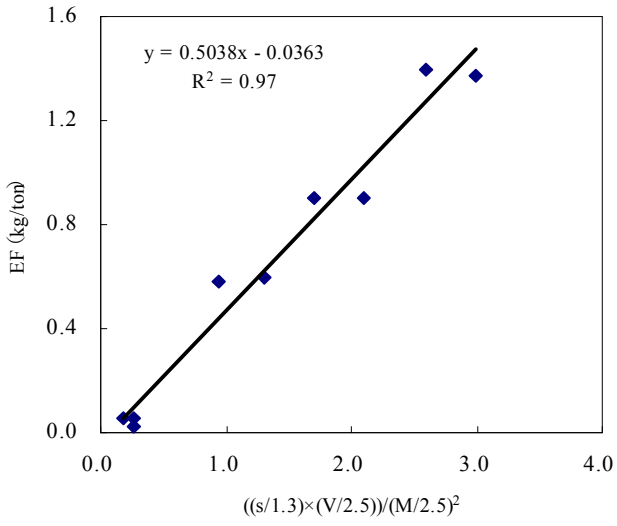

Figure 2. The relationship between emission factors and influential parameters at piles and cracking processes

$$EF = k \times \frac{\left(\frac{s}{1.3}\right) \times \left(\frac{V}{2.5}\right)}{\left(\frac{M}{2.5}\right)^2} \tag{10}$$

where:

s = silt content, %

k= 0.74, 0.48 and 0.23 kg/ton for the prediction of TSP, PM_{10}, and $PM_{2.5}$ emission rate, respectively.

Relationship at bare ground.

In AP-42, the dust emission factor at bare ground was the same as in Equation (9). However, the emission rates were poorly related to moisture and silt content of gravel/sand only at bare ground according to the results of this study and the reports of Orlemann (1983), Fitz and Bumiller (2000), Ho *et al*., (2003), and Chang (2004). From the previous studies, the main influential parameter was wind velocity. After evaluating the relationship between wind velocity and emission rate statistically, the emission factor is as shown in Equation (11). Additionally, the regression equation with R^2, 0.92, is illustrated in Figure 3.

$$EF = k \times \left(\frac{V}{2.27}\right) \tag{11}$$

where,

k = 0.095 kg/ton for TSP,

k = 0.066 kg/ton for PM_{10}, and

k = 0.034 kg/ton for $PM_{2.5}$.

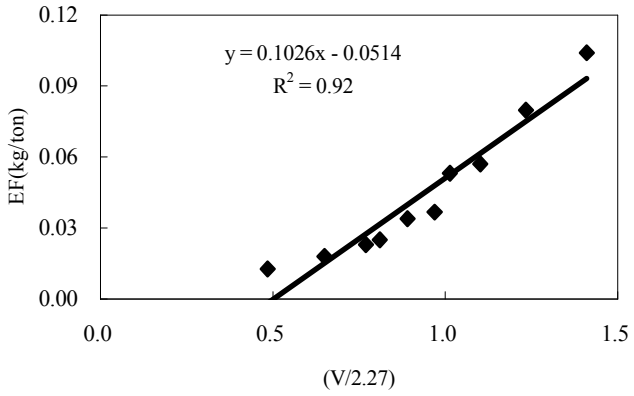

Figure 3. The relationship between emission factor and influential parameters at bare ground.

Relationship at unpaved roads.

The emission rates were related to the type of activity, vehicle weight, velocity, and VKT (numbers of vehicles/m/hour) in unpaved road pollution sources according to the reports of Zhuang (1999), Etyemeziana *et al*., (2003), and Gilliesa *et al*., (2005). In AP-42, the emission factors were related to the number of wheels attached to the vehicles used to load and transport gravel, as well. This is illustrated in Equation (12).

$$EF = k(1.7)\left(\frac{s}{12}\right)\left(\frac{S}{48}\right)\left(\frac{W}{2.7}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{365-p}{365}\right) \tag{12}$$

where,

k = the size coefficient, kg/ton

s = silt content, %

S = vehicles speed, km/hr

W = vehicles weight, ton

w = numbers of tires

P = days of precipitation, day

However, this equation was too complicated for use in Taiwan since certain information, such as vehicle weight, numbers of tires, and days of precipitation were not available generally. Additionally, the dust emission rates depended on the number of vehicles passing (n, VKT), moisture contents (M, %), and days of precipitation (P, days) from the previous studies. Therefore, the equation of emission factors with $R^2 = 0.89$ was developed by regression and dimensionless analysis, as shown in Equation (13) and Figure 4.

$$EF = k \times \left[\frac{\left(\frac{s}{14.5}\right)\cdot\left(\frac{S}{22}\right)\cdot\left(\frac{n}{32}\right)\cdot\left(\frac{365-p}{365}\right)}{\left(\frac{M}{5}\right)^2}\right] \tag{13}$$

where,

k = 1.18 kg/km for TSP,

k = 0.71 kg/km for PM_{10}, and

k = 0.32 kg/km for $PM_{2.5}$.

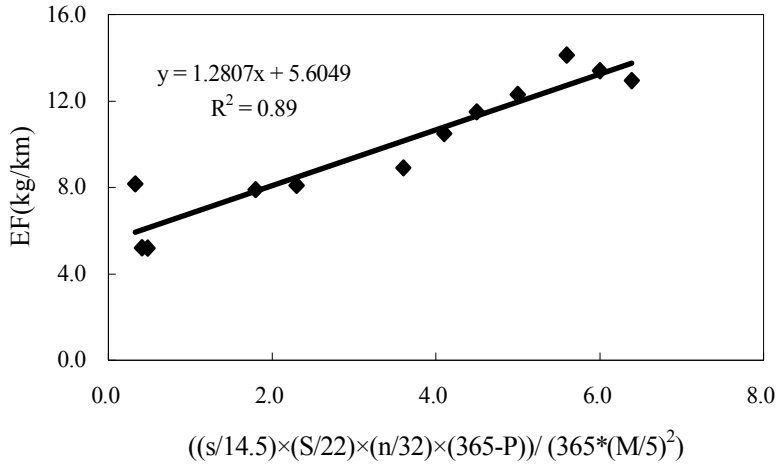

Figure 4. The relationship between emission factor and influential parameters at unpaved road

CONCLUSIONS

In this study, the gravel moisture content at the cracking processes was higher than that at the other pollution sources—storage piles, bare ground, and unpaved road—and resulted in lower emission rate. In contrast, the silt content of the dust at unpaved road was the highest and caused the most pollution. Furthermore, wind erosion caused significant dust emission at each pollution source. It is important to choose effective control strategies in which moisture content of gravel/sand can be preserved, silt content can be maintained low, and the dust at each pollution source cannot be easily blown away. Therefore, it is suggested that the fugitive dust can be effectively controlled by increasing the frequency of spraying water, decreasing the frequency of cracking, and lowering the wind velocity with fences, such as barriers of tree or dust prevention screens. Using a wind tunnel is recommended in future studies to obtain more precise emission-rate prediction.

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