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A THEORETICAL APPROACH TO CORRECTING PM_{10} OVERSAMPLING PROBLEM FOR AGRICULTURAL DUST

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Abstract

The FRM ambient PM_{10} sampler does not always measure the true PM_{10} concentration. There are inherent sampling errors associated with the PM_{10} samplers due to the interaction of particle size distribution and sampler performance characteristics. These sampling errors, which are the relative differences between theoretical estimation of the sampler concentration and the true concentration, should be corrected for equal regulation between industries. An alterative method of determines true PM_{10} concentration is to use the TSP concentration and PM_{10} fraction of PSD in question.

This paper reports a new theoretical method to correct PM_{10} sampling errors for a true PM_{10}/TSP ratio. The new method uses co-located PM_{10}/TSP samplers' measurement to derive the MMD of PSD and true PM_{10}/TSP ratio. Correction equations and charts have been developed for the PM's with GSD's of 1.2, 1.3, ... 2.1, respectively and the PM_{10} sampler with a cut-point of 10 µm and slope of 1.5. These equations and charts can be used to obtain a corrected PM_{10}/TSP ratio for the given GSD and sampler characteristics. The corrected PM_{10}/TSP ratio will be treated as true PM_{10}/TSP ratio for PM_{10} concentration calculations. This theoretical process to obtain a corrected PM_{10}/TSP ratio will minimize the inherent PM_{10} sampler errors and will provide more accurate PM_{10} measurement for the given condition.

Introduction

PM_{10} and $PM_{2.5}$ are both listed as criteria pollutants in the national Ambient Air Quality Standards (NAAQS) and are regulated as indicators of particulate matter (PM) pollutants. By definition, PM_{10} and $PM_{2.5}$ are particles with an aerodynamic equivalent diameter (AED) less than or equal to a nominal 10 and 2.5 micrometers, respectively. The regulation of PM is based upon the emission concentration of PM_{10} / $PM_{2.5}$ measured by Federal Reference Method (FRM) PM_{10} and $PM_{2.5}$ samplers. The pre-separators of the EPA approved samplers are not 100% efficient. As might be expected, there are errors in the measurement of PM_{10} and $PM_{2.5}$. The accuracy of the concentration measurements of PM_{10} and $PM_{2.5}$ has been challenged. In fact, it has been reported that the use of Federal Reference Method PM_{10} samplers to measure emission concentrations of particulate matter having a particle size distribution (PSD) with a mass median diameter (MMD) larger or smaller than 10 µm AED results in significant sampling error – over-sampling or under-sampling, respectively (Buser et al. 2001, Pargmann et al. 2001, Wang et al. 2003). This sampling error is the estimation of the difference between sampler concentration and the true PM_{10} concentration.

The pre-separator (true cut) of true PM_{10} sampler would theoretically remove all particles larger than 10 µm, allowing all PM less than 10 µm to penetrate to the filter. It is currently impossible to obtain a true cut. Typically, PM_{10} pre-separators are assumed to have performance characteristics (fractional efficiency curve, FEC) that can be described by a cumulative lognormal probability distribution with a cut point (d_{50}) and slope. The cut-point is the AED of the particle size collected with 50% efficiency and the slope of the fractional efficiency curve of the pre-collector is the ratio of the 84.1% and 50% particle sizes ($d_{84.1}/d_{50}$) or the ratio of the 50% and 15.9% particle sizes ($d_{50}/d_{15.9}$) or the square root of the ratio of ($d_{84.1}/d_{15.9}$) from the FEC.

The FRM performance standard for samplers is a cut-point of 10 ± 0.5 µm with a slope of 1.5 ± 0.1 (U. S. EPA 40CFR53, 2000). Buser et al. (2001) reported that PM_{10} sampler measurements might be 139 to 343% higher than the true PM_{10} concentration if the pre-collector operates within the designed FRM performance standards sampling PM with a MMD of 20 µm and geometric standard deviations (GSD) of 2.0 and 1.5, respectively. The research results indicated inherent PM_{10} sampling errors associated with PM_{10} sampler due to the interaction of particle size and sampler performance characteristics. Moreover, Pargmann et al. (2001) and Wang et al (2003) reported shifts in pre-separators cut points when exposed to PM larger than the designed cut point of the samplers.

The inherent PM_{10} sampler errors due to the interaction of the sampler performance and PSD characteristics result in an unequal regulation between various industries. Since the intent of PM regulations is to protect public health; then, all the industries should be equally regulated. To achieve equal regulation among different industries, which emit PM with different MMD's and GSD's, PM_{10} measurements must be corrected to account for the PM_{10} sampler's inherent errors.

Besides PM_{10} sampler's measurement, there is an alternative way to determine PM_{10} concentration by combining measurements of total suspended particulate (TSP) concentration and PSD of the PM in question. The true PM_{10} concentration equals the TSP concentration times the mass fraction of PM less than or equal to 10 µm from PSD. This alternative way of determining PM_{10} concentration leads to a theoretical method to correct PM_{10} sampler errors, which is to use co-locating PM_{10}/TSP samplers' measurements to derive a PSD of the PM, and thus to obtain the true PM_{10} fraction of the PSD for the true PM_{10} concentration calculation (Parnell et al, 2003). A more in-depth discussion of this approach to correcting PM_{10} sampling errors will be address herein.

New Theoretical Approach to Correcting PM_{10} Sampling Errors

Science Behind the New Theoretical Approach

PM Particle Size Distribution. One of the most important characteristics of suspended particles is the size distribution of the particles. "Hinds (1999) states that lognormal distribution is used extensively for aerosol size distributions because it fits the observed size distributions reasonably well". A lognormal distribution, which is normal distribution with respect to $\ln(d_p)$, can be characterized by two parameters: MMD and GSD. The frequency function of a lognormal mass distribution in term of the particle size d_p can be expressed as:

$$df = \frac{1}{\sqrt{2\pi} * d_p * ln(GSD)} exp\left[\frac{-\left(ln\, d_p - ln(MMD)\right)^2}{2(ln(GSD))^2}\right] dd_p \qquad \text{(Hinds, 1999)} \qquad (1)$$

The GSD is a dimensionless quantity with a value greater than 1.0. It is defined by:

$$GSD = \frac{d_{84.1}}{MMD} = \frac{MMD}{d_{15.9}} = \left(\frac{d_{84.1}}{MMD}\right)^{1/2} \qquad \text{(Hinds, 1999)} \qquad (2)$$

where:

$d_{84.1}$ = diameter where particles constituting 84.1% of total mass of particles are smaller than this size
MMD = mass median diameter of PSD, and
$d_{15.9}$ = diameter where particles constituting 15.9% of total mass of particles are smaller than this size

The particle size distribution can also be described as a cumulative distribution F_x, which gives the mass fraction of all the particles with diameters less than X. Theoretically; the cumulative distribution function is presented as:

$$F_x = \int_0^x \frac{1}{\sqrt{2\pi} * d_p * ln(GSD)} exp\left[\frac{-\left(ln\, d_p - ln(MMD)\right)^2}{2(ln(GSD))^2}\right] dd_p = F\left(d_p, MMD, GSD\right) \qquad \text{(Hinds, 1999)} \qquad (3)$$

Based upon equation 3, the true mass fraction of PM_{10}, also known as true (PM_{10}/TSP) ratio, can be determined as follows:

$$\left(PM_{10} / TSP\right)_{true} = \int_0^{10} \frac{1}{\sqrt{2\pi} * d_p * ln(GSD)} exp\left[\frac{-\left(ln\, d_p - ln(MMD)\right)^2}{2(ln(GSD))^2}\right] dd_p \qquad (4)$$

PM_{10} Sampler Performance Characteristics. A sampler's performance is generally described by its fractional efficiency curve or fractional penetration curve. A fractional efficiency curve is a description of the efficiency of which a particle with a selected diameter will be captured by the pre-separator. The fractional efficiency curve is most commonly represented by a cumulative lognormal distribution with a cut–point and a slope. The cut-point, also known as d_{50}, is the particle size where 50% of PM is captured by the pre-separator and 50% of the PM will penetrate to the filter. The slope is the ratio of the 84.1% and 50% particle size ($d_{84.1}/d_{50}$) or the ratio of the 50% and 15.9% particle size ($d_{50}/d_{15.9}$) or the square root of the ratio of

($d_{84.1}/d_{15.9}$) from the fractional efficiency curve. The mathematical expression of a sampler's fractional collection efficiency curve is as follows:

$$\eta_x = \int_0^x \frac{1}{\sqrt{2\pi} * d_p * ln(slope)} exp\left[\frac{-\left(ln\, d_p - ln\, d_{50}\right)^2}{2\left(ln(slope)\right)^2}\right] dd_p = \eta\left(d_p, d_{50}, slope\right) \quad (5)$$

In the equation 5, η_x is the sampler collection efficiency for particles with diameters less than X. Based upon this sampler fractional collection efficiency curve; the sampler fractional penetration curve can be mathematically expressed as:

$$P\left(d_p, d_{50}, slope\right) = 1 - \eta\left(d_p, d_{50}, slope\right) = 1 - \int_0^x \frac{1}{\sqrt{2\pi} * d_p * ln(slope)} exp\left[\frac{-\left(ln\, d_p - ln\, d_{50}\right)^2}{2\left(ln(slope)\right)^2}\right] dd_p \quad (6)$$

The measured (PM_{10}/TSP) ratio, also referred to as the sampled mass fraction of PM_{10}, can be theoretically estimated by combining particle size distribution (equation 1) and the sampler's performance characteristics (equation 6) as follows:

$$\left(PM_{10} / TSP\right)_{measured} = \int_0^\infty f(d_p, MMD, GSD) * P\left(d_p, d_{50}, slope\right) dd_p \quad \text{(Buser, et al., 2002)} \quad (7)$$

<u>*Over-Sampling Rate and True PM_{10}/TSP Ratio Calculations.*</u> The sampling error, also referred to as over-sampling rate (OR) hereby, is the relative differences between theoretical estimation of the sampler concentration and the true concentration and is defined by equation 8. The negative over-sampling rate indicates an under-sampling problem.

$$OR = \left(\frac{Measured}{True} - 1\right) = \frac{\left(PM_{10} / TSP\right)_{measured}}{\left(PM_{10} / TSP\right)_{true}} - 1 \quad \text{(Buser, et al., 2002)} \quad (8)$$

$$OR + 1 = \frac{\left(PM_{10} / TSP\right)_{measured}}{\left(PM_{10} / TSP\right)_{true}} = \frac{\int_0^\infty f\left(d_p, MMD, GSD\right) * P\left(d_p, d_{50}, slope\right) dd_p}{\int_0^{10} \frac{1}{\sqrt{2\pi} * d_p * ln(GSD)} exp\left[\frac{-\left(ln\, d_p - ln(MMD)\right)^2}{2\left(ln(GSD)\right)^2}\right] dd_p} \quad (9)$$

Equation 9 (Buser et. al, 2002) is the theoretical model to determine the sampling error, which will be used in the iteration process to derive true (PM_{10}/TSP ratio). However, there are four unknowns (MMD, GSD, d_{50} and slope) in the equation 9. It has been assumed in this research that PM_{10} sampler has a cut-point of 10 µm and slope of 1.5. Then, equation 9 can be used to calculation over-sampling rate for a given MMD and GSD. For the iterating process to derive true (PM_{10}/TSP ratio), equation 8 can be rewritten as:

$$\left(PM_{10} / TSP\right)_{true} = \frac{\left(PM_{10} / TSP\right)_{measured}}{OR + 1} \quad (10)$$

<u>*PM_{10} Concentration Calculation.*</u> One way to determining PM_{10} concentration is to combine co-locating PM_{10}/TSP samplers' measurements to derive true PSD of the ambient PM, and thus to obtain true PM_{10} fraction of PSD for the true PM_{10} concentration calculation as follow:

$$\left(Con.PM_{10}\right)_{true} = \left(PM_{10} / TSP\right)_{true} * Con.TSP \quad (11)$$

where:

(Con. PM_{10})$_{true}$ = true PM_{10} concentration and,
Con. TSP = Measured TSP concentration

Theoretical Iterating Process to Derived True PM_{10}/TSP Ratio Using Co-Located PM_{10} and TSP Measurements

A theoretical iterating process to derive the true PM_{10}/TSP ratio using co-located PM_{10} and TSP measurement has been developed. This theoretical process is one way to correct PM_{10} inherent sampling errors associated with agricultural dust, which has MMD greater than 10 μm.

To illustrate this new theoretical process, it is assumed that a PM_{10} sampler has cut-point of 10 μm and slope of 1.5. The iterating process was conducted for measured PM_{10}/TSP ratios of 10%, 20%, … 80% and GSD of 1.2, 1.3, … 2.1. Table 1 shows an example of this work. The following is the outline of this process:

1. Obtain co-located PM_{10}, TSP concentration measurement and take the ratio of their concentrations as a cumulative mass percentage (R_1%) of PM_{10} in the PSD, which is
$$\text{Measured } (PM_{10}/TSP) = R_1\%$$
2. Fit the R_1% of PM_{10} into lognormal distribution with given GSD to obtain MMD_1, which is the MMD without correction
3. Theoretically calculate the PM_{10} sampler (with given d_{50} and slope) over-sampling rate (OR_1%) for MMD_1 (equation 9)
4. Go to equation 10 to obtain new mass percentage of PM_{10} (R_2%), which is
$$R_2\% = R_1\% \,/\, (1+ OR_1\%)$$
5. Fit the R_2% of PM_{10} into lognormal distribution with given GSD to obtain MMD_2
6. Theoretically calculate the PM_{10} sampler (with given d_{50} and slope) over-sampling rate (OR_2%) for MMD_2 (equation 9)
7. Go to equation 10 to obtain new mass percentage of PM_{10} (R_3%)
$$R_3\% = R_1\% * (1+ OR_2\%)$$
8. Fit the R_3% of PM_{10} into lognormal distribution with given GSD to obtain MMD_3
9. Repeat the process until $\left| MMD_{n+1} - MMD_n \right| < 0.05$ μm
10. MMD_{n+1} is the corrected MMD with the mass fraction of PM_{10} as corrected (PM_{10}/TSP) ratio, which is
$$\text{Corrected } (PM_{10}/TSP) = R_{n+1}\% = R_1\% * (1+ OR_n\%)$$

Results and Discussions

Table 2 lists the results of this theoretical iteration process used to derive a MMD and (PM_{10}/TSP) ratio of ambient PM by using PM_{10} and TSP co-locating measurements for the correction of the PM_{10} over-sampling problem. Figures 1-10 illustrate the relationship of measured (PM_{10}/TSP) ratio and corrected (PM_{10}/TSP) ratio. Theoretical correction equations are also included in these figures to obtain corrected PM_{10}/TSP ratio. Figure 11 is the summary of the figures1-10. It can be used as a correction chart for corrected (PM_{10}/TSP) measurement. The results listed in table 2 suggest that:

- PM_{10} over-sampling problem occurs only when MMD is greater than 10 μm.
- The greater MMD, the higher sampling error
- PM_{10} over-sampling errors increase with decrease of GSD
- The correction factors (K) for true (PM_{10} /TSP) ratio listed in the table 2 and the slopes of the correction curves in the figure 11 indicated that GSD has more impact on PM_{10} over-sampling error than MMD does.
- The correction factors (K) for true (PM_{10} /TSP) ratio listed in the table 2 also indicate that PM_{10} sampling error is not as great for urban dust that typically has MMD of 6.5 μm, as for agricultural dust, which typically has MMD of 20 μm.

The final goal of this research is to find a way to obtain an accurate PM_{10} concentration measurement. The following is the outline to apply the results of this research for PM_{10} measurement assuming that PM_{10} sampler has a cut-point of 10 μm and GSD of 1.5:

1. Obtain co-located PM_{10}, TSP concentration measurements
2. Take the ratio of PM_{10}/TSP concentration as mass fraction of PM_{10}
3. Use equations in the figures 1-10 to calculate corrected (PM_{10}/TSP) ratio, or go to the correction chart in the figure11 to obtain corrected (PM_{10}/TSP) for the PM with given GSD
4. Treat corrected (PM_{10}/TSP) ratio as true (PM_{10}/TSP) ratio
5. Use equation 11 to calculate PM_{10} concentration

Summary

The FRM ambient PM_{10} sampler does not the measure true PM_{10} concentration under certain conditions. There are inherent sampling errors associated with the PM_{10} samplers due to the interaction of particle size distribution and sampler performance characteristics. These sampling errors, which are the relative differences between theoretical estimation of the sampler concentration and the true concentration, should be corrected for equal regulation among all industries. An alterative method of determines true PM_{10} concentration is to use the TSP concentration and PM_{10} fraction of PSD in question.

This paper reports a new theoretical method to correct PM_{10} sampling errors for a true PM_{10}/TSP ratio. The new method uses co-located PM_{10}/TSP samplers' measurement to derive the MMD of PSD and true PM_{10}/TSP ratio. Correction equations and charts have been developed for the PM's with GSD's of 1.2, 1.3, ... 2.1, respectively and the PM_{10} sampler with a cut-point of 10 µm and slope of 1.5. These equations and charts can be used to obtain a corrected PM_{10}/TSP ratio for the given GSD and sampler characteristics. The corrected PM_{10}/TSP ratio will be treated as true PM_{10}/TSP ratio for PM_{10} concentration calculations. This theoretical process to obtain a corrected PM_{10}/TSP ratio will minimize the inherent PM_{10} sampler errors and will provide more accurate PM_{10} measurement for the given condition.

Future Work

There are several limitations to apply the results from this research. First of all, the correction equations and charts are only valid for the PM_{10} sampler with a cut-point of 10 µm and slope of 1.5. Since the FRM performance standard for PM_{10} sampler is a cut-point of 10 ± 0.5 µm with a slope of 1.5 ± 0.1 (U. S. EPA 40CFR53, 2000), more correction charts are needed for the samplers with cut-point other than 10 µm, such as 9.5 µm or 10.5 µm and slope other than 1.5, such as 1.4 or 1.6. Moreover, the shifts in cut-point have been reported (Parmann et al., 2001, Wang et al., 2003). Further work is needed for the correction of PM_{10} sampling error with the cut-point shifting problem by using the method developed in this research. Also, the new method can be adapted for the correction of $PM_{2.5}$ sampler errors.

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Table 1. An example of the iterating process to derive PSD of PM by using co-located PM_{10} and TSP samplers' measurements for PSD's with GSD=2 (assuming PM_{10} sampler has cut-point of 10 μm and slope of 1.5)

Measured Con.			**Measured Con.**			**Measured Con.**		
TSP sampler	100	$\mu g/m^3$	TSP sampler	100	$\mu g/m^3$	TSP sampler	100	$\mu g/m^3$
PM_{10} sampler	30	$\mu g/m^3$	PM_{10} sampler	20	$\mu g/m^3$	PM_{10} sampler	10	$\mu g/m^3$
Measured PM_{10}/TSP	30%	Derived MMD 14.378	Measured PM_{10}/TSP	20%	Derived MMD 17.89	Measured PM_{10}/TSP	10%	Derived MMD 24.30
if MMD=14.378 measured/true ratio=108.46%			if MMD=17.89 measured/true ratio=116.81%			if MMD=24.30 measured/true ratio=134.29%		
Corrected 1st PM_{10}/TSP	27.66%	Derived MMD 15.0782	Corrected 1st PM_{10}/TSP	17.12%	Derived MMD 19.2817	Corrected 1st PM_{10}/TSP	7.45%	Derived MMD 27.07
if MMD=15.078 measured/true ratio=110.03%			if MMD=19.2817 measured/true ratio=120.39%			if MMD=27.07 measured/true ratio=142.53%		
Corrected 2nd PM_{10}/TSP	27.27%	Derived MMD 15.2017	Corrected 2nd PM_{10}/TSP	16.61%	Derived MMD 19.56	Corrected 2nd PM_{10}/TSP	7.02%	Derived MMD 27.66
if MMD=15.2017 measured/true ratio=110.32%			if MMD=19.56 measured/true ratio=121.12%			if MMD=27.66 measured/true ratio=144.33%		
Corrected 3rd PM_{10}/TSP	27.19%	Derived MMD 15.2273	Corrected 3rd PM_{10}/TSP	16.51%	Derived MMD 19.61	Corrected 3rd PM_{10}/TSP	6.93%	Derived MMD 27.79
if MMD=15.2273 measured/true ratio=110.37%			if MMD=19.61 measured/true ratio=121.26%			if MMD=27.79 measured/true ratio=144.72%		
Corrected 4th PM_{10}/TSP	27.18%	Derived MMD 15.2306	Corrected 4th PM_{10}/TSP	16.49%	Derived MMD 19.63	Corrected 4th PM_{10}/TSP	6.91%	Derived MMD 27.82
			if MMD=19.63 measured/true ratio=121.31%			if MMD=27.82 measured/true ratio=144.82%		
			Corrected 5th PM_{10}/TSP	16.49%	Derived MMD 19.63	Corrected 5th PM_{10}/TSP	6.91%	Derived MMD 27.82

Table 2. Summary of derived PSD's and theoretical correction factors (K) for true (PM_{10} /TSP) ratio (assuming sampler d_{50} = 10 µm, slope = 1.5)

	GSD = 1.2				GSD = 1.3			
Measured PM_{10}/TSP	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**
10%	12.63	17.65	0.0916%	109	13.99	18.30	1.01%	9.90
20%	11.66	14.59	2.00%	9.97	12.46	14.94	6.27%	3.19
30%	11.00	12.57	10.52%	2.85	11.47	12.75	17.69%	1.70
40%	10.47	11.17	27.13%	1.47	10.69	11.27	32.37%	1.24
50%	10.00	10.00	50.00%	1.00	10.00	10.00	50.00%	1.00
60%	9.55	8.94	73.05%	0.82	9.36	8.85	67.98%	0.88
70%	9.08	7.92	89.95%	0.78	8.72	7.77	83.27%	0.84
80%	8.58	5.52	100.00%	0.80	8.02	6.67	93.87%	0.85

	GSD = 1.4				GSD = 1.5			
Measured PM_{10}/TSP	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**
10%	15.39	19.53	2.30%	4.35	16.79	20.79	3.53%	2.83
20%	13.27	15.56	9.44%	2.12	14.06	16.19	11.74%	1.70
30%	11.93	13.14	20.78%	1.44	12.36	13.49	22.99%	1.30
40%	10.89	11.42	34.65%	1.15	11.08	11.56	36.03%	1.11
50%	10.00	10.00	50.00%	1.00	10.00	10.00	50.00%	1.00
60%	9.18	8.76	65.41%	0.92	9.02	8.65	63.99%	0.94
70%	8.38	7.59	79.42%	0.88	8.09	7.40	77.08%	0.91
80%	7.53	6.42	90.63%	0.88	7.12	6.18	88.31%	0.91

	GSD = 1.6				GSD = 1.7			
Measured PM_{10}/TSP	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**
10%	18.24	22.10	4.56%	2.19	19.72	23.50	5.36%	1.87
20%	14.85	16.81	13.37%	1.50	15.63	17.50	14.51%	1.38
30%	12.78	13.83	24.50%	1.22	13.20	14.18	25.50%	1.18
40%	11.26	11.70	36.92%	1.08	11.44	11.84	37.53%	1.07
50%	10.00	10.00	50.00%	1.00	10.00	10.00	50.00%	1.00
60%	8.88	8.55	63.10%	0.95	8.74	8.44	62.50%	0.96
70%	7.82	7.22	75.57%	0.93	7.57	7.05	74.53%	0.94
80%	6.74	5.94	86.68%	0.92	6.40	5.70	85.52%	0.94

	GSD = 1.8				GSD = 1.9			
Measured PM_{10}/TSP	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**
10%	21.23	24.95	5.98%	1.67	22.75	26.31	6.50%	1.54
20%	16.37	18.20	15.36%	1.30	17.13	18.91	15.99%	1.25
30%	13.60	14.53	26.22%	1.14	14.00	14.88	26.76%	1.12
40%	11.61	11.98	37.93%	1.05	11.77	12.10	38.23%	1.05
50%	10.00	10.00	50.00%	1.00	10.00	10.00	50.00%	1.00
60%	8.62	8.35	62.08%	0.97	8.50	8.26	61.77%	0.97
70%	7.35	6.88	73.79%	0.95	7.14	6.72	73.24%	0.96
80%	6.10	5.49	84.67%	0.94	5.83	5.28	84.02%	0.95

	GSD = 2.0				GSD = 2.1			
Measured PM_{10}/TSP	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**	**Derived MMD without correction**	**Derived MMD with correction**	**Corrected PM_{10}/TSP**	**K**
10%	24.30	27.82	6.91%	1.45	25.77	29.40	7.23%	1.38
20%	17.89	19.63	16.49%	1.21	18.65	20.35	16.88%	1.18
30%	14.38	15.23	27.18%	1.10	14.75	15.57	27.51%	1.09
40%	11.92	12.25	38.48%	1.04	12.07	12.37	38.65%	1.03
50%	10.00	10.00	50.00%	1.00	10.00	10.00	50.00%	1.00
60%	8.39	8.16	61.54%	0.97	8.29	8.08	61.36%	0.98
70%	6.95	6.56	72.83%	0.96	6.78	6.42	72.49%	0.97
80%	5.58	5.09	83.52%	0.96	5.36	4.91	83.13%	0.96

- MMD without correction: is the MMD derived from (PM_{10}/TSP) measured by co-locating these two samplers
- MMD with correction: is the MMD derived from corrected (PM_{10}/TSP) ratio obtained through iterating process
- Corrected PM_{10}/TSP: is the PM_{10} fraction of PSD after correcting for over-sampling error through iterating process
- K is the correction factor for PM_{10}/TSP ratio, which is:

$$K = (\text{measured } PM_{10}/TSP) / \text{Corrected } PM_{10}/TSP \quad (12)$$

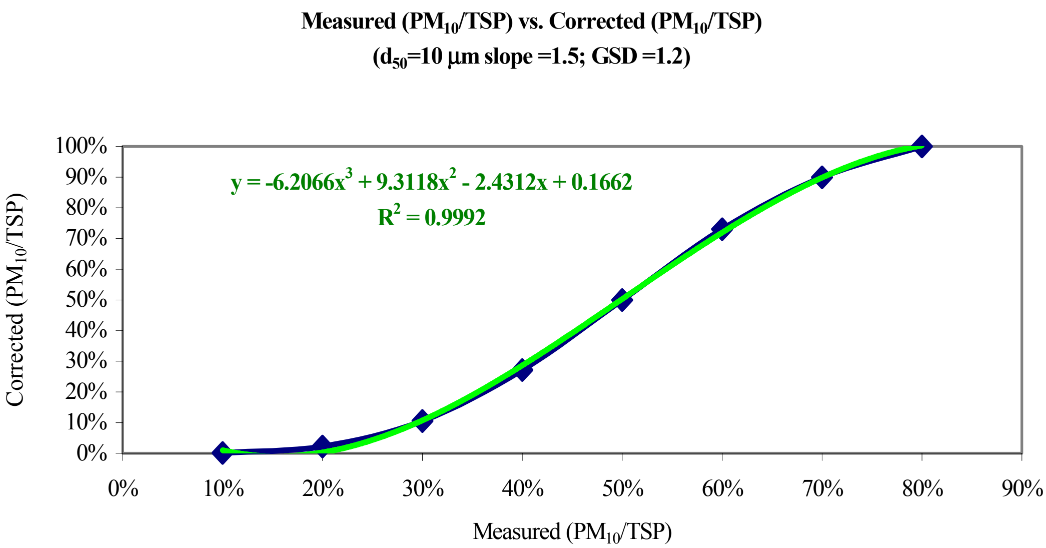

Figure 1. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=1.2.

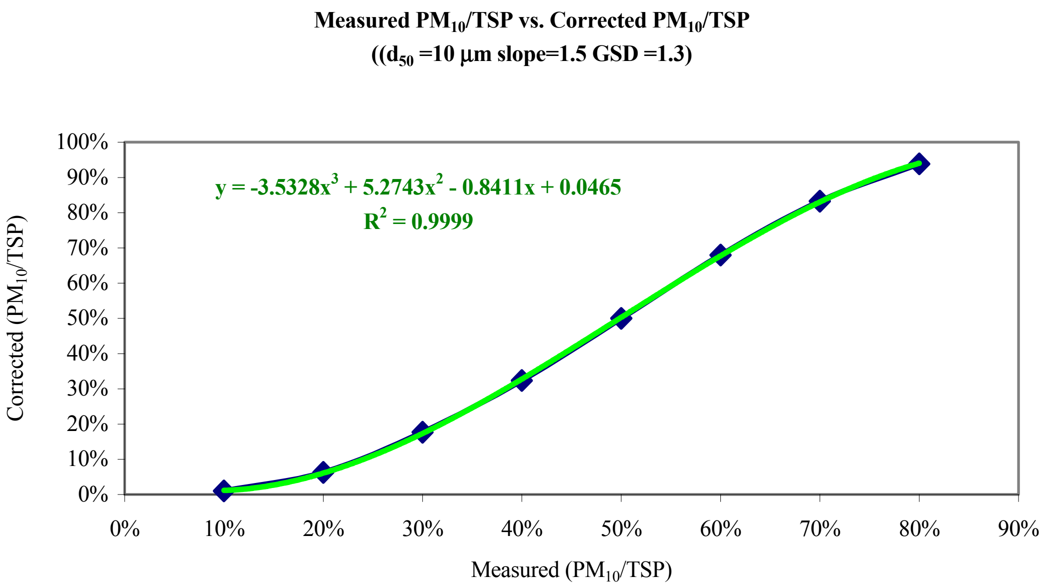

Figure 2. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=1.3.

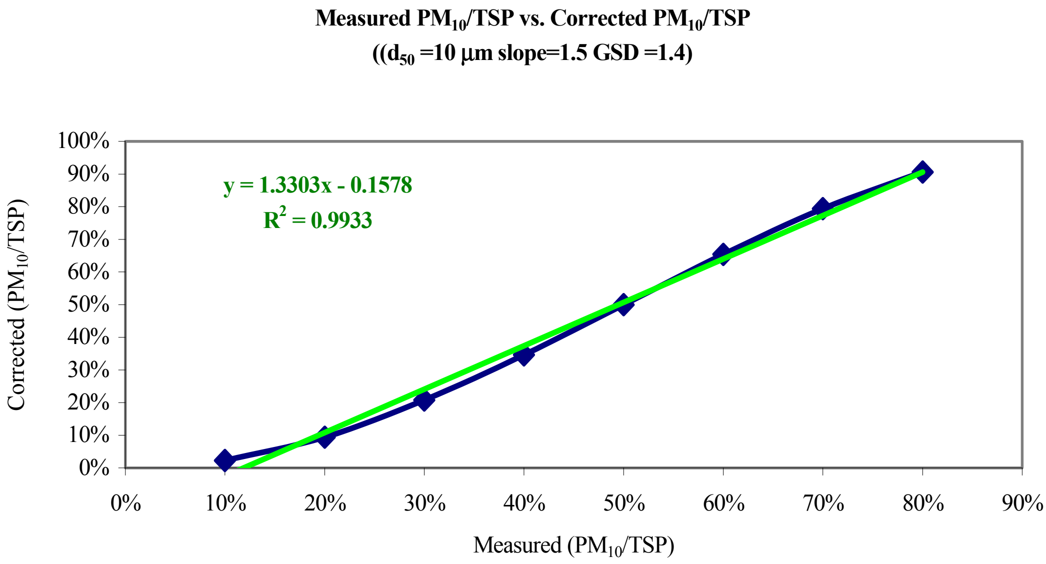

Figure 3. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=1.4.

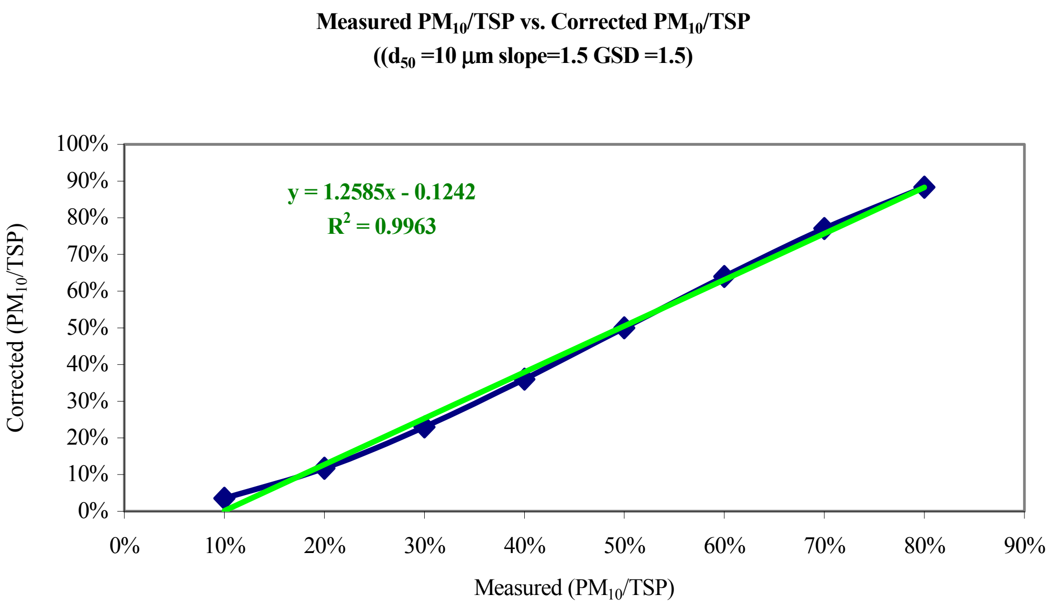

Figure 4. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=1.5.

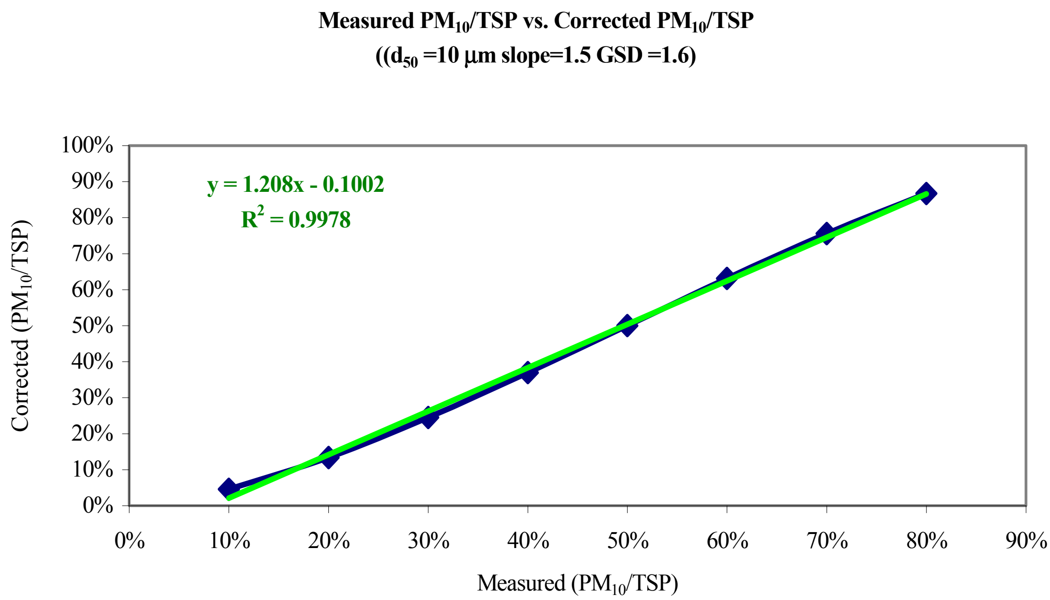

Figure 5. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=1.6.

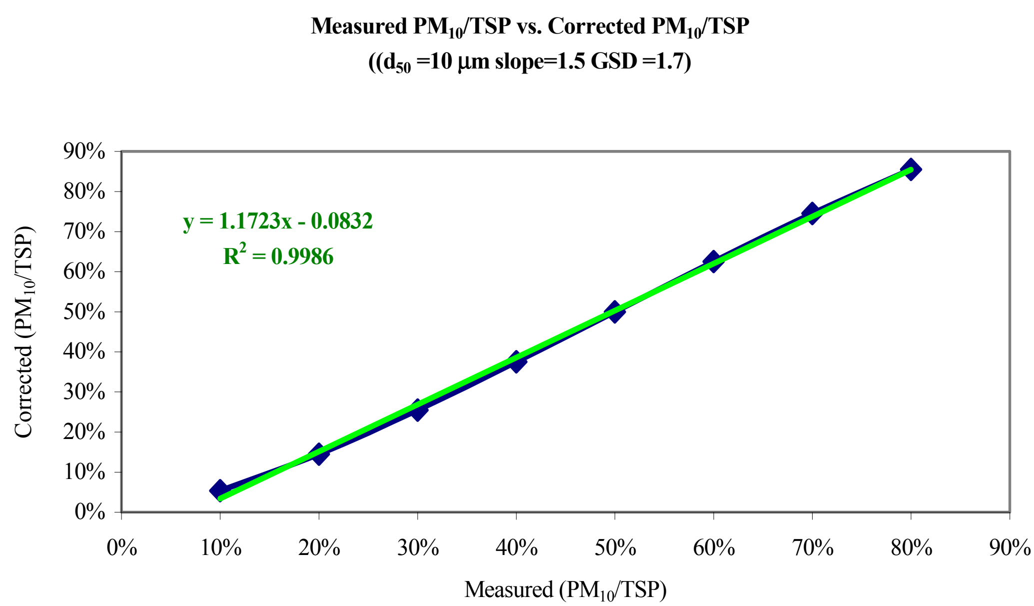

Figure 6. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=1.7.

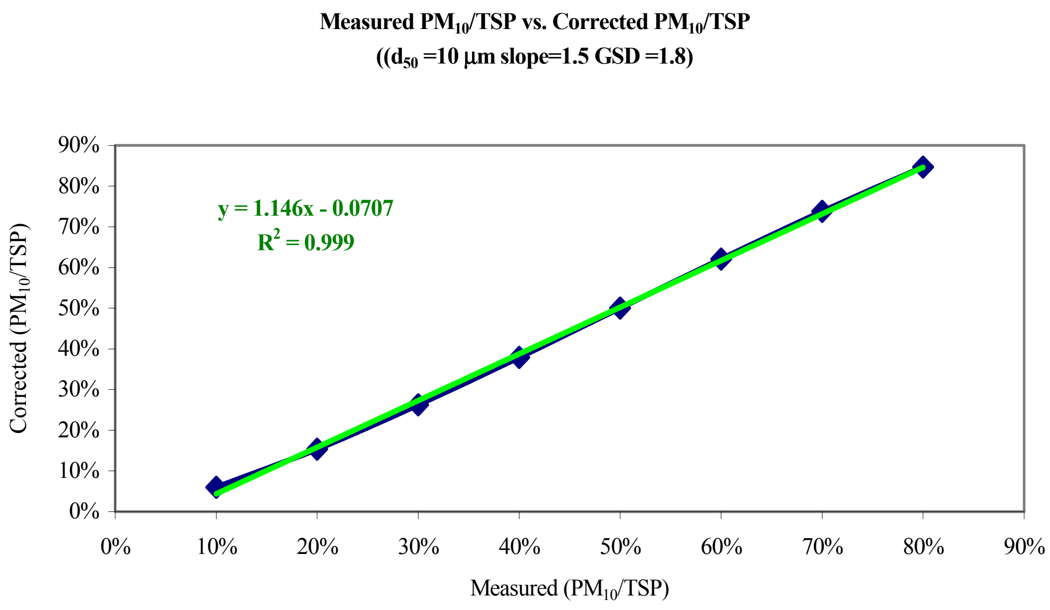

Figure 7. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=1.8.

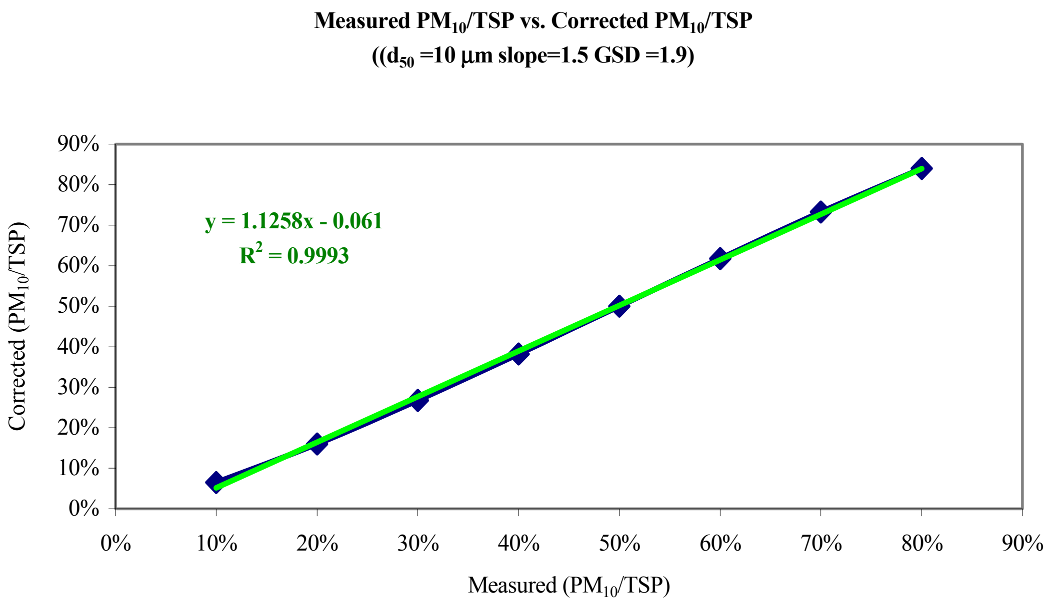

Figure 8. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=1.9.

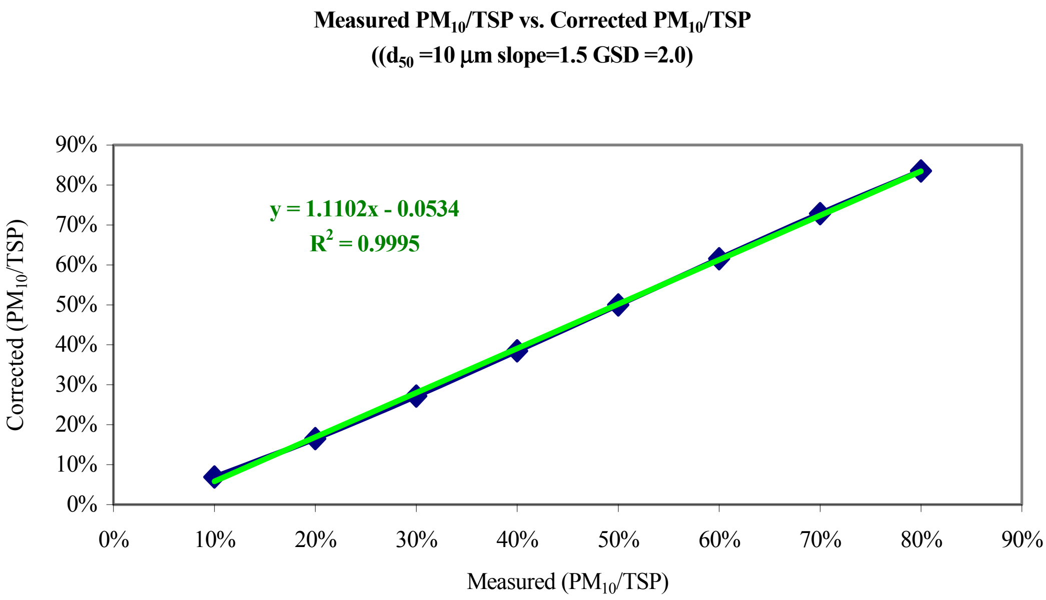

Figure 9. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=2.0.

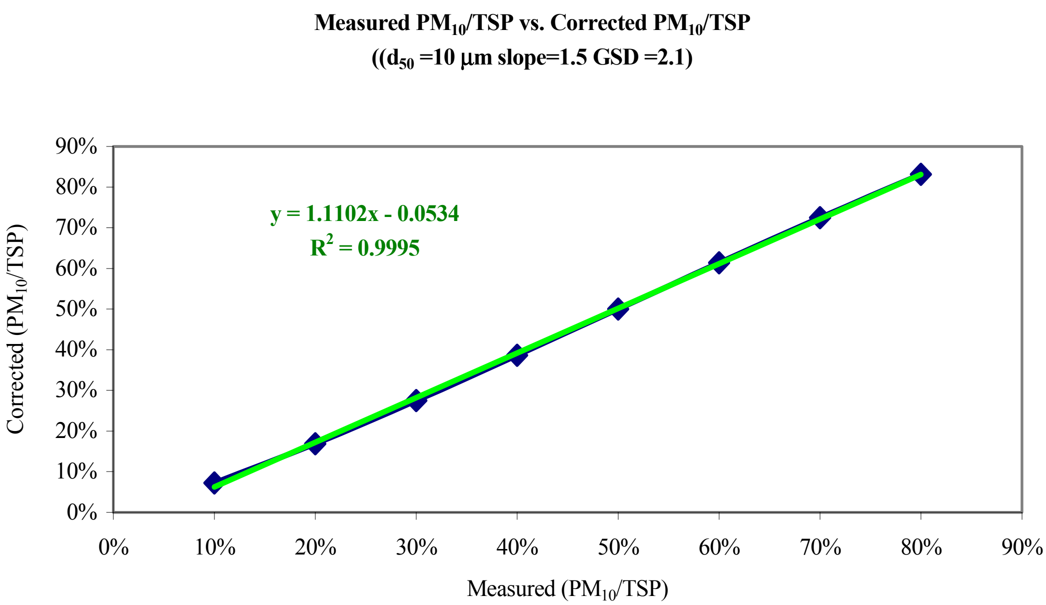

Figure 10. Relationship of measured PM_{10}/TSP ratio and corrected PM_{10}/TSP ratio for the PM with GSD=2.1.

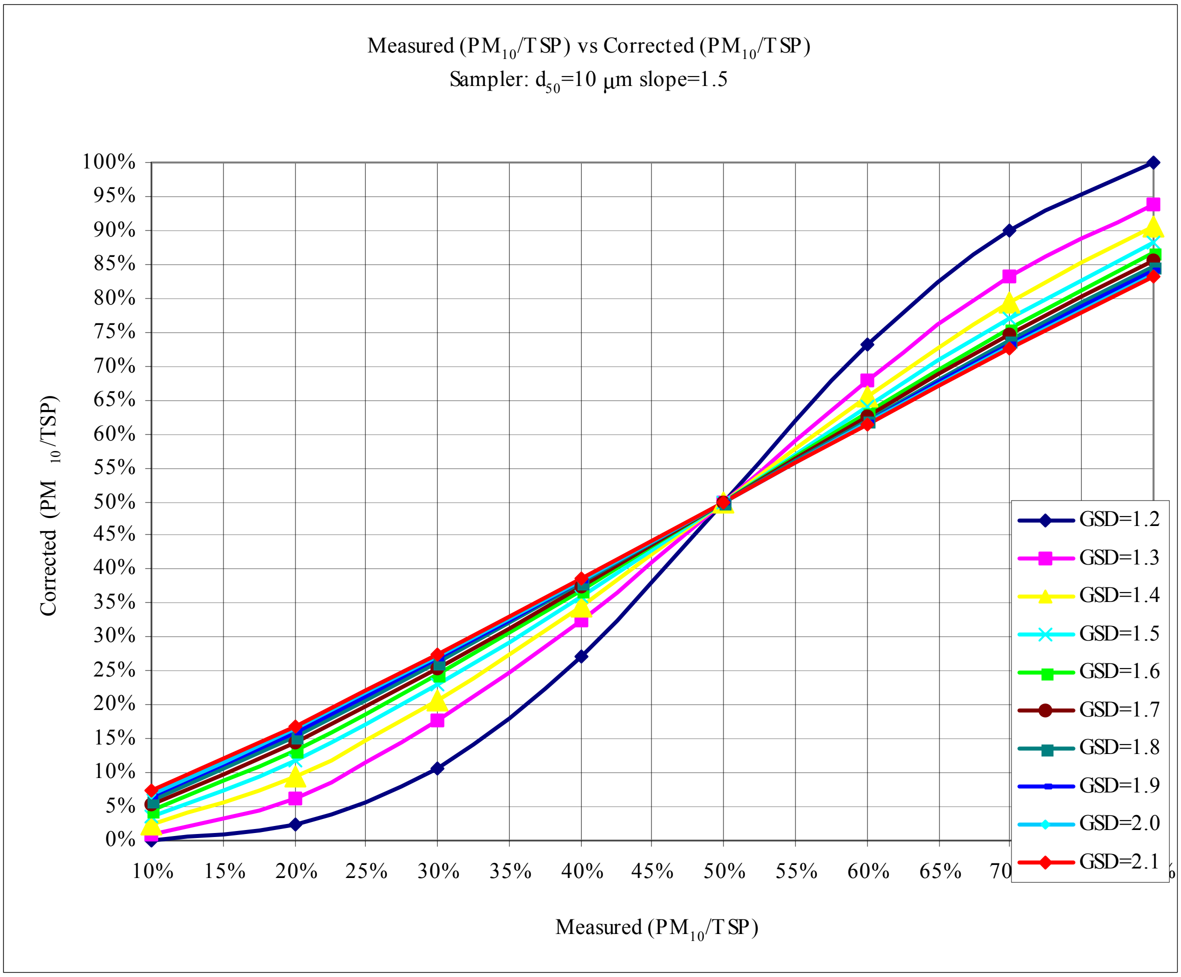

Figure 11. Correction chart for PM_{10}/TSP.