Mineral Dust Emissions at Metalliferous Mine Sites

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Abstract Mineral dusts produced from mining activities pose a risk to human health and the surrounding environment. The particle size distribution of dust is important for determining environmental, occupational health and physiological impacts. Dust is generally thought of as particulates with a diameter of between 1 and 60 μm, but it can be further divided into nuisance dust or total suspended particulates, fugitive dust, inhalable dust, thoracic dust, and respirable dust. This review considers aspects of mineral dust related to the mining of metalliferous ores including: (a) sources of mineral dust at mine sites (i.e. land clearing, drilling and blasting, transport operations, crushing, milling, screening, stockpiles); (b) control measures to reduce dust generation; (c) monitoring techniques; (d) mineral dust characterization to quantify particle concentration, size and morphology and chemical composition; and (e) prediction of mineral dust properties. Predicting the physical and mineralogical characteristics of dust is important for effective dust management and control strategies. At present, there are no appropriate testing procedures available to predict the chemical and mineralogical properties of mineral dust from mining operations. Further work is required to understand mineral fractionation according to grain size and to provide a rapid test methodology that would predict dust composition.

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Introduction

Atmospheric transport of dust is an important mechanism for the distribution of contaminants over large spatial scales and prolonged time periods. Mining processes provide multiple pathways for the production and dispersal of mineral dust into the surrounding environment. Dust source activities include removing overburden, blasting, crushing, hauling on unsealed roads, and dispersion from waste dumps or ore stockpiles. Dust dispersal represents a significant risk to human health and the local environment. The health risks associated with inhalation of dust depends on the physical properties of dust, such as the particle size and shape, composition, solubility, and reactivity in respiratory fluids (Plumlee and Ziegler 2003). Mineral dusts sourced from mining activities that are of particular concern include those rich in crystalline silica (e.g. quartz, tridymite, cristobalite), coal, and dusts containing metals and metalloids such as As, Pb, Cd and U (NIOSH 2002). Mining remains one of the most dangerous occupations in the world, but it is through exposure to hazardous mineral dusts that long term health implications are realized (Stephens and Ahern 2001).

This review aims to provide an overview of the existing literature on dust from metalliferous mining operations. The literature presented relates to: (i) dust sources and control measures; (ii) monitoring techniques; (iii) mineral dust characterization; and (iv) predicting dust composition. This review does not include computational methods relating to modeling of mine dust emissions and dispersal and excludes discussion of aerosols produced from industrial activities, carbon (black soot) from vehicular transport and fossil fuel burning and emissions from underground mine workings.

Definitions

- A range of terms exists to describe the different classes of dust for the purpose of sampling and monitoring (*Australian Department of Environment's Best Practice Dust Control Handbook* 1998; WHO 1999) and occupational health impacts (ISO 1995): *Mineral dust* is a primary particle emitted directly into the atmosphere, as individual grains or aggregates. It is usually <60 μm in diameter but can be up to 100 μm. The composition of the mineral dust varies widely according to the source.
- *Nuisance dust* describes dust that results in adverse aesthetic effects, such as settling on surfaces and causing discoloration and soiling. It ranges in size from 0.001 to 50 μm, and is generally termed *total suspended particulates* (TSP). The larger particles are inhalable and can cause irritation of the mucosal membranes (i.e. nose, throat, eyes).

- *Fugitive dust* refers to dust derived from a mixture of sources which may not be easily defined. For example, mine dust is frequently derived from multiple sources, including during transport of material (vehicular or conveyor) and processing (crushing and grinding).
- The proportion of *particulate matter* (PM) that can be inhaled into the body can be defined through sampling conventions. These conventions describe the fraction of particles penetrating the respiratory regions according to specified conditions (e.g. wind speed and direction of air movement near the body) and the relationship with aerodynamic diameter (British Standard Institute 1993).
- *Inhalable dust* is the proportion of dust that can be inhaled through the nose and mouth and deposited there. It includes a range of particle sizes generally between 5 and 10 μm and larger (<100 μm) (ISO 1995). Human health effects tend to be associated with particles with an aerodynamic diameter of less than 10 μm ($\leq$ PM10).
- *Thoracic fraction* is the mass fraction of inhalable dust that penetrates beyond the larynx (ISO 1995). The PM10-2.5 fraction makes up >50 % of the inhalable particles which can be deposited into the upper airways and lungs.
- *Respirable dust* is the particulate fraction that can be inhaled beyond the terminal bronchioles into the alveoli or gas exchange region of the lungs and pose a greater health risk through absorption of trace elements into the blood stream. The respirable fraction makes up >50 % of the inhalable particles less than 4 μm in diameter. This dust fraction is termed the $PM_{2.5}$ fraction.

Dust can also be divided into sub-classes of environmental, occupational health and physiological effects, as presented by Petavratzi et al. (2005) (Table 1).

Implications of Dust Dispersal

The dispersal of dust and aerosols from mining activities to the surrounding environment via wind deposition provides a pathway for the accumulation of heavy metals and contaminants in the environment. Exposure to heavy metals by ingestion or inhalation of contaminated soils and directly emitted particulates can result in absorption of soluble substances or physiological responses in the body

Table 1 Classification of dust types (Petavratzi et al. 2005)

Environmental effect classes	Occupational health effect classes	Physiological effect classes
Generated dust Total suspended dust Nuisance dust Fugitive dust	Inhalable dust Thoracic dust Respirable dust	Toxic dust Carcinogenic dust Fibrogenic dust Explosive dust Nusiance dust

Table 2 Hazardous mineral dust generated during metalliferous mining

Mineral types	Description	Analysis	Health impacts
Asbestos	Highly fibrous silicate minerals. Two groups: serpentine (chrysotile) and amphiboles (actinolite, tremolite, anthophyllite, amosite and crocidolite). Long, thin, strong fibres	TEM	Carcinogen (US EPA 1986)
Crystalline silica	Microcrystalline quartz and polymorphs: cristobalite and tridymite are hazardous	XRD and IR	Silicosis. Lung cancer (IARC 1997)
Sheet silicates	Talc, pyrophyllite, kaolinite, vermiculite and zeolite (erionite)	XRD	Talcosis, bronchitis and emphysema (Ross et al. 1993)
Mineral dusts	Dusts containing U, Pb, Hg, As	FESEM	Child development (e.g. Boreland and Lyle 2006)

TEM transmission electron microscopy, *XRD* X-ray diffraction, *IR* infrared spectrophotometry

(e.g. production of fluid in the respiratory tract) to remove foreign particles (Plumlee and Zeiger 2003). The World Health Organization air quality guidelines for reducing the effects on health from air pollution (WHO 2000) should be referred to for the latest summary on the risks associated with inhalation of particulate matter. As described in the Air Quality Guidelines Global Update 2005 (WHO 2006), current scientific research suggests that guidelines cannot be proposed that will completely protect against adverse health impacts of particulate matter. The guidelines presented by the WHO should be applied with caution as health effects have been reported for relatively low ambient PM concentrations and with a range of different individual responses to PM exposure. While particle size is the main focus of regulatory standards, the health risk of particles is also influenced by their chemistry and shape. In the case of mine dusts, understanding the mineralogy and geochemistry is imperative to managing the hazards posed by different dusts (Table 2) (Best Practice Handbook: Airborne Contaminants, Noise and Vibrations 2009). The US National Research Council's Committee on Research Priorities for Airborne Particulate Matter (National Research Council 2004) summarized the characteristics of PM that may be important to health responses in relation to toxicity and bioaccessibility. These factors include size mode, mass concentration, acidity, particle surface chemistry and area, particle chemistry (metals, carbon) and solubility. Plumlee and Zieger (2003) provided a summary of heavy metals and metalloids sources, pathways and known or postulated health effects associated with deficiencies of constituents (e.g., essential minerals Ca, Fe), as well as health effects associated with excessive exposure to non-essential elements that are toxic (e.g., Pb, Cd, Hg).

Dust Generation and Control in Mining

The quantity and nature of dust generated at mine sites is controlled by many different factors. The mineralogy of the rock will influence rock-breakage characteristics, while the climatic conditions (e.g., precipitation, wind gustiness) will control the degree of dust dispersal. Dust sources can either be point sources (e.g., rock breakage circuits), which are more easily managed relative to fugitive sources (e.g., unsealed roads). Over the past 30 years the US Bureau of Mines (USBM) and now the National Institute for Occupational Safety and Health (NIOSH) have conducted extensive research to lower silica concentrations in dust from metal/non-metal operations. Various control technologies are recommended, as described in Cecala et al. (2012).

Accurate quantification of dust emissions at mine sites facilitates the development of appropriate dust control strategies. The US Environmental Protection Agency's (US EPA) *AP-42 Compilation of Air Pollutant Emission Factors,* now in it in its fifth edition, provides emission factors for more than 200 categories of air pollution sources. The emission factors are a representative estimate of the quantity of a pollutant emitted to the atmosphere in relation to a specific activity involved in the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance or duration of the activity emitting the pollutant (e.g. kilograms of particulate emitted per megagram of coal burned). The emission factors are calculated based on averages of data that aim to reduce biases from site specific or short-term variability.

Exposure to respirable dust at surface mines primarily results from (i) overburden drilling and (ii) haul road dust. In minerals processing, sources of dust include belt conveyors, transfer chutes, crushing, milling, storage bins/hoppers and stockpiles. Unpaved roads generated most of the dust emissions in open pit mines but these emissions can be reduced by up to 72 % by spraying with water (Huertas et al. 2012a). Ghose and Majee (1998) showed that dust production in Indian opencast mines was predominately from coal processing (72 % from crushing, conveyor belts, unloading), wind erosion (17 %), overburden removal (7 %), coal extraction (3 %), and topsoil removal (1 %). The following section highlights the main dust sources at mine sites and the control measures used to mitigate dust dispersal.

Land Clearing

Surface mining operations require topsoil and overburden to be removed and relocated. The dust generated from land clearing is nuisance dust since it originates from diffuse sources (Best Practice Dust Control Handbook 1998). The larger size fraction of mineral dust generated from land clearing limits the spatial distribution of dust generated by this activity.

Table 3 Total dust generated per meter coal, limestone and iron ore drilled according to drill hole diameter (DDH) (Pandey 2012)

DHH (mm)	Coal (kg m^{-1})	Limestone (kg m^{-1})	Iron ore (kg m^{-1})
60	3.7	7.8	12.7
100	10.2	21.5	35.5
150	23	48.6	79.5
200	40.9	86.4	144.5
250	63.8	134.9	220.7
300	92	194.5	318.2

Control options to reduce dust emission rate for dozing activities are limited to changing the material moisture content by wet spray systems, which can suppress dust emission. Meteorological conditions can also be considered to avoid clearing during gusty conditions. Cecala et al. (2012) outline the theory behind wet spray systems and operational and maintenance issues for these dust control mechanisms.

Drilling and Blasting

The process of drilling for blasting operations at mines is a notorious source of respirable dust, which can lead to high exposure levels for the workforce involved (Cecala et al. 2012). The rate of dust generation during blast hole drilling has been shown to increase with the diameter of the drill, as well as rock hardness (Table 3). A study quantifying the rate of dust generation from sources in gold and platinum mines in South Africa concluded that blasting generated extensive amounts of dust, and that higher levels of mechanization led to higher generation rates (Biffi and Belle 2003).

Blasting is the first step in the comminution sequence to liberate valuable minerals from waste by initial fragmentation of the rock. At open pit and strip mines blasting is a controlled operation, which occurs intermittently to fragment the rock being mined. Blasting can be optimised to reduce the cost of crushing and grinding and to suit the processing requirements of each individual mine. Blasting results in the initial formation of a concentrated dust cloud that can affect the local region. The particle size distribution generated during blasting is highly variable but can produce a high proportion of fines (PM10).) Updated estimates of emission factors for TPS (<30 µm) and PM10 can be found in the *Emission Estimation Technique Manual for Mining Version 3.1* (EA 2000, 2012). The surface mining dust control strategies for drilling and blasting were reviewed by Cecala et al. (2012).

Transport

Transport of ore, waste rock and tailings and ore concentrate can generate significant quantities of fugitive dust. The transport of waste rock and ore at a mine site by haul trucks on unsealed roads can be one of the largest sources of particulate emission, requiring the most expensive dust control mechanisms (e.g. Amphonsah-Dacosta 1997). Dust emissions at sites of loading, unloading and stockpiling of processed materials (e.g. coal, iron ore, phosphorites) can have significant impacts on the surrounding environment. The grain size fraction of the final products is often fine (50–100 μm) and therefore easily dispersed. There are numerous published examples of dust emission studies at ports during handling of iron ore (e.g. Port Headland, BHP Billiton), coke (e.g. Valencia Harbour; Moreno et al. 2009), and phosphorites (Silva et al. 2012).

Control technologies to reduce dust emissions from unpaved roads are limited by the availability of water, particularly during dry seasons. Different methods available include a range of additives that are mixed with water to reduce the evaporation and agglomeration of particulates over unpaved roads. Huertas et al. (2012a) summarized the advantages and disadvantages of each of these methods (Table 4).

Table 4 Comparison of control technologies for unpaved roads (Huertas et al. 2012a)

Substance	Mechanism	Advantage	Disadvantage
Water	Wets the particles, increasing their mass and agglomeration	Low cost Minimum environmental impact	Requires regular application Overwatering can lead to problems
Salts	Hydroscopic substances that attract and retain soil moisture	Reduce evaporation to a third Compact material	Corrosive Removed by rain Environmental impacts
Surfactants	Reduce surface tension of water	Easy to apply	Low residual effects
Resin emulsions	Act as adhesives to agglomerate the fines	Low solubility Non-corrosive Seals the surface	Disappear with road maintenance Require heavy use
Lignin derivatives	Act as adhesives to agglomerate the fines	No water requirement Not removed with road maintenance	Disappear with rain Slippery when wet Environmental impacts
Bitumen	Paves the road	Insoluble to water Seals against water Long lasting	Expensive
Polymers	Act as adhesives to agglomerate the fines	More effective agglomeration than resins Suitable for long-term applications Low environmental impact	Require regular application Expensive

Crushing, Milling and Screening

Crushing, milling and screening operations can be major sources of dust due to major reductions in grain size during comminution and segregation processes. Estimates of dust emissions from common mineral processes demonstrate that dust emissions increase as the size of the material processed decreases (US EPA 2004). For example, in the case of coal, a mean particle size as fine as 5 µm may be necessary (Mankosa et al. 1989). In contrast, in Australia a number of fine grinding stirred mills are being used for beneficiation of fine grained base metal ores (e.g. Century Zinc, McArthur River, George Fisher) (Jankovic et al. 2000).

Crushing is performed in a series of size reduction steps, which vary from hard ores (Cu, Au, Fe ores), which may require three stages of crushing to soft ores (uranium, bauxite) that require little or no crushing. Crushing can be achieved by different equipment through either slow compression of particles against rigid surfaces or by impact. The next stage of size reduction for mineral processing generally involves wet grinding in tumbling mills where breakage occurs by compression, chipping and abrasion using an assortment of grinding media. The product of primary grinding can result in particles between 40 and 300 µm for tumbling mills but varies according to the type of mill (Table 5). In the case of stirred mills, particle sizes of a few microns (<15 µm) can be achieved but with high energy costs (Herbst et al. 2003; Cecala et al. 2012). Grinding is most often performed with a slurry, which reduces dust emissions to negligible levels, but where dry grinding is used dust emissions can be considerable. Since grinding operations can produce particles that are within the respirable size range, this source of dust dispersal poses a significant health threat to workers.

Cecala et al. (2012) discuss in detail the dust control mechanisms for crushing, grinding and screening. Briefly, dust suppression during crushing can be achieved through the application of water, by enclosure of the dust source with or without exhaust ventilation or a combination of wet and dry methods. Milling or grinding operations that utilize dry milling should use enclosed milling circuits and transfer points to contain dust dispersal. Dust control systems during the screening process should also be fully enclosed to minimize dust dispersal.

Stockpiles

Storage piles of ore (short-term), waste rock and tailings (long-term) and other aggregate materials are integral to any mining operation. Storage piles are usually

Table 5 Summary of grain size reduction parameters for milling (Herbst et al. 2003)

Comminution equipment	Feed size (cm)	Product size (µm)	Conditions
Ball mill	1	>20	Wet or dry
Autogenous mill	<25.4	>200	Wet or dry
Stirred ball mill	<150	>0.2	Wet

left uncovered due to the access requirements for frequent material transfer. Dust emissions can occur throughout the storage cycle, during loading and unloading of material and erosion by strong winds. Dust emission from stockpiles will depend on the grain size of the aggregate material, age of the pile and moisture content. The US EPA AP-42 (US EPA 2006), provides emission factors for particulate emissions from stockpiles which depend on the particle size of the storage material, wind speed and material moisture content.

Fine-grained tailings in tailings dams or other storage facilities are susceptible to wind erosion and therefore, dispersion of dust. The particle size distribution of tailings is heterogeneous with sizes ranging from fine silt to sand. There are numerous studies documenting the contamination of the surrounding environment by metal and metalloid bearing dusts sourced from abandoned tailings. For example, Abdelouas (2006) described the geochemistry and mineralogy of radioactive dust dispersed from tailings produced during uranium mining, which is known to cause lung cancers; high As concentrations were observed in the >8 μm fraction of dusts generated at an abandoned mine tailings site in Nova Scotia, Canada (Corriveau et al. 2011). A study in southeast Spain showed that the PM10 fraction of dust sourced from oxidised ferruginous tailings was preferentially enriched in metalloids such as As and Sb (Moreno et al. 2007).

There are several control mechanisms for reduction of dust generated from various stockpiles (Cecala et al. 2012). Factors that can reduce wind erosion include: (i) material that is compacted, roughened or kept moist; (ii) material that contains stable clods that are large and dense enough to resist wind erosion; and (iii) vegetated surfaces or surfaces that are covered in vegetative materials (e.g. straw). Reduction of wind velocity near the ground surface using vegetation or barriers reduces erosion. Various chemical suppressants are available to the mining and minerals industry which include wetting agents, binders, crushing agents, foaming agents and foam binders. However, the most effective coating as a dust control method is the formation of a crust on the surface of the material, preferably a non-toxic crust. These can be produced by mixing bentonite clay with soil or the application of Guar Gum polymer to the surface of a tailings pond. The orientation and configuration of storage piles can be optimized according to wind conditions and pile height to reduce fugitive dust emissions (Badr and Harion 2007).

Mineral Dust Measurement and Monitoring

Since the 1950s the minerals industry has had in place preventative measures to limit its workers exposure to dust through the implementation of Occupational Exposure Limit values (OELs) at the work place in European Union member states and other countries including Australia (e.g. Guidance on the interpretation of workplace exposure standards for airborne contaminants; Safe Work Australia 2012). Accurate measurement and monitoring of dust concentrations are essential for the management of dust-related lung diseases. Dust monitoring is particularly

Table 6 Permissible exposure limits (PEL) for different mineral dusts (SME Mining Engineering Handbook 2011)

Dust type	PEL
Crystalline silica	0.01 mg/m^3
Silicates	
Asbestos	5 fibres/cc
Mica	706/million m^3
Cement	1056/million m^3
Talc	706/million m^3
Coal dust	2 mg/m^3 or 10 % crystalline silica
Metallic dusts	
Mercury	0.05 mg/m^3
Lead	0.15 mg/m^3
Antimony, arsenic	0.5 mg/m^3
Manganese	5 mg/m^3
Iron, zinc, molybdenum	5 mg/m^3
Uranium (insoluble)	0.2 mg/m^3
Vanadium (V_2O_3)	0.5 mg/m^3

concerned with the particle size of dust, since particle size determines the exposure route and consequently the health impacts. At mine sites, the monitoring of dust emissions is an integral part of the dust control strategies. Dust management plans for the minerals industry aim to reduce and control dust emissions around mine sites. Dust management plans include: (i) identifying potential dust sources; (ii) implementing measures to avoid and or minimize dust generation; (iii) complying with legislation and other obligations; (iv) reducing negative environmental and human health impacts of dust; and (v) rigorous monitoring and reporting, and systematically investigating dust related incidents (e.g. Lingard and Gibson 2011).

Meteorological monitoring (wind speed and direction, precipitation) may also be required to enable accurate interpretation of dust monitoring data. According to the agency overseeing the mine approval process, baseline air quality conditions prior to mining need to be assessed as part of a monitoring program. The air quality monitoring programs are implemented according to the specifics of each operation, in order to meet air quality guidelines regulated by state and federal bodies (Airborne Contaminants, Noise and Vibration 2009). For example, in Australia, the National Environment Protection Measure for Ambient Air Quality recommends a maximum concentration of 50 µg/m^3 over a day. The more hazardous finer particulates PM2.5 are limited to an annual average of 8 and a 25 µg/m^3 maximum over a 24-h period (DSEWPC 2013). The permissible exposure limits (PEL) for the exposure to various respirable dusts is shown in Table 6. The PELs are taken from SME Mining Engineering Handbook (2011) showing PELs for various respirable dusts, adapted from the general guidelines provided by the American Conference of Governmental Industrial Hygienists (ACGIH 1972).

The 50 μg/m^3 PM10 criterion has proved problematic in its interpretation and compliance for the mining industry as explained in the Best Practice Handbook for Airborne Contaminants, Noise and Vibrations (2009). An example is given from the Hunter Valley, where the combined emissions of multiple mines can affect the air quality in nearby communities. Invariably, background sources of emissions can be significant. Therefore, the 50 μg/m^3 criterion is often applied as an incremental goal, that is, the concentration above background emissions from other sources. Also, consideration must be given to the fact that this standard can be breached when there are bushfires, deliberate burning-off or dust storms.

Monitoring Methods

Dust monitoring methods vary in sophistication and are fit for purpose according to the compliance monitoring required. The specific locations of dust monitoring instruments should reflect the nature of the dust sources and include control sites, which provide an indication of background levels during the mining operations. The frequency of sampling will vary according to the objectives of the monitoring programme and sampling equipment.

In general, there are two approaches to dust monitoring, passive techniques that generally monitor TSP and do not require a power source, so are relatively inexpensive (e.g. dust deposition gauges; personal exposure samples); and active systems that require a power source to measure nuisance dust and different particle sizes (e.g. high volume samplers; continuous particle monitors).

Dust Deposition Gauges

Dust deposition gauges are ideal for longer term and remote monitoring of dust deposition at low cost. Settable particulate matter can be sampled using a high-density polyethylene. (HDPE) funnel connected to a HDPE bottle similar to a rain gauge style of passive fallout collectors. The dust gauges are left in position for set periods of time (months) before the gauge is removed. The contents can then be filtered in the laboratory and the total dust deposition measured. This monitoring method provides information about the rate of atmospheric deposition but cannot provide data on short timescales or high-resolution particle size information.

High Volume Air Samplers

High volume air sampling (HVAS) devices (Fig. 1) are recommended for monitoring of TSP and PM10. Precise volumes of air are continuously drawn through a

Fig. 1 Two high volume air samplers monitoring TSP and PM10 at an offsite location near a mine (*left*). Close up of the filter paper shown under the lid of the TSP sampler (*centre*). The PM10 high volume sampler situated adjacent to the TSP sampler (*right*) (color figure online)

filter paper beneath a protective hood, which prevents particulates from falling onto the paper. The sampling is carried out for a set time period (24 h cycle/week) onto a filter of known weight, which can be reweighed to determine the mass of particulates collected. The concentration can then be calculated together with the total volume of air drawn in during the 24-h period according to the standard method for TSP and PM10. For PM10, a size selective inlet attached to the sampler ensures that only particles with a diameter less than 10 µm are collected. Deleterious elements such as Pb, Cd and Zn can be measured on the TSP and PM10 fraction collected on the filters, by chemically digesting the filter paper and analysing the metal concentrations using atomic absorption spectrometry (AAS) or inductively coupled plasma mass spectrometry (ICPMS).

Dichotomous Samplers

The dichotomous sampler (dicot) is another particulate sampler that can be used to meet requirements of the regulator (e.g., US EPA 1999; AS 3580.97:1990). The instrument separates particulate matter into coarse (2.5–10 µm) and fine (<2.5 µm) fractions by removing the larger particles through impact, while the finer inhalable particles are separated by a virtual impactor technique. The filter papers are weighed in the laboratory prior to dust sampling under controlled climatic conditions, and the mass of particulates collected during a 24-h period is determined gravimetrically. Teflon can be used as a filter media, which can then be analyzed for the chemical composition of the particulate matter.

Real Time Air Quality Monitoring

A wide range of dust monitors are available, which can provide information about dust concentration in real time. The most common type of sampler used to measure dust in mine air is the gravimetric sampler. This is described in detail in Colinet (2010).

A tapered element oscillating microbalance (TEOM), is a sampling device designed to monitor size specific particulates on a continuous near real-time basis, without the delay required for laboratory-based gravimetric determination of PM concentration or data averaged over a 24-h period. For details on how the TEOM system works see Patashnick and Rupprecht (1991).

Light scattering devices, can also be used in real-time dust monitoring. These incorporate a near-infrared light emitting diode source, a silicon detector, and collimating optics. Particulates passing though the sensing chamber scatter light, which is proportional to their concentration. For example, the DustTrak™ DRX Aerosol Monitor 8533 can simultaneously measure size-segregated mass fraction concentrations corresponding to PM1, PM2.5, PM10 and total PM size fractions. Real time monitoring can be implemented to prevent the measurement of concentrations exceeding trigger levels or compliance levels.

Personal Dust Exposure Monitoring

Personal dust samplers are an extremely important part of work place health and safety in industries such as coal and metalliferous mining. The personal dust samplers were originally developed to measure respirable coal mine dust mass to provide accurate exposure data at the end of a work shift in an effort to reduce the incidence of coal workers pneumoconiosis (Volkwein et al. 2004). The National Institute developed an advanced type of personal dust sampler for Occupational Safety and Health (NIOSH) in partnership with industry. This instrument, known as the personal dust monitor (PDM), provides continuous information about the amount of respirable coal mine dust in the breathing zone of an individual. This device incorporates a miniaturized tapered-element oscillating microbalance mass sensor that can provide time resolved measurements on a screen display. The PDM then gives the wearer information on the cumulative dust concentration, and the permissible exposure limit that has been reached. The PDM performance in underground coal mines shows that this device provides data that is equal to or better than manual dust collection and analysis methods available (Volkwein et al. 2006).

The personal DataRam (pDR) is another common personal dust sampler that provides real time information (Colinet 2010). This operates by dust-laden air passing through a sensing chamber in the sampler. A light beam passes through the dust. A sensor in the sampler measures the amount of light scatter caused by the dust and relates this scatter to a relative dust concentration. This concentration is correlated to the time when the sample was measured and stores this information in the internal data logger. The logged data can be analyzed for specific time intervals (e.g., loading a cut), with average dust concentrations calculated for these intervals.

Biomonitoring

Lichens have been used in biomonitoring studies for more than 50 years to monitor the levels of pollution resulting from human activities (Nimis et al. 2000). Lichens are ubiquitous throughout the natural environment as well as in urban areas. They are perennial organisms and therefore provide year round monitoring of pollutants predominantly from aerial sources. There are numerous examples of the use of lichen in environmental biomonitoring programs to monitor trace elements (e.g. Al, As, Ba, Cd, Cu, Fe, Mg, Ni, Pb, Zn) in the atmosphere on large spatial scales (e.g. Sloof and Wolterbeek 1991; Conti and Cecchetti 2001). Different methods can be applied to lichens in biomonitoring studies which include: (i) index of atmospheric purity, where compositional changes in the lichen community are correlated with changes in the levels of atmospheric pollution; and (ii) direct analysis of contaminants in the thallus (tissue of lichen) in high pollution zones, which are transplanted from low pollution areas and fixed to suitable surfaces in the monitoring areas (Conti and Cecchetti 2001).

Fugitive dust in zones associated with mining can be sampled using lichens on yearly timescales, providing valuable information to distinguish the background signal from the deleterious metals associated with industrial activities. Samples of lichen are processed by microwave acid digestion to dissolve the heavy metals, which can be measured by ICP-AES, ICP-MS or electrothermal atomic absorption spectrometry (ETAAS) (Dolgopova et al. 2006). Furthermore, systematic scanning electron microscopy (SEM) investigation of particulates on the surfaces of the thalli can be carried out using back-scatter mode and scanning electron microscopy energy-dispersive X-ray spectrometry (SEM-EDS) to quantify the mineralogy and qualitative estimates of elemental abundance (Williamson et al. 2004). However, lichen cannot be used to assess the ambient air quality relating to human health studies. Williamson et al. (2008) demonstrated that lichen were able to trap larger blast-furnace particulates (mean equivalent spherical diameter of 2.2 μm) derived from a Cu smelter in Karabash, Russia, but the smaller particles were not captured by the lichens. Furthermore, due to the size selective bias, the composition (and therefore source) of the TSP sampled by sampling pumps was different to that of the lichen.

Mineral Dust Characterization

Understanding the mineralogy and morphology of dust has important implications for the heath risks associated with dust inhalation. The toxicity of individual mineral dusts has been investigated, with examples for silica (Richards and

Wusteman 1974; Fubini et al. 1999), kaolinite (Lapenas et al. 1984), talc (El Ghawabi et al. 1970), and mica (Shanker et al. 1975). The following sections describe techniques used to determine the mineral composition of dust. A summary of research techniques relating to dust characterization is shown in Table 7.

IR and XRD Techniques

Infrared (IR) spectrophotometric and X-ray diffraction (XRD) methods are two techniques applied to dust samples, specifically to monitor quartz which is a lung carcinogen (Ferg et al. 2008). X-ray diffraction can distinguish between complex mixtures of minerals, whereas IR techniques have been used in particular to measure polymorphs of silica. There are three main crystalline forms of silica; quartz, tridymite and cristobalite of which there are two variations of each (high and low). Measurement of crystalline silica from filters is typically performed as per the NIOSH IR analytical Method 7602 and XRD analytical Method 7500.

Madsen et al. (1995) reviewed IR, XRD and colorimetry methods for quartz analysis. IR analysis is based on the bonding energy of minerals. It measures the vibrational energy of the covalent bonds between silicon and oxygen. However, interferences are possible due to overlapping spectral peaks at 798 cm^{-1} from other phases of silica and silicates with similar tetrahedral SiO_4 structures (Madsen et al. 1995). An understanding of the sample matrix is therefore important when considering IR analysis, as chemical and heat treatments can be applied to remove some interferences. This method is not suitable for all sample matrix but is less expensive than powdered XRD.

XRD is more costly that IR, however it is less prone to interferences. Gualtieri et al. (2009) used XRD to monitor asbestos dust in Italian communities. This study explains how samples must be prepared to prevent interference of the filter on the analysis of the dust composition. Dust samples were analysed for different polymorphs of minerals by scanning different diffraction lines characteristic of each polymorph. Treatment in a muffle furnace at 500 °C for 1 h was necessary to separate the overlap of the main basal diffraction peaks of kaolinite and chrysotile. At 500 °C, the crystal lattice of chrysotile remains unmodified, while kaolinite decomposes (Criado et al. 1984; Cattaneo et al. 2003).

Particle Size Distribution

The particle size distribution of mineral dusts generated during mining is an important factor controlling the depth of dust deposition in the respiratory system. The particle size distribution of dust collected on filters can be measured using a Coulter Counter Multisizer. This instrument is a multi-channel analyzer based upon the electrical sensing zone (ESZ) or Coulter principle. The number and size of the

Table 7 Summary of techniques used to establish the mineralogical composition of mineral dust

Study	Location	Sampling	Particle concentration	Size and morphology	Chemical composition
Jones et al. (2002)	Openpit coal mine, Margam, South Wales	HVAS with PM10 selective inlet or TSP head on polycarbonate filter	Gravitational method	FESEM	SEM-EDX TEM-EPXMA
Moreno et al. (2005)	Almadén, Spain	polycarbonate filter		FESEM	SEM-EDX XRD ICP-MS
Panigrahi et al. (2006)	Chromite mine, Sukinda valley, India	Respirable particulate matter samplers; HVAS	Laser particle size analyser Cascade Impactor		Cr(VI) extracted from dust using colorimetric method
Meza-Figueroa et al. (2009)	Nacozari de García, tailings impoundment, Mexico	Mine tailings; efflorescences; soils; residential soils and road dust			XRD
Gualtieri et al. (2009)	Bologna, Modena, Reggio Emilia, Italy	HVAS on a Whatman cellulose nitrate membrane (PM10); fallout particulates; soil samples	Gravitational method	Optical microscopy SEM	SEM TEM
Magiera et al. (2011)	Various industry dusts	Fly ashes; dust from lignite combustion; cement dusts; dusts from coke production		SEM	XRD, Mossbauer spectroscopy
Pachauri et al. (2013)	Agra, North Central India	TSP collected by HVAS onto quartz fiber filter paper	Gravitational method	SEM	SEM-EDX

particles is measured by suspending the sample in a conductive liquid and monitoring the electrical current that passes between two electrodes, on either side of a small aperture. As the particles pass through the aperture, it changes the impedance of the current between the two electrodes, producing a pulse with a magnitude proportional to the particle volume. The small quantity of sample required make the Coulter Multisizer ideal for quantifying the grain size distribution of dust (McTanish et al. 1997). The Coulter Counter Multisizer has been used to determine the particle size distribution of TSP collected on filters using low volume samplers mostly in relation to agricultural sources of dust (e.g. Sweenten et al. 1998) and in studies comparing the PM10 fraction measured using different sampling devices (Capareda et al. 2005).

Other studies have analyzed the particle size distribution of the samples using particle laser diffraction in a Malvern Mastersizer by dispersion in a surfactant (Ferg et al. 2008) or a Scanning Mobility Particle Sizer, which consists of a Condensation Particle Counter (CPC) combined with an electrostatic classifier (Beccaceci et al. 2010). The Malvern Mastersizer provides a range of different particle sizing products for the analysis of sub-nano meter to millimeter. These specific laser diffraction or light scattering devices for measuring the particle size distribution have been shown to be more accurate than SEM techniques, which are limited by the sample preparation and the statistics of small sample sizes (Ghosal et al. 1995). However, little to no mineralogical information is available with these methods.

Scanning Electron Microscopy

Since the 1970s, scanning electron microscopy (SEM) fitted with X-ray Energy Dispersive Spectrometers (EDS) has been applied to characterize the physical and chemical characteristics of mine dust (DeNee 1972; White and DeNee 1972). Dust particles can be analyzed by mounting them on a stud or plate distributed evenly over a sticky carbon tape; or attaching segments of inert filters on to the studs. SEM-EDS has been used in numerous studies to characterize airborne particulate matter because it can simultaneously provide information about the size, morphology and chemical composition of particles (Jones et al. 2002; Reynolds et al. 2003, Vassilev and Vassileva 2004; Casuccio et al. 2004).

The limitations of SEM-EDS analysis include: (i) it only provides an approximate particle composition in terms of elemental composition; (ii) low efficiency in the detection of elements with low atomic masses (Jones et al. 2002); and (iii) when using filters (e.g. composed of quartz; polycarbonate) from HVAS, the experience of the SEM operator is required to accurately identify the spectra which can be affected by the composition of the filters. To obtain quantitative particle composition the filter should be composed of Teflon, which does not cause spectral interferences. An alternative method, X-ray photoelectron spectroscopy (XPS or electron spectroscopy for chemical analysis or ESCA) could be used (Huertas et al. 2012b).

Transmission Electron Microscopy

Transmission electron microscopy (TEM) is a powerful method for the semi-quantitative to quantitative characterization of individual dust particles. This technique is recommended as ISO standard for determining the concentration of asbestos fibres in ambient air and includes the measurement of the length, width and aspect ratios of asbestos structures (ISO 10312:1995). Transmission electron microscopes fitted with EDS can: (i) detect elements with masses larger than carbon ($Z \geq 6$); (ii) observe particles as small as 0.001 μm (in comparison a FESEM can image 0.1 μm); and (iii) determine the crystalline structure of the particle by the electron diffraction pattern. The phase identification of particles by analysis of electron diffraction patterns is time consuming, therefore this method is applied to selective particles, in addition to analysis of chemical composition by SEM (e.g. Kandler et al. 2007). For identification of an asbestos fibre using typical TEM analysis the definition specifying a minimum aspect ratio of 3:1 for particles longer than 5 μm is not valid. Many non-asbestos particles would fit this definition, therefore, Harris et al. (2007) developed a protocol that supplements FESEM with the TEM analysis method. This method allows the overall particle shape, surface topography and the side and termination (particle end) geometries to be characterized and reduces the number of non-asbestiform particles identified. This combined FESEM-TEM analysis was applied to the characterization of mineral dust from a former vermiculite mine in Montana, USA, where amphibole particles were classified into six primary groups: fibre, acicular, prismatic, bladed, columnar and bundle. Unique morphological features can be observed with FESEM that cannot be observed in a standard TEM image, which allows asbestos and non-asbestos particles to be differentiated (Harris et al. 2007).

Raman Spectroscopy

Raman spectroscopy is a powerful technique for identifying structural details of minerals (i.e. to differentiate between polymorphs), and information on elemental speciation and crystallinity (Das and Hendry 2011). Raman spectroscopy has been widely applied to characterize the chemical composition of atmospheric aerosols and dust, for example: (i) respirable diesel and coal particulates in coal mines (Suhartono et al. 1996) and carbonaceous aerosols in urban environments (Sze et al. 2001); (ii) the chemical interactions between mineral dust and organic acids (Laskina et al. 2013); and (iii) chemical species and mineral dust in polar ice cores in Antarctica (Sakurai et al. 2010).

Raman mapping is a valuable tool that can be used to determine how various chemical components are spatially distributed within a single particle and has been used to determine the spatial distribution of chemical species within dust particles (Laskina et al. 2013). Instrument that map both physical and chemical characteristics of submicron particles are now available (e.g. Malvern MorphologiG3-ID). A study by Rinaudo et al. (2003) applied FT-Raman spectroscopy to distinguish between the three principle minerals of the serpentine group (chrysotile, antigorite and lizardite), which have a very similar chemical composition but a significantly different structure.

Geochemical Assessment

Dust management plans for mine sites are to comply with set limits for the concentration of deleterious elements in the TSP and PM10 fraction collected using HVAS. Also, a thorough assessment of the geochemical composition of dust, particularly from metalliferous mines is important for understanding metal and metalloid loading and transfer of environmentally significant elements. The concentrations of metals and metalloids in dust can be established using appropriate sampling protocols and analytical tools such as AAS, ICP-AES or ICP-MS. For example, elevated trace metal contents (Cu, Zn, As, Pb) of size segregated soil samples analyzed by ICP-AES and ICP-MS has been used to identify anthropogenic sources from smelter facilities (Parra et al. 2014).

Guidelines for metal and metalloid concentrations in air pollutants know to have health effects are reported by WHO (2000). Arsenic is a human carcinogen and no guideline for a safe level of inhalation exposure has been recommended considering a linear-dose response (WHO 2000). Heavy metals such as Pb, Co, Cd, Cu, and Cr are toxic at certain levels and are considered hazardous contaminants that can accumulate in the human body. For example, Cd has a half-life of 10 years in the human body. Experiments on animals demonstrate that Cd can produce acute toxic effects on organs such as the kidney, liver, pancreas and lung (Godt et al. 2006). Chromium (VI) compounds can cause chrome ulcers, corrosive reactions on nasal septum and eczematous dermatitis. The toxicity of Pb has been explained by its interference with different enzyme systems or displacement of essential metal ions (WHO 2000). The toxicity of metals and metalloids is also dependent on their ion speciation and redox state. For example, chemical species with net neutral charges are most easily transferred across cell membranes; while elements such as Cr and As are more toxic in their hexavalent and trivalent states, respectively (Plumlee and Ziegler 2003).

Methods for Predicting Particle Size and Mineralogy of Dust

Traditional dust emission estimation factors used in the mining industry do not take into account geological variability or rock type. The dust emission factors for blasting, comminution and road haulage are the same for both coal and metalliferous mine operations (NPI 2012). Methods for predicting dust characteristics could be developed following a similar approach to those used to predict rock fragmentation during blasting and comminution. Over the past few decades there has been a push to optimise rock breakage for metal extraction. This has led to research predicting rock fragmentation and blast size distribution of rocks (McKee et al. 1995). A new dust prediction tool has been developed by Michaux (2009), who adapted a small scale comminution crush test to characterize rock, in terms of its texture and propensity to generate dust. The GeM Comminution Index (GeM Ci), developed in the AMIRA P843 project, takes discrete pieces of drill core and measures the size distribution after applying energy (Kojovic et al. 2010). The resulting particle size distribution represents the rock breakage signature, which can be used to calculate the GeM Ci Dust Index (GeM Ci DI) for each rock type (Eq. 1) (Michaux 2009).

$$GeM\ Ci\ DI = \frac{\beta}{\tau} \tag{1}$$

where:

β (%) of whole sample passing 106 μm after GeM Ci crushing

τ (%) of whole sample passing 1.18 mm after GeM Ci crushing

The shape of the size distribution of the cumulative (%) passing fragmentation was shown to be similar for crushing and blasting of the same rock type (Moser et al. 2003; Michaux 2009). The GeM Comminution Index can therefore be used to estimate the size distribution of particles <100 μm, released during blasting and crushing processes, as well as during transport of material. The <100 μm fraction produced can: (i) provide information on the ratio of TSP, PM10 and PM2.5 fractions produced for each rock type; (ii) be analysed for morphology and mineralogy of each size fraction; and (iii) simulate the proportion of particles that may become airborne.

A second method, applied to understanding mineral fractionation during crushing to predict mineral liberation and flotation behaviour, could also be adapted to understand the morphological and mineralogical characteristics of dust. There is very little data available in the literature on the mineralogy of different size fractions produced during comminution. Only one such study by Berry et al. (2013) is presented. In this research, 32 samples from two IOGC deposits were crushed to −3.3 mm and the resulting size fractions analysed using QXRD. The bulk mineralogy was calculated by weighted least squares to calculate the preferred weight percent minerals, by combining the chemical assay with the QXRD results (Berry et al. 2011). This provided a robust estimate of the high abundance minerals based on QXRD with the higher precision of chemical assay used to define less common minerals.

The fractionation of minerals into different size fractions varies according to mineral hardness, which controls how minerals crack and fracture. Therefore, weaker minerals are expected to experience greater size reduction than harder minerals for the same crushing energy. Berry et al. (2013) observed that coarse size fractions were enriched in harder minerals such as quartz, while softer minerals like barite were concentrated in the finer fractions. Mineral fractionation into size fractions was not always predictable; in some samples K feldspar was enriched in both the coarser fractions (+475 μm) and the finer fraction (−53 μm). Furthermore, pyrite and magnetite fractionation was determined by the grain size of the mineral, in contrast to chalcopyrite, which fractionated according to the rock hardness (Berry et al. 2013). Data collected on rock hardness (e.g. Equotip; Keeney 2008) and mineral fractionation by size (Berry et al. 2013), may be used to understand the mineralogical fractionation in dusts. This could add significant value to the analyses undertaken as part of geometallurgy data collection, since understanding mineral grain size fractionation is an important factor in mineral processing.

Conclusions

This review presents details on mineral dust generated during metalliferous mining and processing activities. Dust generated during mining activities provides a pathway for the accumulation of heavy metals and contaminants in the surrounding environment. The amount of mineral dust generated, its dispersal, and types of health and environmental risks depend on many factors. These include geology, local climate, topography, working methods and mine operations, dust control measures, mineralogy and metallurgical characteristics of some ores, and the land use of the area around the mine.

At mine sites, fugitive dust generation can result from land clearing, drilling and blasting, transport on unsealed roads, and the release of fine particles from waste repositories and ore stockpiles. Finer grain size fractions are produced from crushing milling and screening operations, which act as point sources for dust dispersal. Similarly, dust emissions from transport and stockpiling of ore concentrate and tailings repositories are well known sources of mineral dust. Dust suppression and control mechanisms can reduce dust produced by wind erosion. These include wetting and chemical agents to bind the material together, and enclosure of crushing circuits and transfer points.

Dust monitoring methods are generally determined by the specifications for work place health and safety to meet the air quality guidelines regulated by federal organizations. Low-cost technologies include dust deposition gauges for long term monitoring dust deposition. High volume air samplers provide size specific (e.g., PM2.5 and PM10) determinations of dust flux while a range of options exit for real time dust monitoring. Biomonitoring methods are also used to monitor the trace metal flux to the surrounding environment.

Geochemical and mineralogical characterization of dust is required to understand potential risks to human health and local environment. Particle shape is another important factor in determining the hazardous nature of dust particles. Geochemical characterization is carried out through ICP-MS and ICP-AES methods, while SEM a powerful tool for characterizing mineralogical attributes of mineral dust.

Grain size is the major control on the risk of exposure to mineral dust through digestion and inhalation. Predictive tools are required to evaluate the risks of dust generated by mining operations and facilitate the selection of appropriate dust management strategies. Existing predictive tool focus on dust dispersion modelling however, there has been little research on predicting the dust properties (e.g., mineralogy of grain size fractions). Future work should consider appropriate methodologies for predicting mineral fractionation across the size spectrum, which would allow more advanced dust management schemes.

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