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The evaluation of airborne respirable particulates in opencast mining area of Jharia coal field using grimm 1.109 real-time portable aerosol spectrometer

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Key words: Grimm 1.109; PM_{10}; $PM_{2.5}$; PM_1; SEM-EDX.

Abstract

Mining of coal is believed to be an environmentally unfriendly activity as all the components of environment are affected adversely. Out of these, air environment in particular is getting deteriorated significantly by various mining and associated activities, thereby causing severe harmful consequences to the exposed population. In spite of this, coal mining is essential for the development of the nation as coal forms the back-bone for electricity generation. The main emphasis of this research study has been given on the assessment of the respirable particulate matters (PM_{10}, $PM_{2.5}$, PM_1)generated due to variety of mining activities specifically drilling, loading & unloading, movement of heavy duty vehicles in haul road, mine fire, etc by Grimm 1.109 Portable Aerosol Spectrometer. The study included three - hour of sampling events at three selected sampling location during peak working hours in an Opencast project (OCP) of Jharia coal field(JCF). Meteorological data during study period were also collected. The emission rate (Q) for the two selected locations in OCP was evaluated. The first location reflects drilling operation whereas second location represents the emission due to combined effect of loading/unloading operation along with mine fire. The results from Grimm 1.109 Portable Aerosol Spectrometer revealed high concentration of particulate matter (respirable, thoracic and alveoli fractions) due to various mining activities. The SEM-EDX analysis of PM_{10} samples collected on a fiberglass filter using a Respirable Dust Sampler was also performed in order to determine morphological/elemental status of particulate matter.

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Introduction

Airborne particulates of respirable range are common in the opencast coal mining area. Exposure of workers to these particulates has been reported to lead to adverse health effects. Monitoring networks generally utilizes online instruments such as Tapered Element Oscillating Microbalances(TEOMs); (Patashnick & Rupprecht, 1980) or b-attenuation monitors(Willeke & Baron, 1993).In case of calibration of the both instruments, temperature and humidity issues are taken into account (Allen *et al.*, 2004; Hauck*etal.*,2004).

Particulates which remain suspended in air are within size range from 0.005 to 100µm. Particles small enough may be inhaled through the nose (nasal route) or the mouth (oral route).Suspended particulates are commonly classified as follows: less than 0.1 µm in diameter (ultrafine or alveolic); less than 2.5 µm in diameter (fine, or thoracic fraction); between 2.5 and 10 µm in diameters (coarse, or inhalable fraction); or all particles up to about 40 µm. However, there are big differences between individuals in the amount deposited in different regions (Lippman *et al.*, 1980).Most of the particles larger than 10 µm do not reach the alveoli, because they are retained in the upper airway and the trachea bronchial tract. On the contrary, the finer particles easily reach the alveoli, where they can be absorbed into the blood stream. Maximum alveolar deposition is reached for particles with diameter inferior to 0.1 µm (Hinds WC, 1999). In this connection, necessary emphasis need to be given on study of physical and chemical features of fine particulates generated in the open cast coal mining area. Past studies depicts that "ultrafine" particles (0.1 µm) cause most of the observed health effects (Pope &Dockery, 2006;Brugge,Durant, &Rioux, 2007; Davidson, Phalen,& Solomon, 2005).

There are several commercially available direct-reading real-time aerosol monitors which are used in measuring work place particulates. One such real-time aerosol monitor is the Grimm 1.109 Portable Aerosol Spectrometer (referred to as Grimm hereafter) as shown in Fig1. The Grimm measures particles by light scattering technology where scattered light signals are detected on a recipient diode. Signals are grouped, based on particulate size, by a multichannel size classifier(Cheng, Y. H,2008; Grimm*et al.*,2009).The Grimm has the capability to simultaneously measure particulatesranging in aerodynamic diameter of0.22–32 µm in 31 channels(Peters *et al.*,2008). The Grimm has been widely used to measure particulates. Cheng, 2008 used the Grimm 1.108 Portable Aerosol Spectrometer to monitor particulates in an iron foundry. They concluded that the Grimm provides precise measurements of particulate matter but the measurement accuracy can be improved by the use of a calibration factor compared to reference gravimetric methods(Cheng, Y. H, 2008). The direct-reading instruments to measure particulates are better than the traditional gravimetric methods. The advantages of direct-reading instruments are: they provide real-time data, they are simpler to use, and in the long run they are generally less expensive to operate when compared to costs associated with standard methods(Grimm *et al.*,2009; Lehocky*etal.*,1996).

The open pit mining operations cause air pollution and major pollutants are total suspended particulate (TSP) matter and particles with an equivalent aerodynamic diameter smaller than 10 µm (PM_{10}) (Brulle *et al.*, 2006). The major coal mining activities that lead to particulate pollution are drilling, blasting, overburden loading and unloading, coal loading and unloading, road transport over unpaved roads, losses from exposed overburden dumps, coal handling plants and exposed pit faces (Lippman *et al.*,1980). The particulate emissions from different mining activities ultimately deteriorate the ambient air quality within mines as well as surrounding areas. There exists a number of research studies using GRIMM 1.109 Spectrometer for the assessment of ambient air quality in various industrial as well as non-industrial situations (Shahsavani *et al.*,2012;Mecham *et al.*,2010;Matthew *et al.*, 2011).

However, there exists limited study for assessing individual emissions and there resultant ambient air deterioration for surface mine usingportable device like GRIMM 1.109 Spectrometer. The Grimm 1.109 spectrometer is light weight than traditional gravimetric equipments (Respirable dust sampler) and canbe carried directly to the source to get more accurate assessment of particulate emission of the individual source point which leads to develop accurate emission inventories. Under this background, the present research study has been initiated in order to assess the concentration of respirable particulates(PM_{10}, $PM_{2.5}$, PM_1) and particulate concentration in terms of occupational health(namely - respirable, thoracic and alveoli fractions) generated due to different mining activities specifically drilling, loading & unloading, movement of heavy duty vehicles in haul road, mine fire, etc. by Grimm 1.109 Portable Aerosol Spectrometer. Emission rate was also calculated for PM_{10}, $PM_{2.5}$, PM_1 generated from above mentioned mining activities.

Materials and methodology

Description of study area

Bharat Coking Coal Limited (BCCL), a subsidiary of Coal India Limited, is a prime producer of coking & non-coking coal in India. It operates coal mines in the state of Jharkhand and West Bengal. Its operation is spread over 305 Km^2 in the districts of Dhanbad, Bokaro and Burdwan. Mining operation is spread over two coalfields namely Jharia Coalfield and Ranigunj Coalfield. Jharia coalfield (JCF) occupies an important place in India's industrial and energy scenario by virtue of being the only storehouse of prime coking coal and important source of coal for various activities (Fig 2). This is situated in Dhanbad district of Jharkhand and lies between latitude 23° 39' to 23° 48' N and longitudes 86° 11' to 86° 27' E. Cluster VII covers 12 mining lease holds with 14 underground/opencast mines. The total leasehold of this Cluster is 2127.70 Ha. It is located in the East Central part of JCF. It falls between the latitude 23° 47' 00" to 23° 43' 10" N and longitudes 86° 22' 54.6" to 86° 24' 45" E. The Cluster has long history of fire and subsidence.

Instrumentation

The concentrations of coarse (PM_{10}), fine ($PM_{2.5}$), and ultrafine (PM_1) particulate matter were measured using a Grimm model 1.109 aerosol spectrometer. The advantages of this instrument over other real-time measurement instruments, such as TEOM or DMA(Differential mobility analyzer) devices, are its convenience, its low maintenance requirements, and its ability to run for long periods without specific supervision (Burkart *et al.*, 2010). The ability to measure particulate matter concentrations in time intervals ranging from 1 s to 60 min is considered to be another advantage offered by the instrument.

This study included three - four hour of sampling events at three selected sampling location during peak working hours. The instrument was set for specific coal mining activities, such as drilling, loading & unloading, movement of heavy duty vehicles in haul road, mine fire in the selected OCP of JCF and the device was switched on. The first sampling location was selected as such where drilling (as prime activity) was going on while the second sampling location was chosen as such where electrical shovel was used to drag burning coal and unloading of the same to nearby water body to cool it and the third sampling location involves measurement of the particulate concentration at about 300m away from the active mining activities. This reflects the overall situation due to various mining activities.

The air enters the monitoring device via the sample inlet and is forwarded in a straight short way into the optical chamber. The sample inlet is equipped with a pneumatic locking device. At the beginning of every measurement the device makes a self-test where all optical, pneumatical, and electronical components were being checked. The self-test lasts about 30 seconds. Afterwards the actual measurement starts and the LCD-display shows the data every six seconds in a continuous manner. This enables real-time measurements of the dust concentration. While taking the device from one sampling location to the other, the device is put to standby mode and when reaching the sampling location the device is put back to operational mode. Database thus developed was transmitted to an external PC for compilation via built-in RS-232 interface.

Determination of emission rate

The modified Pasquill and Gifford formula was used to calculate the emission rate(Peavey *et.al.*, 1985)

$C_{(X,O)} = Q/\pi u \sigma y \sigma$

Where, $C_{(X,O)}$ = Pollutant concentration, g/s

π =3.1416

u=mean wind speed, m/s,

σy=standard deviation of horizontal plume concentration evaluated in terms of downwind distance x, m

σz=standard deviation of vertical plume concentration evaluated in terms of downwind distance x, m.

Particulate concentration was measured by Grimm spectrophotometer 1.109. Necessary meteorological data was obtained from the weather monitoring station installed at the Department of environmental Science & Engineering, Indian School of Mines, Dhanbad.

Determination of Dispersion Coefficients

The dispersion parametersσy and σz are dependent on atmospheric condition (i.e., stability of the atmosphere) as well as the terrain and topography of the concerned area. The estimation of σy and σz based on readily available ambient data has been attempted by several authors. The essential features of these attempt are the classification of atmospheric stability in terms of wind velocity, surface roughness, topography, terrain, incoming solar radiation(day time) and cloudiness (night time).The earliest measurement were given by Sutton(Sutton,1953).The current preference is to use Pasquil stability classification(Pasquil,1961).The correlations for σy and σz are calculated in thestudy using the most widely used approach given by Gifford(1961) based on Pasquil stability categories.The correlations are commonly referred to as the Pasquil-Gifford curves or Pasquil-Gifford Turner curves as shown in the Fig 3 and Fig 4.

Determination of Stability Class

The values for diffusion coefficients are normally determined based on the stability of the atmosphere. Two principal meteorological variables that influence stability and instability conditions are wind and vertical temperature gradient (a positive gradient is called temperature inversion, zero gradient is neutral and a negative gradient is termed lapse rate).

The temperature gradient is coded in terms of a Pasquill Stability Category A – G as shown in Table 1. Category A represents a strong lapse condition, where category G represents a temperature inversion as may be found on a calm straight winter night. Pasquill Stability Category are then evaluated in combination of day time incoming solar radiation, night time cloud cover and the magnitude of the wind vector measured at ground level as shown in Table 1.

SEM-EDX analysis

To assess the morphology and elemental composition of the particles in opencast mining area, PM_{10} samples were collected on a fiberglass filter using Respirable dust sampler (APM 460 NL). The filter was then analyzed for particle morphology and elemental composition using the SEM-EDX (FE-SEM Supra 55)system at the Petroleum Engineering Department of ISM, Dhanbad.

Result and discussion

Particulate mass concentration

The number of particulates of respirable range(<10micron) was found considerably high during various activities occurring in the open cast mining area as compared to when activities are stopped. The size of the particles determines the respiratory penetration and retention of aerosols, with fine particles having much stronger acute respiratory effects. The Box plot of particulate matter(PM_{10},$PM_{2.5}$, PM_1) concentration and particulate concentration in terms of occupational health (namely - respirable, thoracic and alveoli fractions)has been generated by the GRIMM software and has been shown in the Fig 5-10 and their descriptive statistics has been shown in Tables 2-7.

Table 1. Determination of Pasquill Stability Category.

Surface wind speed(m/s)	Day time incoming solar radiation in mW/cm²				1 hr before Sunset or Sunrise	Night time cloud cover in Octas		
	>60 (Strong)	30-60 (moderate)	<30 (slight)	O'cast		0-3	4-7	>8
<2	A	A-B	B	C	D	F-G	F	D
2-3	A-B	B	C	C	D	F	E	D
3-5	B	B-C	C	C	D	E	D	D
5-6	C	C-D	D	D	D	D	D	D
>6	D	D	D	D	D	D	D	D

Table 2. Descriptive statistics of PM (PM_{10}, $PM_{2.5}$, and PM_1) in first sampling location.

Variable	PM_1 [μg/m³]	$PM_{2.5}$ [μg/m³]	PM_{10} [μg/m³]
Minimum	45.2	46.7	70.5
Maximum	248.3	342.5	1171.5
Mean	61	81.7	213.6
Std. Deviation	22.1	43.2	173.4
Whisker 90%	69.3	124.8	442.3
Upper Quartile	59.6	80.9	246.1
Median	55.8	67.2	141.8
Lower Quartile	52.2	61.4	110.8
Whisker 10%	49.8	56.6	98.5

Table 3. Descriptive statistics of PM (PM_{10}, $PM_{2.5}$, and PM_1) in second sampling location.

Variable	PM_1 [μg/m³]	$PM_{2.5}$ [μg/m³]	PM_{10} [μg/m³]
Minimum	45.6	48.9	80.1
Maximum	1420.9	5364.7	6819.8
Mean	113.9	191	601.8
Std. Deviation	130.8	371.7	877.7
Whisker 90%	196.4	336.7	1185.1
Upper Quartile	110.1	168.4	586.3
Median	76.6	103.9	314.1
Lower Quartile	58.8	73.8	205.5
Whisker 10%	51.6	61.7	127.1

Overall mean values of 213.6, 81.7, 61μg/m³ were obtained for PM_{10}, $PM_{2.5}$, and PM_1, respectively, with corresponding maximum values 1,171.5, 342.5, 248.3 of μg/m³at location 1 where drilling was the dominant activity. During drilling, bailing airflow flushes the cutting from the hole. The material is ejected from the hole at ground level with significant velocity. The major dust sources are dust escaping through the drill stem seal at the top of the drilling table, dust entrained from the dumping of the collector fins on the mine bench and dust discharged out of the collectors exhaust because of impaired filter capture (Page and Organiscak, 2004).

Table 4. Descriptive statistics of PM (PM_{10}, $PM_{2.5}$, and PM_1) in third sampling location.

Variable	PM_1 [μg/m³]	$PM_{2.5}$ [μg/m³]	PM_{10} [μg/m³]
Minimum	43.6	48.3	72.2
Maximum	1517.7	2365.9	15832.1
Mean	89.9	130	369.4
Std. Deviation	155.5	217.3	742.5
Whisker 90%	101.3	192.8	667.3
Upper Quartile	60.4	99.8	342.6
Median	53.5	74.6	196.7
Lower Quartile	49.7	63.5	140.2
Whisker 10%	47.4	58.2	113

Table 5. Descriptive statistics of PM (in terms of occupational health) in first sampling location.

Variable	Alveolic [μg/m³]	Thoracic [μg/m³]	Inhalable [μg/m³]
Minimum	51.5	67.6	71.1
Maximum	487.5	1349.8	4610.3
Mean	105.3	220.4	397.6
Std. Deviation	60.9	190.6	537.2
Whisker 90%	174.1	450.1	905
Upper Quartile	111.5	258.2	446.4
Median	82.2	141	210.6
Lower Quartile	73	109.5	124.6
Whisker 10%	66.5	97.2	105.4

Table 6. Descriptive statistics of PM (in terms of occupational health) in second sampling location.

Variable	Alveolic [μg/m³]	Thoracic [μg/m³]	Inhalable [μg/m³]
Minimum	59.2	80	80.1
Maximum	5843.3	7378.4	28232.6
Mean	258.8	636.5	1409.2
Std. Deviation	430.8	951.9	2742.3
Whisker 90%	454.3	1265.2	2765.3
Upper Quartile	247.5	605.6	1221.5
Median	146.7	325.8	627.3
Lower Quartile	99.2	207.6	334.5
Whisker 10%	79	129.2	171.4

Table 7. Descriptive statistics of PM (in terms of occupational health) in third sampling location.

Variable	Alveolic [μg/m³]	Thoracic [μg/m³]	Inhalable [μg/m³]
Minimum	54.7	69.8	72.5
Maximum	4069.1	18731.9	66199.6
Mean	176	395.8	851.7
Std. Deviation	279.4	878.1	3379.9
Whisker 90%	279.9	683	1297.3
Upper Quartile	153.4	353.9	624.5
Median	101.5	197.4	316.9
Lower Quartile	82.7	139.8	180.7
Whisker 10%	72.4	115.8	128.5

Overall mean values 601.8,191.0,&113.9 of μg/m³ were obtained for PM_{10}, $PM_{2.5}$, and PM_1, respectively, with corresponding maximum values of 6,819.8, 5,364.7,1,420.9 μg /m³ at location 2 where electrical shovel was used to drag burning coal and unloading of the same to water body for cooling it. Therefore, here basically mine fire and loading activities was major contributor of dust generation along with black smoke. Black smoke typically contains at least 50% respirable particulates of <4.5 μmin aerodynamic diameter and its equivalent to PM_{10} (Ostro 1994). Besides the respirable particulate matter, the emitted smoke is expected to contain carbon oxides (CO and CO_2), nitrogen oxides (NO_X), sulphur oxides (SO_X) and hydrocarbons (HC). The combined effects of particulate matter and gaseous pollutants are expected to be the major concern for workers health.

Table 8. Calculated emission rate at selected three locations of JCF.

Location	Dominant activities	Emission rate (PM_{10}) in g/s	Emission rate ($PM_{2.5}$) in g/s	Emission rate (PM_1) in g/s
Location 1	Drilling, etc.	0.056	0.022	0.016
Location 2	Loading/unloading (electrical shovel), mine fire, etc.	0.105	0.034	0.020

Overall mean values of 369.4, 130, & 89.9µg/m³ were obtained for PM_{10}, $PM_{2.5}$, and PM_1, respectively, with corresponding maximum values of 15,832.1, 2,365.9,1, 517.7 µg /m³at third location point (representative for overall situation) which was recorded about 300 m far off from the mining activities. As expected, these values were comparatively less in comparison to earlier locations, i.e., at the vicinity of mining activities.

Fig. 1. Grimm 1.109 Portable Aerosol Spectrometer.

It was seen that the number of finer particulate range was more as compared to the coarser particulates as depicted in the distribution graph of particle diameter against particle number (Fig 11-13), generated by the Grimm Software.PM_{10} particles are often visible, and are caused by smoke, dirt and dust from haul roads and other active mining activities. This may cause less severe health effects whereas fine particles 2.5 micrometers and below are not visible, and are more dangerous to human health as they may contain toxic organic compounds and heavy metals. It is these finer particles that lodge deep in the lungs, and are the more dangerous particles resulting from open-cut coal mining. Existence of more number of finer particulates further aggravated the harmful consequence in coal mining areas.

Fig. 2. Site map of Jharia Coalfield.

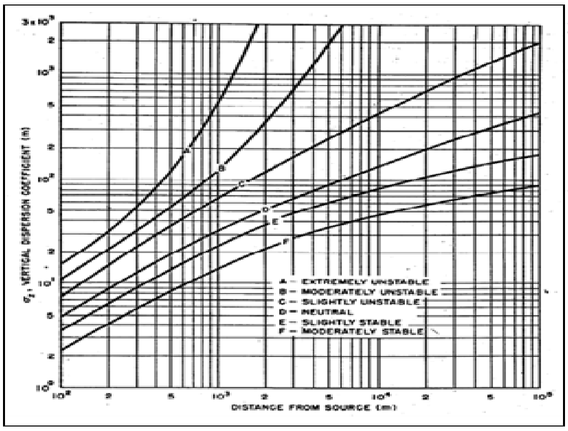

Fig. 3. Vertical diffusion σzvs.downwind distance from source for Pasquil's turbulence types.

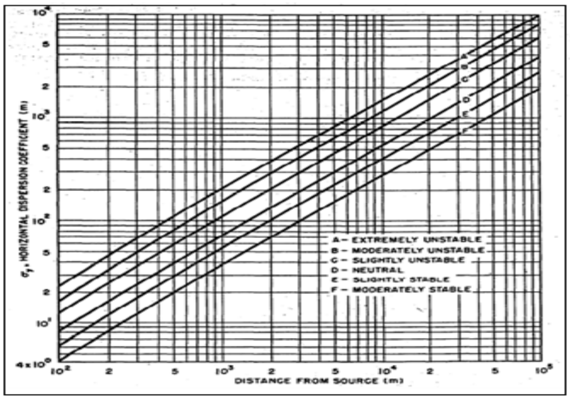

Fig. 4. Vertical diffusion σy vs downwind distance from source for Pasquil's turbulence types.

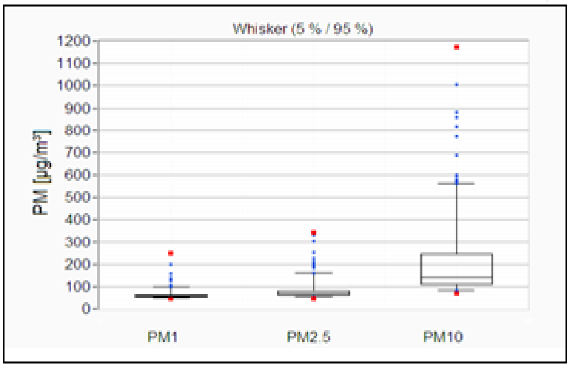

Fig. 5. Box plot of PM (PM_{10}, $PM_{2.5}$, and PM_1),in first sampling location.

Emission rate calculation

Emission rates in g/s for two monitoring locations were evaluated as shown in Table 8. Emission rates generated during loading/unloading and mine fire situation (Location 2) constitutes maximum emission

and coarser particulates have been found slightly dominating in comparison to finer particulates. However, in case of drilling operation (Location 1) it has been found that there is more or less equal contribution from finer and coarser particulates in respiratory range.

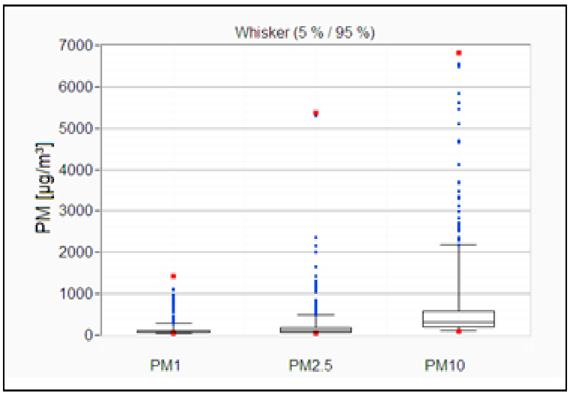

Fig. 6. Box plot of PM (PM_{10}, $PM_{2.5}$, and PM_1),in second sampling location.

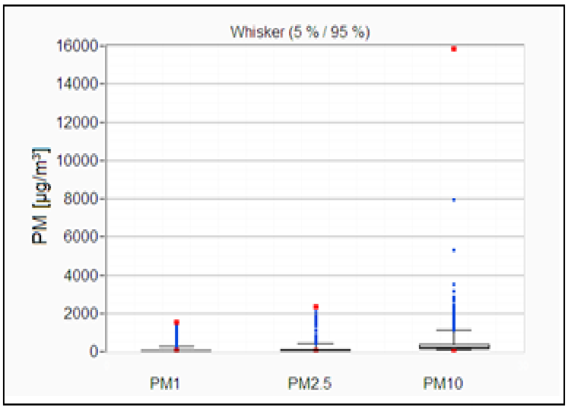

Fig. 7. Box plot of PM (PM_{10}, $PM_{2.5}$, and PM_1),in third sampling location.

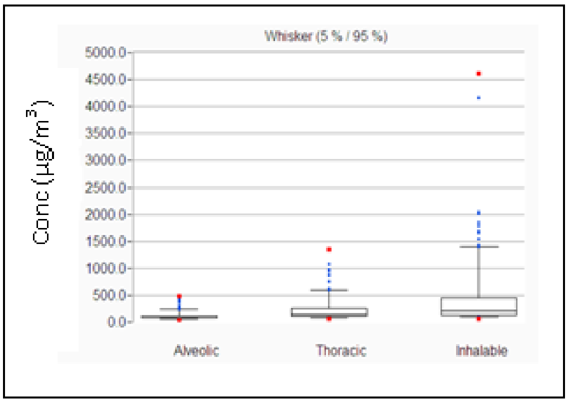

Fig. 8. Box plot of PM (in terms of occupational health) in first sampling location.

Characteristics of particles in the open-cast mining area

A SEM-EDX micrograph for PM_{10} is shown in Fig 14. The spherical, amorphous and typically non aggregated particles are distinct of carbonaceous particles type dominated by carbon with traces of S and K (Pipal *et al.*, 2011) as shown by spherical particles in SEM analysis.

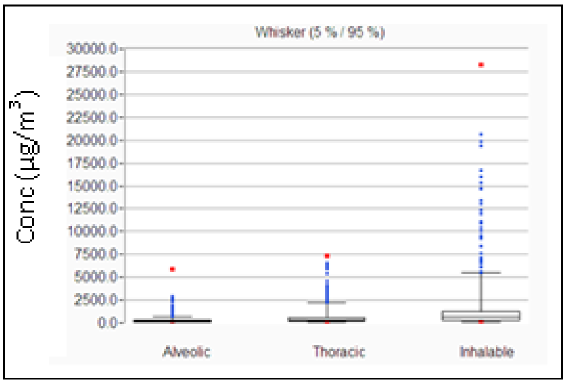

Fig. 9. Box plot of PM (in terms of occupational health) in second sampling location.

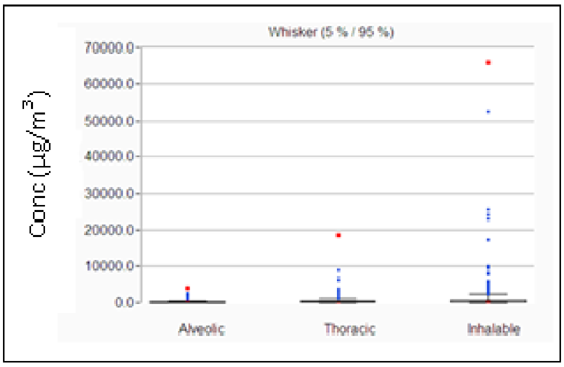

Fig. 10. Box plot of PM (in terms of occupational health) in third sampling location.

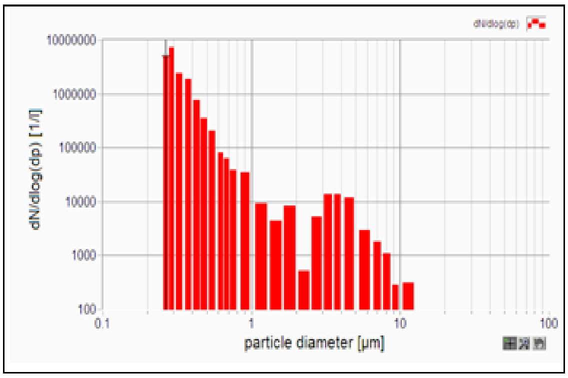

Fig. 11. Distribution graph of particle diameter against particle number of first sampling location.

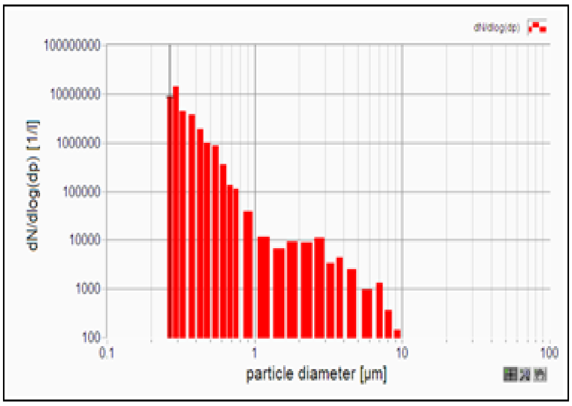

Fig. 12. Distribution graph of particle diameter against particle number of second sampling location.

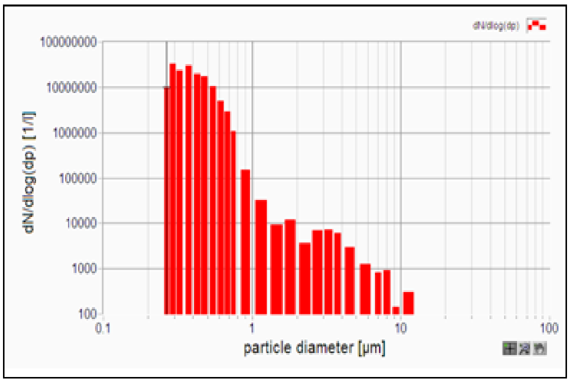

Fig. 13. Distribution graph of particle diameter against particle number of third sampling location.

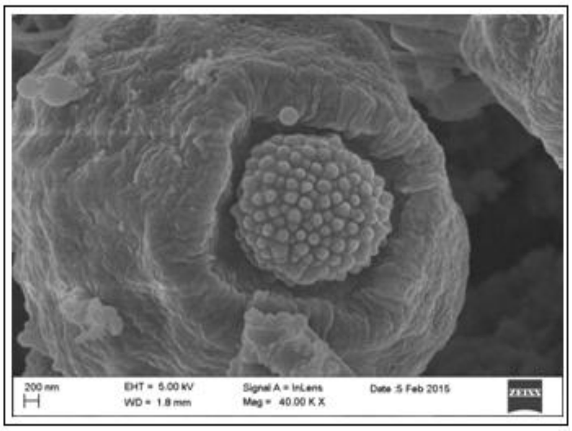

Fig. 14. SEM micrograph of PM_{10} from Opencast coal mining area.

The major elements present in PM_{10} particles are Si (17.72%), Al(15.89%), O(40.49%),C(13.49) and other elements present in minor quantity are Na(0.23),S(0.34),K(1.07) and Fe(1.04%) as depicted in the SEM-EDX graph(Fig-15).The elemental mapping of trace metals (dominant elements) with different colour coding(Brown-Carbon, Green-Oxygen, Red- Aluminum, Silica-Blue) has been shown in Fig 16. The possible explanation of the presence of elements like Si, Al, Fe, and K are due to their origin from soil, crustal dust and some anthropogenic activities. Si associated with Al, Na, Fe and K illustrated the presence of mineral, clay and feldspar particles (Shao *et al.*, 2007).

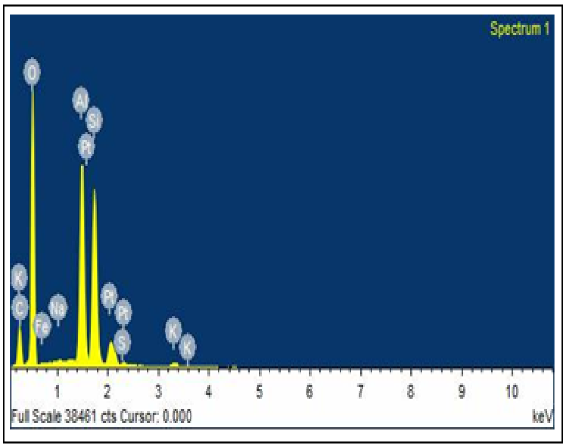

Fig. 15. Quantitative estimates of elemental compositions of the PM_{10}.

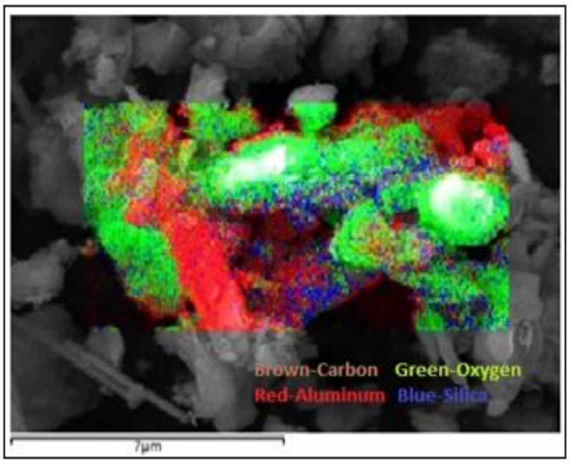

Fig. 16. Elemental mapping of PM_{10}.

Conclusion

The research study reveals that all mining activities particularly drilling, loading/unloading, transportation as well as mine fire generate considerable quantity of particulate matter (respirable, thoracic and alveoli fractions). It has been also shown that generation of finer particulates (≤ 2.5 µ) has more or less equal contribution to that of coarser particulates within respiratory fraction. These finer particle fractions generally travel greater distance in the environment and poses greater potential risks to human health. Evaluation of emission rate at both the monitoring locations also reveals the same pattern. The SEM-EDX analysis of PM_{10} particles shows the presence of Si (17.72%), Al(15.89%), O (40.49%), C(13.49) as dominant elements while the other elements present as minor quantity are Na(0.23),S(0.34),K(1.07) and Fe(1.04%).The presence of elements like Si, Al, Fe, and K are due to their origin from soil, crustal dust and some anthropogenic activities.

Generation of considerable particulate matters in continuous manner demands the necessity for evaluation of suitable preventive measures.

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